RFID SYSTEMS IN THE NON-RESIDENTIAL CONSTRUCTION INDUSTRY

Improving construction logistics

BY R.J.H. (RENS) VAN DEN HURK (BASc.)

Date: 15 Dec. 2016

Master's Thesis: Main Report (Public)

UNIVERSITY OF TWENTE.

heijmans

Colophon

FACULTY OF ENGINEERING TECHNOLOGY (CTW)
3TU Federation – In cooperation with TU-Delft & TU-Eindhoven

Master of Science: Construction Management and Engineering

Date
15 December 2016

Title
RFID SYSTEMS IN THE NON-RESIDENTIAL CONSTRUCTION INDUSTRY

Subtitle
Improving construction logistics

Status
Final

Course: Master's Thesis Size main report: 61 pages
Size appendices: 84 pages (Appendix D, F, G Confidential)

Author
R.J.H. (Rens) van den Hurk (BASc.)

Telephone
+316 46 23 25 82

E-mail address
rens_vandenhurk@hotmail.com; rensvandenhurk@gmail.com; rensvandenhurk@outlook.com

Institution
University of Twente
Faculty of Engineering Technology
Dept. of Construction Management & Engineering
Mailbox 217, 7500 AE, Enschede
Drienerlolaan 5, 7522 NB, Enschede, the Netherlands

UNIVERSITY OF TWENTE.

Host Company
Heijmans NV.
Business Unit: Heijmans Non-Residential Construction
Dept. of Business Development
Mailbox 2, 5240 BB Rosmalen
Graafsebaan 65, 5248 JT Rosmalen, the Netherlands

heijmans

Supervisors
Chairman: Dr. J.T. (Hans) Voordijk
Associate Professor of Supply Chain Management; University of Twente
Second Supervisor: Prof. Dr. Ir. A.M. (Arjen) Adriaanse;
Professor of Construction Process Integration & ICT; University of Twente
External Supervisor: Ir. B.W.P. (Bas) Mertens
Program Manager of Innovations; Heijmans Non-Residential
Additional supervisor: Ing. A.W.M. (Ton) Fleuren
Director Business Development and Commerce; Heijmans Non-Residential

Keywords:
Radio Frequency Identification, RFID, RFID Systems, Construction Logistics, Supply Chain Management, Non-Residential Construction, Construction Sector

"If you cannot measure it, you cannot control it. If you cannot control it, you cannot manage it. If you cannot manage it, you cannot improve it"

~ Dr. H. James Harrington ~

Samenvatting Nederlands

Probleem omschrijving
Om meer controle te krijgen over de bouwlogistiek wordt door vele onderzoekers de implementatie van een *'Control Tower'* geadviseerd. De huidige bouwlogistiek is een foutgevoelige en inefficiënt proces, resulterend in een verlaagde arbeidsproductiviteit en vele verspillingen op de bouwplaats. Voor deze '*Control Tower'* is het hebben van real-time informatie van de locatie van bouwproducten noodzakelijk. Radio Frequency IDentification (RFID) is technologie waarmee deze informatie verkregen kan worden, echter, doordat onderzoekers slechts <u>één bouwsector</u> omschrijven (er zit veel verschil tussen de projecten) en slechts <u>één soort RFID systeem</u> omschrijven (vele verschillende systemen zijn beschikbaar) is het voor bouwbedrijven onduidelijk wat de toegevoegde waarde van RFID kan zijn.

Onderzoeksvraag
De hoofdvraag van deze Master's thesis luidt als volgt:

'Welk RFID systeem moet toegepast worden onder welke project omstandigheden om de meeste toegevoegde waarde te kunnen leveren aan utiliteitsprojecten"

Onderzoeksmethode
De toegevoegde waarden van een RFID systeem bij utiliteitsprojecten werd in onderzoeksvraag één bepaald met behulp van een literatuur analyse. De project omstandigheden werden in onderzoeksvraag twee geïdentificeerd met behulp van tien expert interviews in vijf totaal verschillende case studies. Deze experts werden gevraagd naar tekortkomingen in de bouwlogistiek op hun projecten, wat de oorzaken hier van zouden zijn en of zij een toegevoegde waarde herkennen in hun situatie. De resultaten van deze tien interviews zijn vervolgens geanalyseerd met een within-case en een cross-case analysis. Met deze analyses werd het duidelijk dat de experts de toegevoegde waarde zoeken vanuit slechts vier verschillende motivaties. Deze motivaties werden in onderzoeksvraag drie gebruikt bij het ontwerpen van verschillende RFID systemen doordat er verschillende soort informatie nodig is. Deze systemen zijn vervolgens omschreven en vergeleken met elkaar, waarna ze zijn voorgelegd aan drie directeuren van het gast bedrijf (Heijmans Utiliteit) te weten: directeur *'Ontwerp & Engineering'*, directeur *'Projecten'* en directeur *'Beheer en Exploitatie'*. Zij zijn gevraagd of zij een potentieel toegevoegde waarde herkennen in deze systemen voor Heijmans. De resultaten zijn vervolgens vergeleken met de resultaten uit het onderzoek tot dusver, waarna de hoofdvraag beantwoord werd.

Resultaten
Veertien toegevoegde warden zijn geïdentificeerd met behulp van het literatuur onderzoek:

1. Product Life Cycle Information	2. Visibility Products Upstream Supply Chain	3. Shipment Visibility of Goods
4. Automate Goods Receiving	5. Real-Time Stock Balances	6. Minimizing the Excess of Stock
7. Minimizing Dwell-Time	8. Minimizing Fraud / Theft of Goods	9. Monitoring Progress / Production
10. Unique Product Identification	11. Localize Products on Site	12. Self-learning Teams
13. Information Upstream – Execution	14. Monitoring Building Performance	

Door verschillende project omstandigheden zochten de experts naar een verbetering in: *'A. Duurzaamheid', 'B. Productiviteit', 'C. Controle over materiaalstromen'* of *'D. Gebouw beheer'.*

Acht RFID systemen zijn omschreven in onderzoeksvraag drie: *'A. Hergebruik producten & Vermindering kilometers', 'B: Off-site Logistiek & On-site productie', 'C. Meer controle in aankomst & Meer controle in opslag'* en *'D: Informatie over producten & Informatie van sensoren'*. Met behulp van de interviews met de directeuren en de bevindingen uit het onderzoek is de volgende ordering gemaakt:

1. Systeem C. Control, subsysteem: *'Aankomst'* (61)
2. Systeem D. Gebouw beheer, subsysteem *'Informatie' (61)*
3. Systeem D. Gebouw Beheer, subsysteem *'Sensoren'* (56)
4. Systeem C. Controle, subsysteem *'Opslag'* (51)
5. Systeem A. Duurzaamheid, subsysteem *'Hergebruik producten* (47)
6. Systeem A. Duurzaamheid, subsysteem *'Vermindering kilometers* (47)
7. Systeem B. Productiviteit, subsysteem *'Off-site'* (37)
8. Systeem B. Productiviteit, subsysteem *'On-site'* (33)

Implementatie interessant

Implementatie niet direct interessant

Aanbevelingen:
Ondanks dat RFID een enorm potentieel lijkt te hebben om meer beheersing te krijgen in de bouwlogistiek zijn het de variatie in de sector, de diversiteit in de vele RFID systemen, geen real-case scenario's en het ontbreken van deugdelijke kosten/baten analyses die de bouwbedrijven terughoudend maken om een dergelijke nieuwe technologie te implementeren. Aanbeveling is dan ook om meer onderzoek te verrichten naar in welke situaties welk RFID systeem echt van toegevoegde waarde kan zijn voor bouwbedrijven.

Summary English

Problem statement

The implementation of a *'Control Tower'* is advised by many researchers in order to increase the control over the construction logistics. This is currently an error prone and inefficient process, which results in a decrease in labour productivity of jobsite workers and many wastes on site. This *'Control Tower'* needs real-time information about the location of construction products throughout the supply chain. Radio Frequency IDentification (RFID) is a technology which can offer this kind of information, however, since researchers describe only the construction sector and a RFID system, it is unclear for construction contractors which RFID system (there are many of them) should be applied in which situation (there are many different types of construction projects) in order to obtain the most added value of it.

Research question

The main research question of this Master's thesis is:

'Which RFID system should be applied under which project circumstances in order to obtain the most added value for non-residential construction projects?'

Methodology

For the first research question, the added values of a RFID system are investigated by use of a literature analysis which describes the pros and cons of a RFID system for the non-residential construction industry. The determining project circumstances are identified by use of ten expert interviews from five totally different case studies. These experts were asked for bottlenecks in current construction logistics, the causes of these wastes and if they see an added value in the overview resulting from the previous question. By use of a within-case and cross-case analysis, the outcome of these expert interviews are analysed from which certain shared motivations became clear. These type of motivations are grouped together in order to identify different RFID Systems. A description and the comparison between these systems are submitted to three directors of the host company: Heijmans non-residential (director of 'Design & Engineering', director of 'Projects' and director of 'Maintenance and Utilization') in order to judge the potential added value of these system at the host company. These outcomes are compared with the findings of the author and the study in order to answer the main research question.

Results

Fourteen added values have been identified during the literature analysis of research question one:

1. Product Life Cycle Information	2. Visibility Products Upstream Supply Chain	3. Shipment Visibility of Goods
4. Automate Goods Receiving	5. Real-Time Stock Balances	6. Minimizing the Excess of Stock
7. Minimizing Dwell-Time	8. Minimizing Fraud / Theft of Goods	9. Monitoring Progress / Production
10. Unique Product Identification	11. Localize Products on Site	12. Self-learning Teams
13. Information Upstream – Execution	14. Monitoring Building Performance	

Due to the project circumstances in the five case studies, the experts search for an improvement in *'A. Sustainability'*, *'B. Productivity', 'C. Control over supplies'* or *'D. Building Management'* .

Eight RFID systems were identified in research question three, which are: *'A: Re-use products & Reduce kilometres'¸ 'B: Off-site logistics & On-site production', 'C: Control in Arrival & Control in stock on site'*, and *'D Information from products & Information from sensors'.* From the judgement of the author and the three directors, the following ranking has been identified in which the RFID systems should be implemented in the host company (total score has been given between brackets):

1. System C. Control: subsystem '*Arrival' (61)*
2. System D. Building Management: subsystem '*Information' (61)*
3. System D. Building Management: subsystem '*Sensors' (56)*

Worthwhile to implement directly

4. System C. Control: subsystem '*Storage' (51)*
5. System A. Sustainability: subsystem 'Re-use products' (47)
6. System A. Sustainability: subsystem '*Reduce kilometres' (47)*
7. System B. Productivity: subsystem '*Off-site' (37)*
8. System B. Productivity: subsystem '*On-site' (33)*

Not worthwhile to implement directly

Recommendations

From this study, it looks RFID does have a huge potential to increase the control over the construction logistics in many ways. However, the variety in the industry, the diversity of the RFID systems, the missing real-case scenarios and the absence of reliable cost/benefit ratios makes construction contractors reluctant against such a new technology in the sector. More research should be done on these subjects to point out specific cases in which RFID really can add value in construction projects.

Preface

Dear reader,

This thesis is the last product of my Master study and at the same time, it forms the closure of a long study path. This long study path has been led and fed by an interest in seeking for improvements in large scale and complex non-residential construction projects. Interests in the construction sector arose during my early ages, in which I spend a lot of time playing with blocks and constructing imaginary structures with LEGO™ and K'nex™. Starting with the Lower General Secondary Education (Basic Professional) (in Dutch: VMBO – Basis), I have learned to follow my interests because it gives myself the motivation which enables me to reach great things. During the first year of this secondary education, this motivation resulted in high school marks in which I jumped from the Basic Professional level via the Combined Professional (in Dutch: VMBO – Gemengd) to the Lower General Secondary Education: Theoretical level (in Dutch: VMBO – Theoretisch / mavo). Meanwhile, I got into touch with craftsmen, the diversity and complexity in the construction sector and I saw how my working activities can contribute to an actual physical structure during my part-time job in the residential construction sector. It is amazing to see my work in real-life years later!

Finishing this Theoretical level in the subsequent three years, I felt I could reach a higher educational level, whereby I started with two more years of the Higher General Secondary Education (in Dutch: havo). For the first time, I struggled with some of my school courses since I had no interests in these courses. However, this has strengthened my motivation to do what I like to do: being part of, and working on, large scale and complex non-residential construction projects. Therefore, the start of my Bachelor of Applied Science in Construction Management felt as the right decision for me. In these four years, I saw how literature could be used into practice, resulting in improvements and optimizations for businesses and for end users. Hereby, I achieved great insights from my first internship (assistant site manager at Van Wijnen Groep NV.), my internship abroad in the beautiful republic of Panama at Mallol y Mallol Arquitectos (inspector of the project el Parlamento Latinoamericano, i.e. el Parlatino), the enthusiastic teachers of the courses of my study and also, my graduation internship at Besix Group (a study towards the strategic approach of MEAT-documents during tenders). Again, this study has been led by my interests in large scale and complex non-residential construction project. In order to be eligible for positions out of my reach with this achieved Bachelor of Applied Science degree, I started the pre-master Civil Engineering at the University of Twente.

The obtained academic skills in this pre-master were sufficient to start with the Master of Construction Management and Engineering, which now comes to an end. Guided by my interests in new ways of working (e.g. Building Information Modelling BIM), searching for the impossible with use of innovations in the construction sector, cooperating with multiple stakeholders in dynamic environments and searching for the optimum in large-scale and complex non-residential construction projects, I was able to apply all these topics into this Master's thesis. Clearly, without the needed space and the right persons around me, I would not have had the opportunity to follow and implement these interests.

Therefore, special thanks I would like to make to my supervisors of the University of Twente: Dr. J.T. Voordijk and Prof. Dr. Ir. A.M. Adriaanse. They had the knowledge and experiences for years, I had only an idea. Formulating this idea into a well-found Master's thesis did took some time. Without the critical view and knowledge of these supervisors, I would never end this thesis. Besides, special thanks I like to make to the host company, Heijmans non-residential and its key actors for me: T. Fleuren and my daily supervisor Ir. B. Mertens. They gave me the needed space and resources to carry out this research and to finish my Master. I am honoured to start my working career at Heijmans non-residential and to see what my motivation and interest can bring to myself and to Heijmans. I am also thankful to the many persons I have interviewed throughout this research (internal and external employees) and to obtain their information and their insights. At last, without the support, the motivating conversations and the patience of my close family, friends and my girlfriend, I would not be able to finish this Master's thesis at this moment. We have experienced some tough times recently. The statement I can give them in return from now on is: '*believe in the impossible, you'll reach extraordinary things*'.

I wish you a lot of reading pleasure and get inspired by the unforeseen possibilities of this technology.

R.J.H. (Rens) van den Hurk
Utrecht the Netherlands, December 2016

Definitions and abbreviations

Added value	an 'amount' added to a product or a service, expressed in a time improvement, a cost reduction or an incensement in quality. New arising products or services can also be of added value
Building Performances	the output (expressed in values) of Heating, Ventilation and Air-Condition (HVAC) installations compared to the use of the building
Control Tower	a fictive control tower which manage and coordinates the flows of men, machine and materials, and its corresponding information flows throughout the (construction) supply chain which is thereby capable in optimizing processes between the multiple actors involved and the multiple projects sites
Construction Logistics	the flow of man, machines and materials (and its corresponding information) throughout the material supply chain towards a project site, its utilization phase and the demolition phase
Construction Phases	the distinguishing constructing phases of a building during its realization phase: substructure, superstructure, roof/façade, finishing and completion
Construction Supply Chain	The supply chain of products from the material supply chain toward the project site (see also material supply chain)
DBFMO	Type of contract in the construction sector: Design, Build, Finance, Maintain, Operate, in which more responsibilities of the project life cycle shift to the main contractor
Dwell-time	The time a product remains in a given state or at the same location
Data	*'Crude discrete or objective data. The objective data indicates only a "what," and is lacking of the "how" or "why" part '* (Parikh, 2001)
EAN	a world-wide applied standard (known from the barcode) for product identification at SKU level (European Article Number)
EPC	a world-wide unique product identification number, developed by GS1 (Electronic Product Code)
Excess of stock	also called: overstock, unnecessary stock which is a waste
GS1	a world-known organisation which develops and implement standards on the subject of electronic communication between companies
Information	*'data which has been processed in a certain way, so that there is a certain level of significance assigned to'* (Davenport and Prusak, 1998)
Lean Management	an operational management philosophy focusing on the highest customer value with the minimal wastes
Material Supply Chain	the phases of the material life cycle of products: Raw materials, Factory, Distributor, Wholesaler, Logistic Service Provider, Final Location
Non-residential Construction	buildings (physical structures) which are not intended as a dwelling
RFID	*'RFID is the process and physical infrastructure by which an unique identifier, within a predefined protocol definition, is transferred from a device to a reader via radio frequency waves'* (Bank 2007)
RFID Tag	the identifier-component (transponder) antenna and microchip included
RFID Reader	the component which displays the receiving RF waves into digital data
RFID System	a composition of components which obtains, displays and processes unique product information throughout enterprise systems
SKU – Stock Keeping Unit	a tradable unit which can be ordered by Customers in a chain (a unit can consists of multiple products)
'Last-Mile'	the transport of products from the last company (node) in the construction supply chain to the project site
Product	a physical article which can be trade
Project Circumstances	an event (or related) which affects a project budget, time or quality
Project Life Cycle	the distinguishing project development phases (also called construction value chain): Project Idea, Project investigation, Conceptual design, Design stage, Realization phase, Utilization phase and Demolition phase
Waste	an event (part of failure costs) which not add value to a product or service (increasing time, increasing costs or decreasing quality)

Table of Content

1. Introduction ... 1
   1.1 Research Motivation ... 1
   1.2 Research Gap ... 1
   1.3 Problem statement, goal and context of the research ... 2
   1.4 Research Questions ... 2
   1.5 Research Methodology ... 3

2. The added value of RFID for the construction sector ... 5
   2.1 Introduction ... 5
   2.2 The RFID system ... 6
   2.3 Advantages of a RFID system ... 7
   2.4 Disadvantages of a RFID system ... 9
   2.5 Added value RFID systems for the construction sector ... 12
   2.6 In conclusion ... 15

3. Data Collection Method ... 17
   3.1 The selection of the case studies ... 17
   3.2 The interview protocol ... 19
   3.3 Project characteristics ... 20

4. Results Interviews ... 22
   4.1 Within-case analysis ... 22
   4.2 Cross-case analysis ... 28
   4.3 The confrontation ... 30
   4.4 In conclusion ... 33

5. RFID systems for non-residential construction projects ... 35
   5.1 RFID System ‘Sustainability’ ... 36
   5.2 RFID System ‘Productivity’ ... 39
   5.3 RFID System ‘Control’ ... 41
   5.4 RFID System ‘Building Management’ ... 43
   5.5 Comparison RFID systems ... 45
   5.6 Validating the findings ... 47
   5.7 In conclusion ... 49

6. Conclusion and recommendations ... 51
   6.1 Limitations ... 51
   6.2 Conclusion ... 53
   6.3 Recommendations ... 57

7. References ... 59

Appendices Master's thesis (public)

Appendix A. Why RFID? 1
a) Identification Technologies 1
b) Localization Technologies 3
c) Communication Technologies 6
d) Comparison matrix 6

Appendix B. The RFID system 9
a) History 9
b) RFID tag 9
c) Radio waves 14
d) Reader 18
e) Middleware 20
f) Enterprise 21
g) The RFID System 21

Appendix C. RFID applications 23
a) RFID applications in other industries 23
b) RFID applications in the construction sector 25

Appendix D. Case Studies (confidential) 29
a) Schiphol Lounge 2 Amsterdam, the Netherlands 30
b) Telecity AMS 1 Amsterdam, the Netherlands 32
c) Eurojust The Hague, the Netherlands 34
d) Hart van Zuid Rotterdam, the Netherlands 36
e) National Military Museum Soesterberg, the Netherlands 38

Appendix E. Interview Protocol 40
a) Interview protocol – <*Project Name*> 41
b) Key figures project <*Project Name*> 43
c) Advantages, Disadvantages, Drivers and Barriers RFID System 45
d) Added value of RFID system 46

Appendix F. Results interviews (confidential) 47
a) Schiphol Lounge 2, Amsterdam, the Netherlands 47
b) Telecity AMS 1 Amsterdam, the Netherlands 50
c) Eurojust The Hague, the Netherlands 53
d) Hart van Zuid Rotterdam, the Netherlands 56
e) National Military Museum Soesterberg, the Netherlands 58
f) Summary results interview 61

Appendix G. Line of Reasoning (confidential) 62

Appendix H. Interview building management systems 67

Appendix I. The RFID Systems in detail 68
a) RFID System 'Sustainability' 69
b) RFID System 'Productivity' 73
c) RFID System 'Control' 77
d) RFID System 'Building Management' 81

chapter

1

“ Constructing is transporting”

~ P.J. (Jurre) van der Ven – Heijmans ~

1. Introduction

This chapter will introduce the research topic of this Master's thesis. First, the motivation will be explained, hereafter, the research gap will be explored, the problem definition, the research goal and research questions will be elaborated upon. The reading guide of this thesis will be given at the end.

1.1 Research Motivation

The construction logistics is recognized by multiple experts as an error prone and inefficient process, resulting in a decrease in labour productivity of jobsite workers and many wastes on site (USP Marketing Consultancy 2009, Persson et al 2010 and Thunberg et al 2013). Many attempts have been made to improve this construction logistics, however, the characteristics of the sector makes it challenging to implement new ways of working and thereby, it is difficult to improve the efficiency.

These characteristics have to be pointed out since the construction sector differs greatly from other sectors. Buildings are not produced in factories, projects are always unique due to its location, its stakeholders and its design plans and the sector is recognized by its fragmented nature. This fragmented nature, see *Figure 1*, results in many different companies working together during the realization phase, all responsible for a very specific part in a relatively short period of time. Due to the increasing responsibilities of the main contractor in construction projects (new type of construction contracts, more actors are involved and a higher complexity of buildings), there is a need to get more control over the construction supply chain and to optimize the construction logistic within, even becoming more important in the future. Therefore, an improvement in the construction logistics is search for in this research.

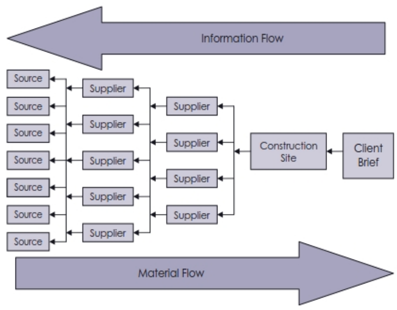


Figure 1 A typical construction supply chain (Barthope et al. 2010)

1.1.1 Heijmans Non-Residential

This study is commissioned by the host company Heijmans non-residential construction, a subsidiary company of the parent company: Heijmans NV., a Dutch listed company (the third biggest construction company in the Netherlands with an annually revenue of €2 billion 2015) that operates in property development, residential buildings, non-residential buildings, roads and civil engineering in the fields of '*living', 'working'* and *'connecting'*. The operating field '*working'* represents the non-residential construction industry, which is the department where this study will be carried out. Heijmans non-residential (annually revenue €421 million in 2015) designs, realises and maintains high-quality electro-technical and mechanical installations, and realises large-scale and complex construction contracts in the market segments of health care, government and semi-government organisations, commercial property, the high-tech clean industry (such as laboratories) and datacentres. At Heijmans NV., the *'contours of tomorrow'* strategy describes the aim of Heijmans NV. to be the best and thereby the most innovative construction company of the Netherlands. This should be achieved by producing the most suitable designs and content in the built-up environment and thus, creating added value for Heijmans' clients and their end users. Striving for a continuous improvement in the core activities and the key words '*Improve and Renew'* defines the ambition of Heijmans NV. perfectly.

1.2 Research Gap

In order to improve the construction logistics during the *realization phase*, control is needed over the supply of products. As mentioned in *Paragraph 1.1,* this phase is very fragmented, making it difficult to optimize processes between the amount of actors involved. However, from the literature, it became clear that more collaboration in the construction supply chain is needed in order to improve the labour productivity, reduce failure costs and thereby decrease construction costs (Yan et al 2013, Deshmukh et al. 2014). The need for more collaboration between construction partners is also present at managers of Heijmans. These managers (see *Chapter 7 References*) have a sense for a more efficient construction logistic process. However, they have no insights what the impact of current logistics on the realization phase is. They appoint, during the preparation of this study, supply chain management and finally the '*Control Tower'* as a tool to obtain more control and collaboration between the construction partners.

1.2.1 Control Tower

This *'Control Tower´* is a fictive control tower, like an air traffic control tower, which manages and coordinates the flows of man, machine and materials, and its corresponding information flows, throughout the supply chain and thereby is capable in optimizing processes between the multiple actors involved (Vries de A. et al 2015). Since supply chain management, defined as *'…The management of upstream and downstream relationships with suppliers and Customers to deliver superior Customer value at less cost to the supply chain as a whole'* (Christopher 1997), is less invasive than the *'Control Tower'*, more resources are needed in order to let this *'Control Tower'* functioning properly. One of the currently missing resources is a proper information and communication system between the actors (Shou-Wen et al 2013). Real-time information about the identification and location of man, machine and materials is needed in order to be capable of optimization between the multiple actors. Currently, this missing resource limits the applicability of the *'Control Tower'*, which increases the attention of researchers to search for suitable technologies in Information and Communication Technologies (ICT) in construction.

1.2.2 Radio Frequency IDentification (RFID)

In other sectors (e.g. retail, logistics, aviation and the defence industry), Radio Frequency IDentification (RFID) systems are proposed for to obtain this real-time information about the location of man, machine and materials (Jaselskis et al 2003, Yagi et al 2005, Song et al 2006 and Shou-Wen J. et al 2013). RFID technology is a composition of components, further explained in *Paragraph 2.2 The RFID system*, which makes it possible to identify and localize unique products from a distance by use of radio waves. Many advantages are achieved with RFID technology in these sectors, which receives increasing attention of researchers in the construction sector as well. Possible advantages for the construction sector are a reduction of human interaction for material handling, an increasing data accuracy, an improving information exchange between partners, the tracking of production progress, it gives more control during unforeseen circumstances, a support for quality, a continuous flow of supply and production on site, optimization of scarce space on site, a support for asset management, a reduction in stock-outs, improved Customer service, a support for after sales and a reduction of stock on site by the possibility of Just-In-Time deliveries (Li and Visich 2006). Nevertheless, there is a lack of empirical evidence to the benefits of these RFID systems, allowing such systems barely to be applied (Tajima 2007, Sarac et al 2010, Sun et al. 2013 and Li et al 2016). Since researchers mainly talk about the construction sector and a RFID system, it is unclear for construction contractors to implement such a RFID system since there are many different RFID systems and there are many differences between the construction projects.

1.3 Problem statement, goal and context of the research

Since RFID systems are barely implemented in practice and researchers describe RFID systems as if there is only one kind of RFID system suitable in all situations, it is too risky for construction contractors to invest in a new technology without knowing the added value of it. So, the problem statement of this research is defined as:

It is unclear under which project circumstances which RFID system can be of added value in non-residential construction projects

Thereby, by providing insights in which RFID system should be implemented under which project circumstances, project teams should be able to benefit from the added values a RFID system can offer in practice. Thereby, the goal of this research is:

Give insights in which RFID system should be applied under which project circumstances in order to achieve an added value in non-residential construction projects

In order to provide reliable outcomes, the context of this research will be demarcated from here. The focus of this research will be on the information and communication exchange around the transportation of products and its related product information. This information exchange will be investigated in the non-residential construction industry since it is expected that the wastes around the transportation of products and its corresponding information is considered significantly higher in this industry due to non-repetitive realization phase, many different specialized companies involved, a great diversity in products used in non-residential buildings and the projects have a great impact on the direct surroundings of the project site (according to Heijmans non-residential).

1.4 Research Questions

In order to achieve this research goal, the following main research question have been formulated, followed up by three research questions and its corresponding sub questions.

Which RFID system should be applied under which project circumstances in order to obtain the most added value for non-residential construction projects?

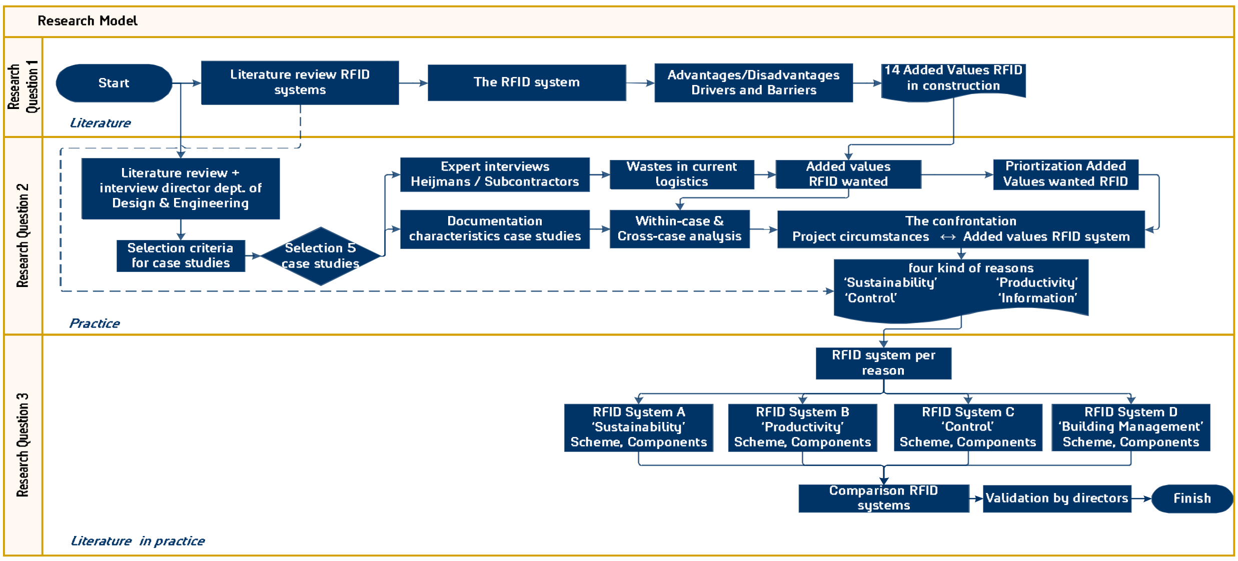
In order to answer this main research question, the following research questions and sub questions are formulated:

1. What are the added values of RFID systems in the non-residential construction projects?
   1.1. What is a RFID system?
   1.2. What are the advantages and disadvantages of RFID systems in the non-residential construction industry?
   1.3. What are the drivers and barriers to implement RFID systems in the non-residential construction industry?
2. Under which project circumstances is which added value of a RFID system the most wanted one and why?
   2.1. Which wastes in logistics are present in construction projects of Heijmans non-residential?
   2.2. What are the differences and commonalities in the wastes in construction logistics in multiple non-residential construction projects of Heijmans?
   2.3. Which added value is wanted in which non-residential construction project of Heijmans?
   2.4. What are the motivations of the experts why these added values are wanted in the non-residential construction projects?
3. Which RFID systems can realize these added values in non-residential construction projects?
   3.1. Which RFID systems have been identified?
   3.2. What are the differences between these RFID systems?
   3.3. To what extent recognize directors of Heijmans non-residential a potential added value in these identified RFID systems?
   3.4. Which RFID system should be worthwhile to implement in non-residential projects?

1.5 Research Methodology

Due to the diversity of different questions and information resources needed, the following research methodology will be used. The Research model to be followed is given in Scheme 5 below.

- Research question one will be answered by use of a literature analysis. From multiple resources (scientific journals, papers and books with relevant literature), the sub questions will be answered.
- Research question two will be answered by use of expert interviews. Five (totally different) case studies will be selected in which ten experts will be interviewed (face-to-face). In *Chapter 4 Results Interviews*, the outcome of these interviews will be analysed by use of an within-case and cross-case analysis.
- The outcome of these analyses will be used in order to identify multiple RFID systems. These systems will be described and submitted to three directors of the host company. They will judge the potential added value of the RFID systems. The outcome will be compared in-between by which the research question can be answered.



Scheme 1 The research model of this study

Research question one will be answered in Chapter 2 The added value of RFID for the construction sector, research question two will be answered in Chapter 4 Results Interviews and research question three will be answered in Chapter 5 RFID systems for non-residential construction projects.

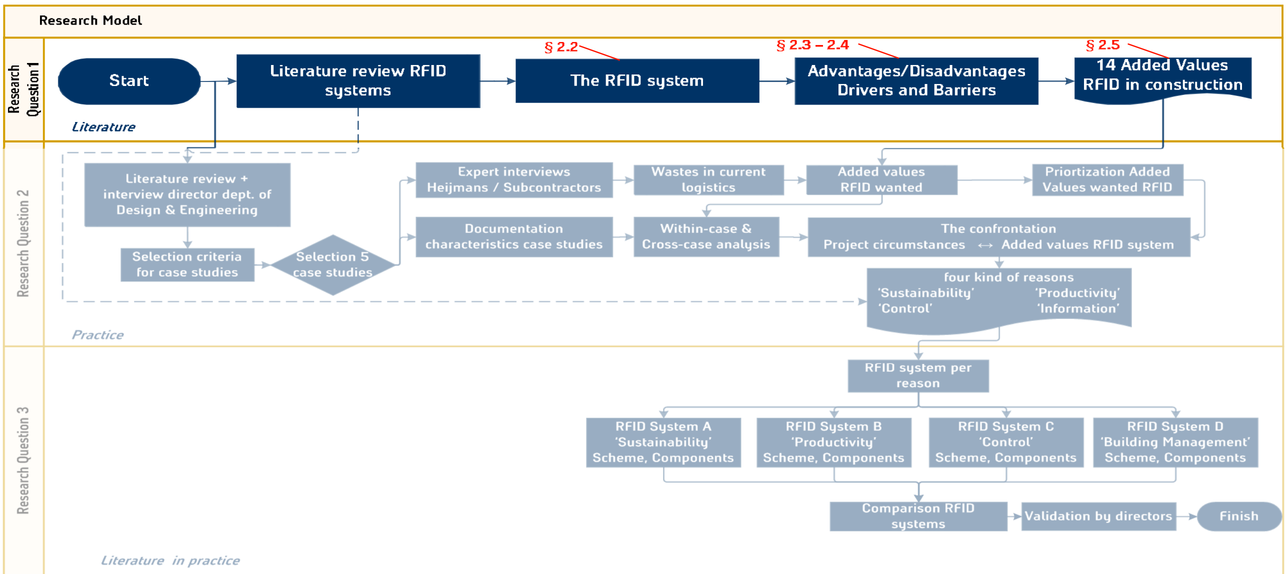
chapter 2

"Self-measurement leads to self-knowledge, which is the first step toward changing behaviour"

~ Quantified Self ~

2. The added value of RFID for the construction sector

In this chapter, it becomes clear what a RFID system is and why a contractor should implement a RFID system by taking a closer look to its advantages its drivers and its disadvantages and barriers to implement a RFID system (or not) in the non-residential industry. At the end of this chapter, the conclusion will be drawn about which added value a RFID system can offer to construction contractors in order to minimize waste at non-residential construction projects. The research model has been given:



Scheme 2 Research model Research question 1

2.1 Introduction

The present project sites have been changing taller, larger and more complex (Kim 2013) and often take place in an uncontrolled, unprepared and dynamic environment where each construction project goes through several phases leading to its completion (Sarac 2010). Waste and inefficient processes at the project site have a huge contribution to the project delays and costs overruns. The materials to be used in buildings account for 50% of the total project costs (Kini 1999). Current material management processes are error-prone and labour-intensive due to the amount of paperwork and human interaction involved. At large and complex projects, a proper material management system is even more problematic (Kasim 2013). Therefore, there is an increasing need to share information among the project partners. Due to the circumstances of the construction sector, this information has to be adequate and in real-time since decisions and communication is based on the information and knowledge available. These current inefficient processes result in the following, daily, problems at project sites according to Muya 1997, Sarac 2010, Sardroud 2012 and Safa 2014:

– Materials are required but not purchased;
– Materials are purchased but not received;
– Materials arriving at the site at the wrong time or wrong quantity;
– Materials whose specifications do not match those in the purchase order;
– Unavailability of information regarding the status of orders;
– Lack of complete and up-to-date information regarding arrival of materials on the site;
– Lack of up-to-date information regarding site stocks;
– Extensive multiple-handling of improperly sorted materials in search of required pieces;
– Missing or surplus of materials;
– Lack of storage space for materials on site;
– Waste of man hours searching for materials and tracking them;
– Materials that are issued to crafts and are subsequently not used or installed;
– Inadequate identification of materials;
– Re-handling and inadequate storage of materials;
– Lost or damaged materials;
– Errors in material take-off

These problems at the project site clearly results in delays and costs overruns in common construction projects. Authors tried to quantify these losses. Holness (2008), for example, estimated the cost of wasted/lost materials and missing tools at United States' project sites for $0.75 trillion in the United States and $2.7 trillion worldwide. Teicholz (2000) used governmental industry data and indicated that the construction's labour productivity declined from 1964 to 2000 at an annual compound rate of – 0.72%. Serpell (1997) found a craftsman' labour time to be only 47% effective, 28% contributory and 25% non-contributory. Grau 2009 found a craftsmen' worktime only for 30% productive and 70% is made up by consultation, waiting, and searching for materials. This inefficiency generates demotivation which at the same time has an additional negative effect on the worker's efficiency.

With these inefficiency and wastes in mind, there is a huge potential in current material management processes to automate and share real-time information about construction materials with the use of upcoming Information and Communication Technologies (ICT). Real-Time Location Systems (RTLS) can currently provide the highest degree of improvement to site tracking practices and project performance (Grau 2009). Radio Frequency IDentification (RFID) is such a technology which can offer real-time information about the identification and location of specific products. The RFID system will be explained in the next paragraph.

2.2 The RFID system

In a most basic form, RFID is defined by Bank et al (2007) as: "RFID is the process and physical infrastructure by which a unique identifier, within a predefined protocol definition, is transferred from a device to a reader via radio frequency waves". This infrastructure is set up by multiple components, see *Figure 2 Components of a RFID system*.

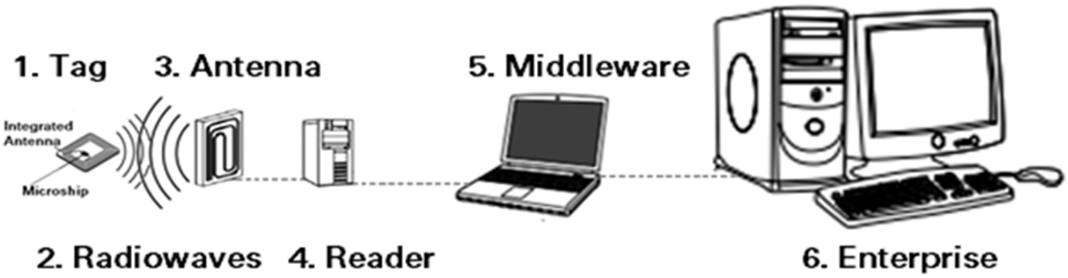


Figure 2 Components of a RFID system

In this system, the RFID tag (1) will be attached on (or placed inside) products and contains an unique number which can be send through radio waves (2) to the antenna (3) of the RFID reader (4). This RFID reader obtains the identification of the RFID tag when this tag is inside the read range of the RFID reader. The exact location of the tag can be send by the tag itself, in combination with an external GNSS sensor such as a GPS device, or multiple RFID readers can determine the RFID tag' position by localisation methods like Time of Flight (TOF) or Time of Arrival (TOA) algorithms. These algorithms determine a tag's position by use of triangulation with the known fixed antenna's position by calculating the difference in time or differences in strength between sending and receiving a signal from the tag, see *Figure 3 Localization based on triangulation*. The middleware (5) process this information to the appropriate enterprise software systems (6) like a SAP or ERP system. In *Appendix B The RFID system*, the whole RFID system is explained, with every component in detail.

With such a RFID system, it becomes possible to identify and localize unique products throughout the supply chain in real-time. This offers the potential for many optimization processes in daily practise at project sites. An overview of possible applications of a RFID system is given in *Appendix C RFID applications*. The reason why to consider RFID as an appropriate technology, has been investigated in *Appendix A*. Unfortunately, there is no in-the-box RFID system for every construction project since each component has its own characteristics and every project has its own characteristics as well. Thereby, choosing the right combination of components for a specific environment becomes a key decision factor for construction companies (Sarac 2010; Li 2016). The advantages and disadvantages of a RFID system will be explained in the next section.

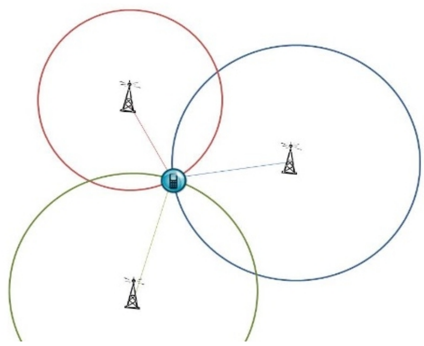


Figure 3 Localization based on triangulation

2.3 Advantages of a RFID system

From this analysis, RFID seems to have a great potential in many different applications in the construction sector, see also *Appendix C RFID applications*. It is this potential why researchers have investigated the advantages and disadvantages of a RFID system in the construction sector. Below the advantages will be described, categorized under the subjects 'technology' and 'supply chain' since RFID can offer advantages over other existing technologies, as well as offering advantages for the whole construction supply chain. These advantages results in drivers for the implementation of a RFID system in the construction sector, described hereafter.

2.3.1 The Technology

The RFID technology offers some advantages compared to current existing technologies in the construction sector and offers organisations new business opportunities. These advantages are noticed by multiple researchers (e.g. Michael 2005; Sarac 2010; Mingxiu 2012; Sardroud 2012 and Li 2016), which include:

- One can read multiple tags automatically and simultaneously from a distance;
- There is no need for a clear line-of-sight between tag and reader;
- There is no need for a clear orientation of the tag;
- RFID can be read through layers of packaging;
- RFID can function in harsh environments (like snow, rain, mud, ice and dust);
- RFID can be reused and reprogrammed and can be read unlimited times;
- RFID can hold great amounts of data locally on the RFID tag or linked to its code;
- RFID makes use of an unique code;
- It is virtually impossible to copy this unique code, ensuring a high level of security;
- 'Hard-case tags' can be placed inside (concrete) products, making it irremovable from the product attached to;
- Additional (environmental) sensors can be attached to the tags, making it possible to send environmental information

With a RFID system, it becomes possible to collect (automatically) real-time information about products and, with sensors, its surrounding. This results in advantages of the system for the whole construction supply chain explained next.

2.3.2 Supply Chain

These technological related advantages offers construction contractors some new business opportunities. In general, an organization can save time, money and effort in daily processes with the information created by RFID systems. Because tags can be read without line-of-sight, simultaneously and automatically from a distance, a RFID system can keep track of the current stock. Thereby, goods receiving at the gate entrance of project sites can automatically be scanned and goods leaving a storage area on-site are automatically being noticed. This offers the possibility for an automatic billing system, preventing fraud and theft on the job site and it keeps the inventory in-control. Workers on a project site are able to identify and localize an unique product, minimizing the excess of stock, counting and searching time of jobsite workers. Managers can hereby keep track on progress on site as well, supporting daily managerial processes and makes the realization phase of construction projects more in-control. RFID creates new and more accurate information about the location of materials than currently is possible, which improves the visibility of products throughout the whole construction supply chain. An overview of the investigated benefits is given in *Table 1*. Some extra information about proven facts and figures of a RFID system in current practice are given in *Appendix C RFID applications*. These advantages result in some clear drivers to implement a RFID system in the construction sector, described in the section hereafter.

• Detailed descriptions of all products in construction supply chain	• Minimizing uncertainty regarding current situation in decision making
• Product Life Cycle information locally	• Improvement information sharing
• Flexibility in organization/ solutions	• Possibility to optimize processes
• Supplier's delivery control	• Improvement material handling
• Production monitoring + continuity	• Automatic Inventory control

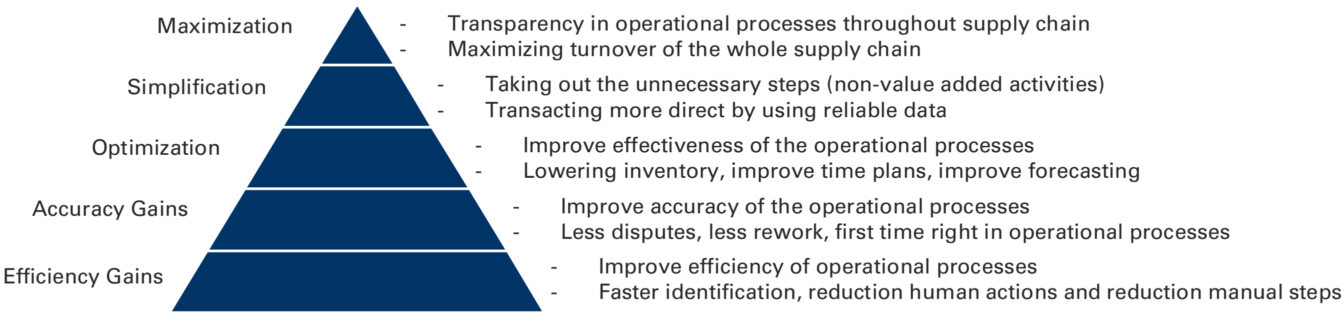
Table 1 Advantages RFID system for the construction sector

2.3.3 Drivers

Although RFID has already been used for over 10 years in other sectors like retail, automotive, transportation and aviation with proven benefits, the construction sector has not taken its advantage yet. The construction sector differs from other industries because buildings are not produced in factories, projects are always unique due to its location, stakeholders and design plans and the industry is recognized by its fragmented nature. These three characteristics results in different processes, different type of projects and different actors at every project. Therefore, the drivers for the implementation of a RFID system in other sectors are not equal to the drivers for an implementation in the construction sector. For the construction sector, the advantages described on the previous page results in the following five driving forces to implement a RFID system in the construction sector, according to Erabuild (2006):

- Tracking and tracing of components, vehicles, parcels, products etc.
- Supply Chain Management and Logistics – improving efficiency
- Product ID - using the right component and device
- Maintenance of service systems improvement
- Track recording of components

RFID provides construction contractors a competitive advantage since they can operate more efficient and create new business opportunities. In the food sector, the use of RFID did raise Customer safety and improves brand protection (Australian Seafood Cooperative Research Centre 2007). Currently, companies in the food sector are obliged to offer information about the point-of-origin at the point-of-sale of food once needed, forced by regulation for safety reasons. With the increasing concerns from the government and public bodies about the use of raw materials today, carbon emissions and sustainable products used inside buildings, one might consider when regulations forces construction contractors or property owners to provide information about the origin of used products in their projects and buildings. Such information can be stored locally on a RFID tag or linked to its unique code. The maintenance of buildings can be much better controlled and predicted with the use of RFID, in combination with external environmental sensors. These environmental sensors can create valuable insights in the performance of a building. RFID can minimize paper work, taking over human processes and minimizes the human effort in daily processes. Decision making can be improved since decisions are based on more and accurate data. RFID can provide the right information about the location of single products at the right time, improving this decision making processes during the realization phase of construction projects. Besides, due to the highly fragmented nature of the industry, many companies are involved during the construction process, which increases the need to exchange data and information even further. This data interchange is even more expected in the future. The data which can be obtained by RFID systems can be used for five distinguished purposes by companies and its supply chain (M. Flederus 2016). This will be visualized by use of the following pyramid.



The higher in the pyramid, the more impact the obtained data can have in a supply chain. Making operational processes transparent throughout the supply chain will result in a continuous improvement in the processes. A summary of these drivers for the construction sector is given in the following table:

• Customer demands for traceability of materials in the future	• Extended use of data (decentralized information)
• Lean construction tools and minimizing waste at construction projects / supply chain	• Demand for more productivity and profitability of construction processes
• Improved worksite security	• 'Intelligent products / processes' – IOT
• Improve market position / corporate image	• New business opportunities (e.g. maintenance)
• Decrease manual and routine tasks at sites	• Speed/visibility through the supply chain

Table 2 Drivers of a RFID system in the construction sector

2.4 Disadvantages of a RFID system

So, RFID seems to have a great potential with clear advantages of a RFID system for construction contractors. However, there are clear disadvantages associated with a RFID system as well. These are described below under the following subjects: ‘Business Processes’, ‘Technical Hurdles’, ‘Ethical Hurdles’, ‘Associated Costs’ and ‘Additional Notes’.

2.4.1 Business Processes

RFID will have a great impact on daily business processes. Current processes are not designed to corporate with real-time information. Authors (e.g. Lu 2011; Sun 2013) noticed that contractors first have to learn more about the technology before they will use the technology. RFID will bring some new extra processes such as tagging the objects, managing an ID-database, use of the information and it have to be maintained. The tagging of materials becomes a managerial hassle since there is a wide variety in materials ranging in size, shape and composition in the construction sector. Other authors (Sarac 2010; Lu 2011; Sardroud 2012) recognized the importance of radio band standards. For example, currently, the Ultra High Frequency band of RFID tags from the USA (902 – 928 MHz frequency band) cannot operate at the radio frequency UFH band of Europe’ RFID readers (865.6 - 867.6 MHz), making it impossible to read a tag from the USA with a reader from Europe. Also, there are no standards between multiple industries. The transportation industry, for example, uses other standards than the construction sector, making it difficult to operate with both standards simultaneously. Even, between RFID manufactures there are differences in the technology. In some cases, one manufacture’ RFID tag cannot be read by another manufacture’ RFID reader, resulting in only close-loop environment applications.

2.4.2 Technical Hurdles

The RFID technology is considered not mature enough for the construction sector yet (Sun 2013). Due to the wide variety of products (different size, shapes and composition), each material will have different influences on the readability of a RFID system. Absorption and reflection of radio waves by metal or liquid materials (Lu 2011, Sardroud 2012) resulting in no readings at all. The cheap passive RFID tags, often called ‘inlays’, are vulnerable for damaging caused by fire or toxic liquids and suffer from its relatively short read range (2-3 metres). The more expensive hard case active RFID tags solves this problem but dramatically increases the price of each RFID tag. Besides, the on-board battery has a limited life time, which has to be managed and the RFID tags are often much bigger in size than passive RFID tags. At last, the technology which will be used, the electromagnetic radio spectrum, is a finite resource. There is an increasing concern of possible interferences between multiple devices operating at the same radio frequency band.

2.4.3 Social Hurdles

Since the construction sector is a labour intensive sector (Erabuild 2006), social hurdles arise by implementation of new technologies. In other sectors, people did concern about their privacy and safety when RFID was applied. Although there is no report which proves radio frequency is harmful to human yet (Lu 2011), people still are concerned about the increasing radio transmissions in the air. Another reason why persons and organizations are reluctant to change is because of the current popularity of barcodes. It is also unclear what the added value of RFID might be. In warehouses, already an extensive identification and localisation system is in place (this can be RFID but most often this is barcode-based system) which enables to operate efficiently. The added value to add another identification and localisation system is thereby limited after shipment from the warehouses to the project site. This lowers the support among different organizations in the construction supply chain (Watson 2007; Nasr 2013). Also, a typical language slang is in place between job site workers in the construction sector. Referring to a cubic metre of sand is not as specific as referring to a specific product, hence, there are many types of sand. Even more specific, ‘yellow sand’ is not that specific as a code for a type of sand since there are many types of ‘yellow sand’, all ranging in composition, density and grain size. In order to eliminate emerging confusion, the industry has to refer to numbers (unique codes) instead of materials like current practice does. At last, people can trust too much on the system, making them blind for unreadable products such as in cases with the presence of steel and liquids.

2.4.4 Associated Costs

Although the costs of simple, passive RFID tags have dropped over the past years due to the widespread employment of RFID tags (from $0.15 - $0.75 in 2005 to €0.05-€0.10 in 2013 apiece), the tags are still more expensive than the barcode (Jaleskis 2003; Lu 2011; Sarac 2010 and Hinka 2013). A RFID system will have at least the following costs:

Hardware Costs	Installation Service Costs	Personnel Costs
• RFID readers • RFID tags • RFID antennas • Cabling & Connectors • Computers (Servers) • Network Switches • Wireless access points & Repeaters	• Setting up Electrical power grid • Install servers and operating systems • Field testing & Calibrating	• Training employees • Reassign internal personnel (lowering initially productivity) • Recruitment employees
Software Costs	**Business Process Reengineering**	**System Integration**
• Middleware System • Database System • Interface System	• Reengineering current business processes • Alignment of construction supply chain partners	• Adjustment of current enterprise software Systems

Table 3 RFID Implementation Costs, source: Bank 2007

** It is hard to quantify the exact costs and savings of a RFID system due to the absence of real-case scenarios and there is no in-the-box system suitable for al projects*

2.4.5 Additional Notes

Next to the above mentioned disadvantages, a few additional notes have to be made as well (based on Sarac 2010). In the observed literature, researchers tend to be proponent or opponent to RFID systems. In case of proponent researchers, they consider RFID as a perfect technology which can eliminate all inaccuracy problems existing in construction supply chains. This will not be feasible in practice. Besides, most studies only treat a single product type in a single-level (close loop) supply chain for a short period of time. Thereby, it is hard to point out the exact added value of RFID for construction supply chains over a longer time. There are many factors which influences the construction' efficiency and RFID deals only with a small part of the whole efficiency of construction projects. When researchers are opponent, they only have developed analytical models, leaving practical situations outside their conclusions, raising the limitations of their studies. The dynamic and uncontrolled environment of the construction sector is hard to duplicate in analytical models. Thereby, the reliability of the studies can be doubtful. Some researchers even suggests RFID as a replacement of current technologies like the barcode. It should be noted here that RFID can be seen as a complementary technology rather than a replacing technology (Ramanathan 2014). At last, it should also be clear that a lack of knowledge and awareness about the potential added value of a RFID system among construction contractors, as well as the lacking Return on Investment figures hinders the implementation of a RFID system in the construction sector. A summary of the investigated disadvantages has been given below.

• Many different sizes, compositions and shapes of frequently changing products and materials	• Lack of organized value chain operations in the industry
• Lack of communication / mutual understanding among different actors in the processes	• Extra processes to be managed (tagging of products, ID database, managing information maintenance systems)
• Fully trusting the technology	• Saturated (finite) radio spectrum
• Immature / limitations technology	• More expensive than current systems
• Implementation, operating and maintenance costs	

Table 4 Disadvantages RFID system for the construction sector

These described disadvantages results in some barriers to implement a RFID system in the construction sector. These barriers will be described in the next section.

2.4.6 Barriers

RFID has already been used for over 10 years extensively in other sectors but rarely in the construction sector. Below, barriers to implement a RFID system in the construction sector are mentioned in order to find out why RFID systems are not implemented yet in the construction sector. The comparison can be made again with other sectors. The characteristics of the sector thereby give insight in the barriers construction practitioners may have. Based on a literature review (Michael 2005; Erabuild 2006; Tajima 2007 and Mohsen 2012), the following barriers are identified:

- There is no dominant actor in the construction sector which enforces RFID like the mandates of retailer Walmart (2005) and the Department of Defence in the USA (2005);
- Due to the fragmentation, many, constantly changing actors operate together in one-of projects, leaving the possibility for a long term investment away;
- The project oriented nature, in combination with the highly competitive climate of the sector, forces organizations in the construction sector to cut down operating costs, resulting in short-term view. This is killing for long term, co-partnering relationships;
- An organization' role differentiate from project to project. In one project, a contractor is acting as a main contractor, responsible for the whole project whereas the same contractor is a subcontractor in another project, making it difficult to assign the added value of RFID over multiple projects for a single contractor;
- It is hard to learn, obtain experience and optimize the technology and processes due to the frequent changes and innovations in the construction sector;
- A lack of industry-wide, inter-industry and international standards makes it impossible to implement open-loop RFID systems, lowering the usability of the system throughout the construction supply chain;
- The cultural behaviour of participants in the construction sector results in an attitude of acceptance of failure costs by redoing work, the involved language slang explained earlier and the naturally resistance to change, blocks the RFID implementation;
- A lack of awareness about the RFID system and a lack of knowledge about its potential added value over current systems for the sector forms a barrier;
- A lack of initiatives in the construction sector lowers the creditability of a RFID system due to the absence of Return On Investment figures.

These barriers result in an unclear allocation of added value for each supply chain' participant, making it hard to split up implementation and maintenance costs and responsible roles of participants. The participant who get most out of the RFID system should take the biggest costs of the RFID system. The immature technology will have still some restrictions in practice, e.g. read range, read speed and readability near metal and liquid objects, for an sector wide adoption of RFID systems (taking the characteristics of common construction projects in mind). The absence of a supply chain wide view of operating parties in a construction supply chain results in optimization inside each organization, instead of optimizations for the whole construction supply chain, lowering the support from supply chain partners. After all, due to the absent of real-case applications, it is unclear which added value a RFID system can offer to each supply chain actor in the construction sector. A summary of these barriers is given below.

• Missing coherence between digital systems (industry wide / inter-industry)	• Resistance of employees / supply chain partners against new technology
• No dominant actor (a "Walmart" in retail) which stimulates the rest of the industry	• Development of new advanced technologies (such as LoRa and Internet-of-Things)
• Missing standardized processes / data handling	• Sluggishness and attitude form involved parties
• Implementation & maintenance cost	• Insufficient implementation efforts
• International competition	• The absence of real case scenarios
• Unclear added value of a RFID system	• Fragmentation in the sector
• Privacy / safety concerns people	• Lack of awareness of the RFID system

Table 5 Barriers of a RFID system in the construction sector

So far, RFID seems to have a great potential for many different applications in the non-residential construction industry. The advantages and drivers, the disadvantages and barriers have been identified. In the next paragraph, this information will be used in order to find out which added value a RFID system can offer to non-residential construction projects.

2.5 Added value RFID systems for the construction sector

RFID is used for many different applications in various sectors. However, the construction sector has its own characteristics and thereby, looking for its own added value for the adoption of new technologies. Often, the motivation for these adoptions can be found in eliminating project delays as well as cost overruns as much as possible. The declining labour productivity and waste at the project sites are two elements in stake which have a huge impact on these delays and costs overruns. Although it is hard to quantify these elements, various studies (Serpell 1997; Love 2002 and Bouwkennis 2014) noticed the presence of these elements at common project site. The study of Serpell 1997 tried to indicate cause-effect relationships of waste at project sites by investigating 17 different construction projects (ranging in houses, offices, hotels) in the period 1990-1994. He found a craftsman' labour time to be 47% effective, 28% contributory and 25% non-contributory, see Figure 4.

Information should be seen as the new value-added for construction project management. RFID can create information about the identification and location of specific products which minimizes waste at project sites (Grau 2009; Kasim 2013). With the pros and cons of RFID system in mind (see previous paragraphs), a RFID system is intended to have an advantageous effect on the following causes of waste at project sites, indicated in the red colour and explained afterwards:

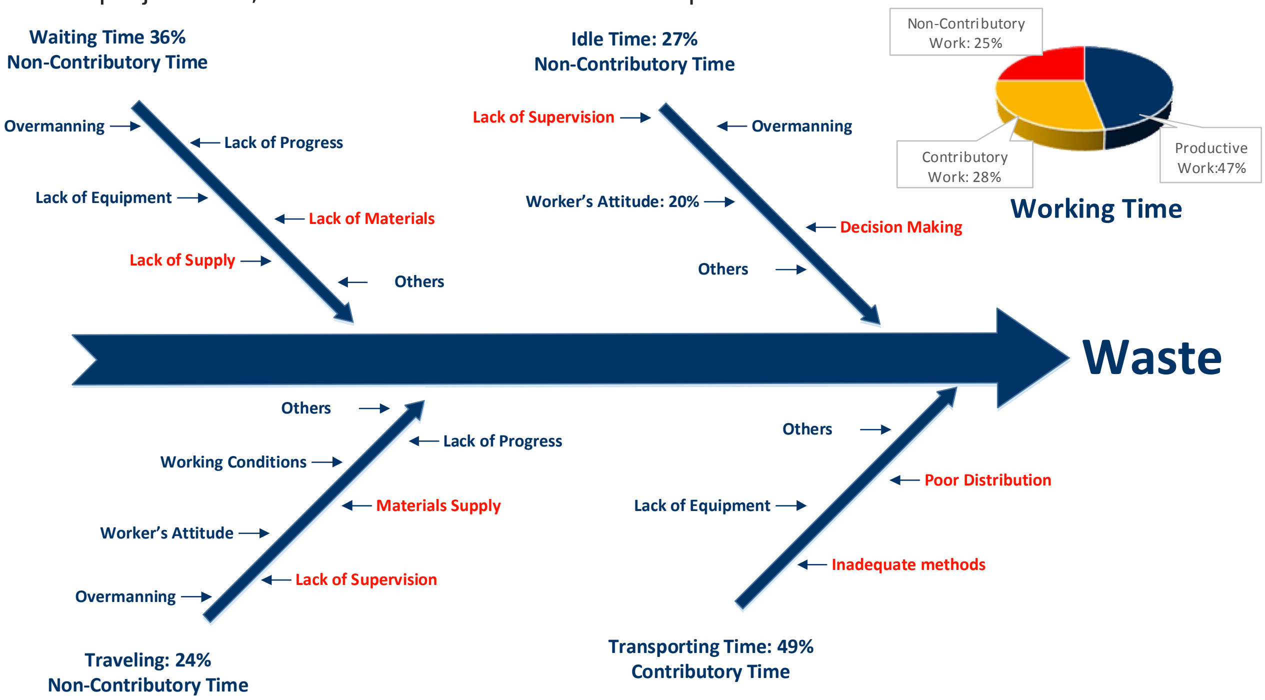


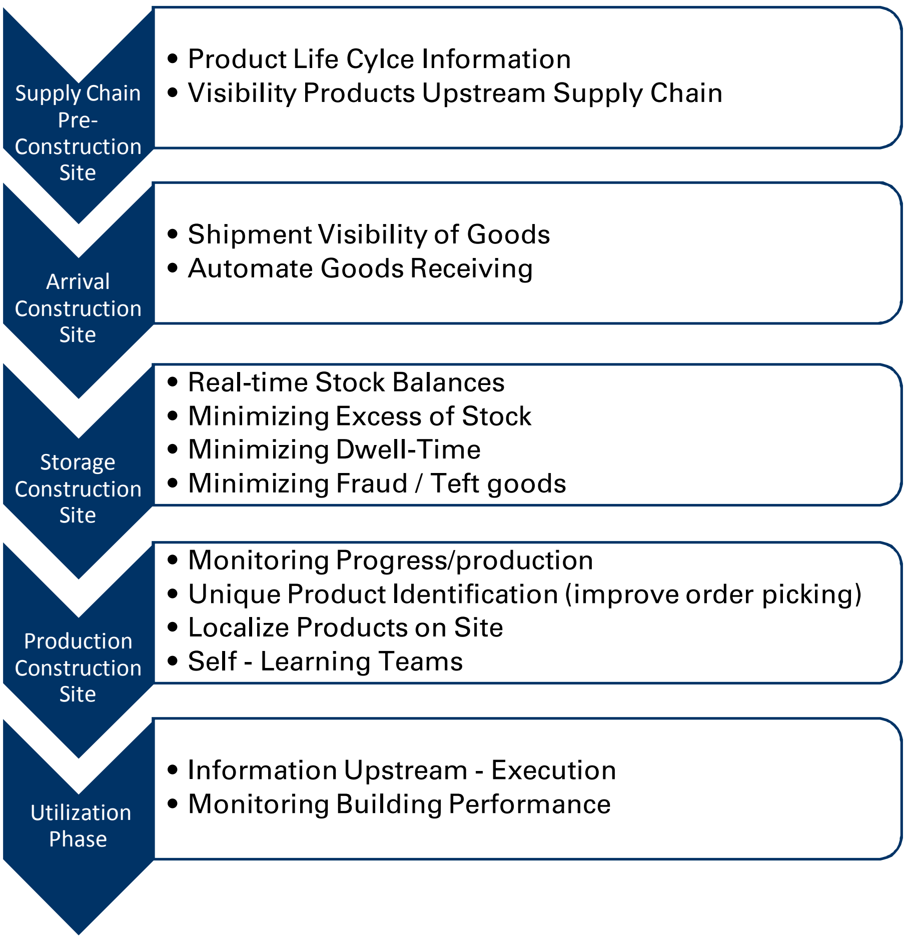
Figure 4 Cause and Effect relationships waste at project sites, based on Serpell 1997

- Lack of Materials: RFID can keep record of products which are stored on-site, in the stock shelves or at a laydown area. Products which are not in the read range of a RFID reader will not be identified. An automatically update can be given when a certain product is below a predefined stock level. This will prevent the waiting time on certain deliveries since materials will be ordered in advanced, without human interaction.
- Lack of Supply: A real-time inventory control system can give suppliers an automatic signal which products have to be delivered when. This will take out the human interaction who previously had to order products manually, eliminating human errors.
- Lack of Supervision: With the unique code of a RFID tag, a job site worker knows exactly which product he or she has to use. Also, it becomes clear which products are on-site (and where they are stored on site), which will improve the productivity of the craftsmen.
- Decision Making: The decision making processes can be improved since RFID can give real-time information about which products are where located throughout the construction supply chain. This will minimizing uncertainty in the decision making process.
- Material Supply: Products which will be delivered at the project site can automatically be scanned by RFID readers when passing the entrance gate (i.e. the reading zone of the RFID reader), confirming the delivery materials. Deliveries can be checked on a management-by-exception basis and there is a Proof-of-delivery. Also, since the location of individual products becomes known, traveling time of job site workers should be minimized.

- Lack of Supervision: In line with 'Material Supply', foremen and managers can give better instructions about which materials are where located on the project site. The materials which have been used can be monitored by computer systems which improves the supervision on site.
- Poor Distribution: Material handling can be improved by automatically scan products. This will eliminate human errors such as wrong counting of materials, wrong transporting of materials on site or by the material supplier and this will minimize re-handling of products on site since it will be known which products has been used where.
- Inadequate methods: RFID can take over human processes and automate processes such as scanning products at the entrance gate and stock shelves, making automatic invoices and automatically suggestion for material ordering possible.

Next to these possible advantageous effect RFID can have on current causes of waste at project sites, RFID can offer some new opportunities. The ability to identify and localize products automatically offers construction contractors a competitive advantage since it gives contractors the ability to optimize processes over and over again (see also visualized pyramid in *Paragraph 2.3.3 Drivers)*. For example, having insights in the route a product have passed provides useable insights and the possibility to measure the delivery process, controlling it, thereby manage it and ultimately improve it. Another application at the project site can be found in the insights of daily practice. When a worker have insights in his own productivity and work performance regarding time spent, he or she can improve his operational performances when he recognized an ineffective worktime. Thereby, a RFID system offer support for self-learning teams, making the realization phase more efficient over and over again. Often, operational managers do not know or recognize the factors that produces waste at project sites, nor they have the tools to measurements the impact of waste on their labour productivity.

Therefore, RFID should be seen as the starting point for optimization in daily processes and allow the management to act in advance in order to reduce their negative effects. The real-time information offers visibility of the location of products throughout the whole construction supply chain, eliminating the uncertainty involved in decision-making and thereby gives the organization the opportunity for a more flexible approach of current processes. Next to these advantageous effect RFID can have on the causes of wastes described in Figure 4, RFID is intended to have the following fourteen added values for contractors:



Scheme 3 Fourteen added values of RFID in Construction

1. Product Life Cycle Information:
   One can store product related information locally on the tag. Static information (e.g. manufacturer, composition, origin, production date) becomes accessible anytime anywhere.

2. Visibility Products Upstream Supply Chain
   It becomes visible at the project site where a certain product is located upstream (e.g.: still in its manufacturing process, stored at a distribution centre or ready for last-mile shipment?)

3. Shipment Visibility of Goods
   It becomes visible where a certain product is located on its route to the project site (i.e.: its 'last-mile' location): in a traffic jam, around the corner or not left the distribution centre at all.

4. Automate Goods Receiving
   As mentioned before, products can automatically be checked-in by passing the entrance gate (i.e. reading zone of RFID reader) on the project site.

5. Real-Time Stock Balances
   A RFID system can monitor stock balances on-site in real-time. Stock levels can automatically be updated once products are added or take out the stock shelves. It is even possible to monitor the stock balances over a big lay-down yard by different set-ups of the RFID infrastructure.

6. Minimizing the Excess of Stock
   An automatic stock control system can prevent the excess of stock since it is known how much stock is stored on site. This can prevent the non-use of products at project sites.

7. Minimizing Dwell-Time
   Since the stock can be managed on a real-time basis, the time differences between ordering products, delivering products, temporary storing products and processing products can be optimized. When such information becomes visible, one can optimize the ordering process, minimizing the stock on site, decreasing the time intervals of products' arrival and processing.

8. Minimizing Fraud / Theft of Goods
   The location of products can become known with a RFID system. Therefore, it becomes visible when a certain products leaves the stock shelves or the project site.

9. Monitoring Progress / Production
   It becomes clear which products are delivered on site and which have left the storage facility. Therefore, it becomes also visible what the amount of deliveries are and the amount of products used. A comparison on time gives insights in the productivity of the job site workers on site.

10. Unique Product Identification
    With the unique number on a RFID tag, it becomes possible to use exactly the product which is intended to use. Differences between products can be invisible from the first point of view.

11. Localize Products on Site
    Radio waves can propagate through multiple materials like paperboard, concrete and sand. One can thereby localize products which are invisible for the human eye such as buried products or products placed behind walls or inside floors. One can also localize the needed products from a distance on site, thereby, making it possible to easily find an unique products on site.

12. Self-Learning Teams
    A job site worker who is often searching for some products can localize the needed products with a RFID system. Given these insights, enabling the job site worker is able to optimize its site lay-out and the temporary storage of products.

13. Information Upstream – Execution
    With the on-board data capacity, it becomes possible to locally store all product-related information (see 1. 'Product Life Cycle Information') as well as dynamic information (e.g.: errors and maintenance reports). Information can be stored locally on-tag or on-network in a database.

14. Monitoring Building Performance
    A RFID system can provide information about the temperature, occupancy and moisture inside a building with the addition of sensors, giving valuable insights in the performance of a building during its utilization phase. One can optimize the HVAC installations with a building occupancy.

2.6 In conclusion

In this chapter, it became clear why a construction contractor should consider to implement a technology which can localize products in real-time from a distance. For this, one needs three features of a technology, which are Identification, Localization and Communication. With the use of a literature analysis, see *Appendix A Why RFID?,* RFID is considered to be an appropriate technology to identify, localize and communicate product' information from a distance.

This identification, localization and communication of individual products becomes possible by use of several components of a RFID system, namely: 1) the RFID tag, 2) radio waves, 3) the RFID antenna, 4) the RFID Reader, 5) the RFID middleware and 6) the Enterprise software systems. With a description of these components, see also *Appendix B The RFID system*, it became clear that there is a huge variety in components and therefore, in the functioning of the RFID system. In order to find out what the added value of a RFID system can be, a closer look is taken to the advantages and disadvantages of such RFID System.

It becomes possible to collect (automatically) real-time information about products and, with sensors, its surrounding with RFID. This capability offers many advantages for the current construction supply chain. These advantages can be found in the field of saving time, money and effort in daily processes. Deduced from these advantages, drivers to implement a RFID system in the construction sector are indicated to be an improvement of routine tasks at site and throughout the construction supply chain, an improvement of worksite security and an improvement of a business' corporate image. A RFID system can also offer new business opportunities as well as the use of intelligent products / processes (e.g. Internet-of-Things purposes), the extent use of data during the utilization phase and it can provide all product' information from upstream to downstream the construction supply chain.

However, some disadvantages are identified as well. They have been found as a disadvantage for the business processes, technical hurdles, social hurdles and associated costs of a RFID system. Besides, it should be questionable how reliable the investigated literature is because most researchers only treat a single product type in a single-level (close loop) supply chain for a short period of time. The exact advantage and disadvantages are therefore hard to point out, which forms clearly a barrier to implement a RFID system in the construction sector. Besides, it is unclear what the added value of a RFID system can be, there is no dominant actor like in the retail industry who has applied RFID for many years (i.e. Walmart) and the characteristics of the construction sector forms a barrier to implement a RFID system as well.

Overall, the literature analysis has resulted in a description of the added value of a RFID system for the non-residential construction industry. RFID can have an advantageous effect on current practice, as well as offering new business opportunities. The indicated fourteen added values of a RFID system are:

<table>
<tr><td colspan="2">1. Product Life Cycle Information</td><td colspan="2">2. Visibility Products Upstream Supply Chain</td><td colspan="2">3. Shipment Visibility of Goods</td></tr>
<tr><td colspan="2">4. Automate Goods Receiving</td><td colspan="2">5. Real-Time Stock Balances</td><td colspan="2">6. Minimizing the Excess of Stock</td></tr>
<tr><td colspan="2">7. Minimizing Dwell-Time</td><td colspan="2">8. Minimizing Fraud / Theft of Goods</td><td colspan="2">9. Monitoring Progress / Production</td></tr>
<tr><td colspan="2">10. Unique Product identification</td><td colspan="2">11. Localize Products on Site</td><td colspan="2">12. Self-Learning Teams</td></tr>
<tr><td colspan="3">13. Information Upstream – Execution</td><td colspan="3">14. Monitoring Building Performance</td></tr>
</table>

Table 6 Added values of a RFID system for the realization phase of Construction projects

In the next chapter, the data collection method of this study will be described.

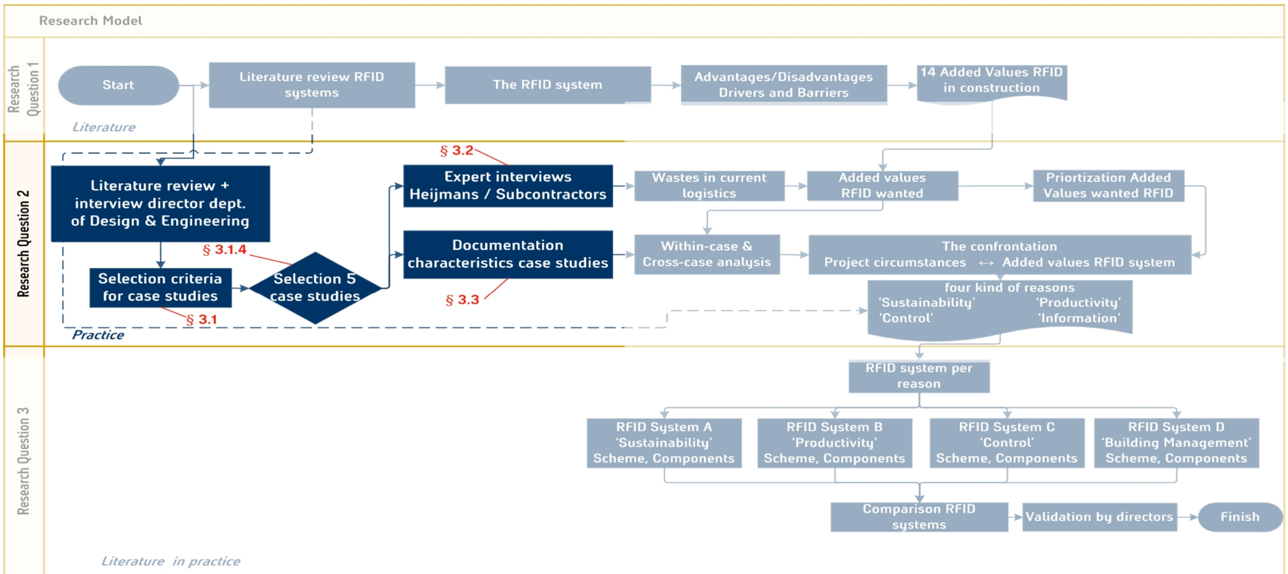
chapter 3

“To achieve great things, two things are needed:
A plan and not quite enough time”

~ Leonard Bernstein ~

3. Data Collection Method

In the previous chapter, it became clear what a RFID system is, what it can and what the advantages and disadvantages are as well as what the drivers and barriers to implement a RFID system are for the non-residential construction industry. From this literature analysis, a list of fourteen added values for construction contractors has been extracted, see *Scheme 3 Fourteen added values of RFID in Construction* on page 13. RFID is meant to be a tool to identify and localize individual construction products throughout the construction supply chain. This should stimulate the information and communication exchange between construction partners throughout the construction supply chain and thereby minimizing waste and increase the labour productivity in non-residential construction projects. However, since every construction project is different to one other, the added values of a RFID system wanted in a certain project will be different in different projects. Therefore, information from practice will be used in order to find out under which project circumstances which RFID system can obtain the most added value for non-residential construction projects. In this chapter, the data collection method will be discussed. By use of case studies and expert interviews, information from practice will be obtained. The selection of these case studies will find place in *Paragraph 3.1 The selection of the case studies*. In *Paragraph 3.2 The interview protocol*, the experts to be interviewed will be explained. The chapter ends with a brief summary over the main characteristics of the selected case studies, given in *Paragraph 3.3 Project characteristics*. In the following scheme, the research model and this chapter' position in this research has been given.



Scheme 4: Research model data collection method

3.1 The selection of the case studies

It is important to get a practical understanding about construction projects in order to determine which added value is the most wanted one in a project. To get these insights, case studies will be used. Yin (2014) noted that case studies are the most appropriate method to get information about a current situation, i.e. the context of this research. In comparison with an experiment and a study of documents about the past only, case studies are suitable in situations where an artefact, in this case the RFID system, is meant to change the context:, waste at the project site. The minimum requirements for the case studies are:

- <u>Heijmans non-residential</u>

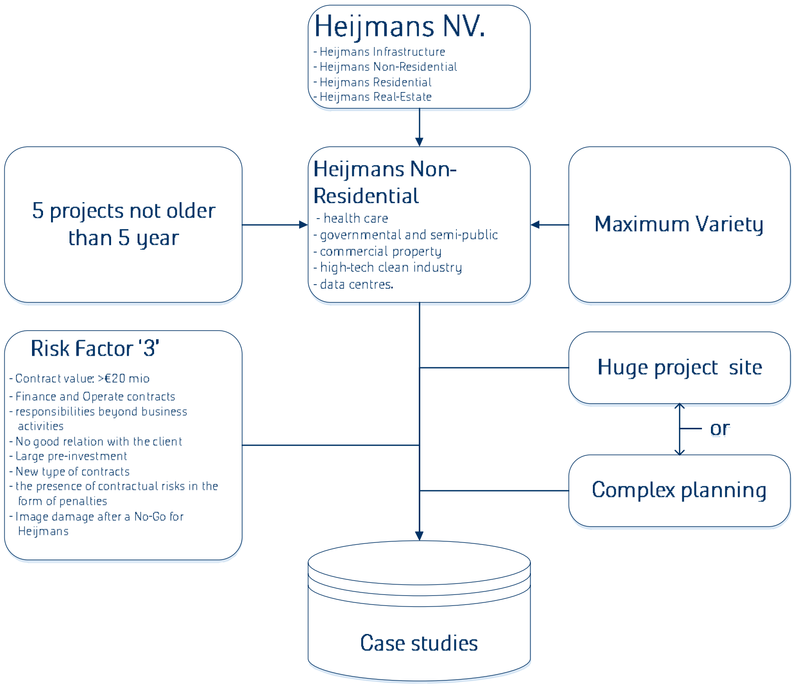
  Heijmans non-residential, subsidiary of Heijmans NV, is the host company of this research, which operates in the following market segments: : health care, governmental and semi-public sector, commercial property, the high-tech clean industry (including laboratories) and data centres.

- <u>Maximum variety</u>

  Since the goal of this research is to determine under which circumstances which RFID system is the most appropriate system, a maximum variety between the case studies is advisable. According to Flyvbjerg (2006), a maximum variation should result in a deeper understanding of causes behind the problems and its consequences in its context.

- <u>Five projects not older than five years</u>
  In order to obtain reliable and valid up-to-date information, the case studies should not be completed (the execution activities) before January 2012 and not more than 5 projects should be investigated due to the time limitation of this research, the volume of information to cope with and the validity of this research (Eisenhardt 1989).

From this database of possible case studies at Heijmans, there are still too many case studies to select. Therefore, a meeting has been scheduled with the director of the department '*Design and Engineering'* of Heijmans non-residential. This department forms the connection between the designs and the realisation of non-residential construction projects. The preparation of the execution and the logistic plans are also part of the responsibilities of this director. During the meeting, the RFID system and its fourteen added values have been explained. After the explanation, one additional requirement and two selection criteria are added for the selection of the case studies, based on the assumption of the director. This additional requirement ('risk factor 3') and the two selection criteria's ('huge project site' and 'complex planning') will be explained on the next page. Schematic, the selection of the case study has been done on the following manner:



Scheme 5 Selection of the case studies

3.1.1 Risk factor '3'

From a commercial point of view, the highest impact RFID can have is assumed in projects with a risk factor '3' at Heijmans non-residential. This risk factor is assigned on projects by an internal management system during the tender phase of Heijmans, reflecting the risks associated with the project, see *Table 7 Risk factor 3*. It is assumed by the director that the most waste at project sites are present at these projects since these projects are the most valuable projects and the most complex projects, therefore, they are of increased risk for the company.

Risk Factor	Contract value	Risk profile
Risk factor 3	>20 million euros	- Finance and Operate contracts - Responsibilities beyond business activities - No good relationship with the client - Large pre-investment - New type of contracts - The presence of contractual risks in the form of penalties - Image damage after a No Go for Heijmans

Table 7 Risk factor 3 of Heijmans Non-Residential

3.1.2 A huge project site

The first selection criteria added by this director is the presence of a large project site. In comparison with small project sites where almost no room for the temporary storage of construction products is available, many waste are suspected to be present like walking distances and searching time of employees, resulting in a lower labour productivity. In comparison, projects with small sites are often well controlled by Just-In-Time deliveries and an increased managerial effort. The mistake jobsite workers make at large project site is to temporary store everything wherever they want. This creates an uncontrollable work situation, a messy project site and thereby, an unsafe project site. It is assumed that the lager the project site, the more walking distances and the more searching time needed, so, the lower the labour productivity is supposed to be.

3.1.3 A complex planning

A tight schedule in projects is not rare for Heijmans non-residential. However, it is recognized by this director that a tight schedule in combination with many different disciplines who are active on site at the same time results in inefficiencies and forms a source of waste at construction projects. An increase in different project partners working all together at the same time on a construction project results in a less controlled execution process, raising the waste at these projects.

3.1.4 Selection of the 5 case studies

From these selection criteria, see also *Scheme 5 Selection of the case studies* on the previous page, the following five case studies have been selected:

1. Schiphol Lounge 2 Amsterdam
2. Telecity AMS1 Amsterdam
3. EuroJust The Hague
4. 'Hart van Zuid' Rotterdam
5. National Military Museum (NMM) Soesterberg

These case studies are described in detail in *Appendix D Case Studies*.

3.2 The interview protocol

Two expert interviews have been scheduled per case study. These expert interviews will follow a semi-open character in order to get qualitative information from the experts. It allows for a deeper discussion besides the predefined questions. The duration of the interviews is approximately one hour. During the interview, notes are taken and audio has been recorded. A protocol will be followed during the expert interviews, see *Appendix E Interview Protocol*. The findings of the interviews are afterwards sent to the interviewee in order to validate these findings. The validated findings will be used for the within-case and cross-case analysis in the next chapter. After these analyses, new obtained insights with use of the literature are submitted to the same experts and asked for feedback by telephone. In each case-study, an employee of Heijmans non-residential (who is responsible for at least the construction logistics of the case study), and an employee of an important subcontractor of the project (who is also at least responsible for their construction logistics), have been interviewed. The expert' requirements are:

- Working years in construction: more than 10years
- Role / responsibility: at least construction logistics
- Project involvement: > 6months
- Availability: at least 1x 60min interview 120min (+ time for the validation)

The interviewees of Heijmans non-residential construction will be asked after the interview which subcontractor should be contacted. This should be a subcontractor who can greatly benefit from the implementation of a RFID system in the project of stake. The advantage to held an interview with a second person with a different perspective on the project is to get information about the daily practice of the subcontractor instead of the general information about the overall construction logistics, obtained by the expert of Heijmans. Since Heijmans non-residential is often the main contractor, the interviewee of Heijmans sees only the outcome of the subcontractor whereas the subcontractor has a deeper grounded knowledge about the causes of wastes on site in their part of the project. Besides, the overlapping data between the two stakeholders can give new and better insights in the project' circumstances. The two expert interviews, in combination with the documentation about the projects, will serve also as a triangulation feature in this study in order to guard the internal validity of the data to be used (Eisenhardt, 1989). For these interviews, the following persons are contacted:

Project	Expert Heijmans Non-Residential	Expert subcontractor
Schiphol Lounge 2 Amsterdam	Project leader	Project leader Company: Verwol Interior realisation
Telecity AMS1 Amsterdam	Main site manager	Project leader Company: Schneider-Electric
Eurojust The Hague	Project leader & main site manager	Main site manager Company: Technical Façade Management TGM
Hart van Zuid Rotterdam	Senior design manager	Project leader Company: Heijmans non-residential
National Military Museum Soesterberg	Project director	Project coordinator Company: Kwakman Finishing

Table 8 Experts interviews

In each interview, firstly, questions are asked about the unique project circumstances from the point of view of the expert. Hereafter, question about the wastes at the project site and their root causes are asked for. Then, the RFID system and its potential fourteen added values are explained. Based on the motivations of these experts, a priority will be assigned to the added values which are wanted in their project. In the following paragraph, a summary of the case study' characteristics has been given.

3.3 Project characteristics

An overview of the project characteristics about the five different case studies is given in the table below. For an extended description of each project, see *Appendix D Case Studies*. Information from these case studies is extracted in two ways. Documentation available at Heijmans non-residential and the internet are used to get a general understanding about the construction projects. Secondly, the expert interviews, explained hereafter, are used in order to get a deeper insight and understanding about the project circumstances of these five projects, resulting in a deeper practical understanding about these project characteristics.

Characteristic	Schiphol Lounge 2	Telecity AMS1	Eurojust The Hague	'Hart van Zuid' Rotterdam	National Military Museum
Selection Criteria	Complex planning	Complex planning	Complex planning	Large construction site	Large construction site
Contract	B (Build)	B (Build, fit-out)	BM (Build, Maintain)	DBM (Design, Build Maintain, not all projects)	DBFMO (Design Build, Finance, Maintain & Operate
Disciplines	Construction (I)* Electrical (I) Mechanical (I)	Construction (I) Electrical (I) Mechanical (I) Infrastructure (I)	Construction (I) Electrical (I) Mechanical (I) Landscaping (I&E)	Construction (I&E) Electrical (I&E) Mechanical (I&E) Real Estate (I&E) Infrastructure (I&E) (depending on project)	Construction (I) Electrical (I) Mechanical (I) Infrastructure (I) Landscaping (E)* Architectural (E)
Type of work	Renovation	New construction	New construction	New construction Renovation/rezoning	New construction, renovation
Phase	Construction completed (2014 – 2015, 11 months)	Under construction (2015-2018)	Under construction (2014-2016) (24,5 months) Maintain: 15yr (+5)	Preparation (2016 – 2018) Construction (7 years) Maintain: 20-24yr	Construction completed (2012- 2014, 21 months) Maintain and Operate: 25yr
Contract Value	B: €17.000.000, -	confidential	BM: €105.000.000, -	DBM: €200.000.000, -	DBFMO: €160.000.000, -
Use	Hallway / shopping area airport	IT systems applications	Agency of the European Union	Area development	Museum and Info centre
Market Segment	Commercial property	Data centres	Government	Government	Government
Client	Schiphol Group	Telecity Group	The Central Governmental Real Estate Agency	Municipality of Rotterdam	Ministry of Defence
Size	Gross floor area: 16.000m² Building height: 2 levels	Gross Floor area: 16.350m² Building height: 72m (15 levels up to <5.4m per level)	Project site: 10.500m² Gross floor area: Main building: 20.000m² Underground parking area: 8.200m² office: -2 levels Low rise: 5 levels (19m high) High rise: 12 levels (51m high) Underground parking area: -3 levels	Total project site: 65.000m², i.e.: + 6.900m² art building + 800m² swimming pool + 28.700m² Ahoy multipurpose centre + 5.200m² retail + Other: 6.900m² + 95 houses + 200 room hotel + 2.800m² school + 6.700m² cinema + 380 parking places	Total area: 4.500.000m² Project site: 450.000m² Gross floor area museum: 27.500m² Depots: 10.000m² Height observation deck: 33m Height museum: 13m, Roof top: 18m (3 levels)
Storage Possibility	Use of a consolidation centre, little on site	Little on site	Little on site	Relatively little, depending on subproject	Very much
Location	Exurban, rural, at an airport (annually 14mln travellers through gate)	Urban area, suburb: university campus	Urban area: inner-city	Urban area: inner-city	Exurban, rural

Table 9 Comparison matrix projects Heijmans Non-Residential Construction, date: 24-05-2016

As one can see from this table, the selection criteria results in five complete different case studies. The results from the expert interviews will be discussed by use of a within-case analysis in the next chapter.

chapter

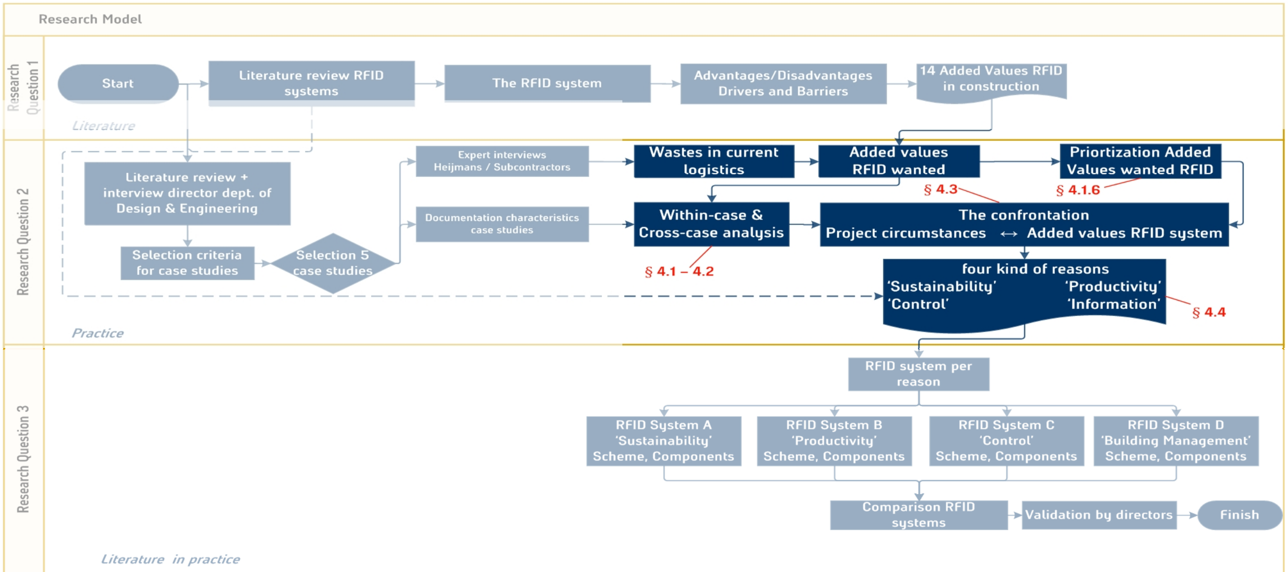
4

“Nothing great was ever achieved without enthusiasm"

~ Waldo R. Emerson ~

4. Results Interviews

The data collection methodology has been set out in the previous chapter. By use of ten expert interviews from five different case studies, information from current non-residential construction projects will be obtained. In order to understand why an added value wanted can be different in different construction projects, the different project circumstances and motivations of the experts will be analysed in this chapter. The outcome of these interviews will be analysed with use of a within-case and with a cross-case analysis. These analyses will be used to determine under which project circumstances which added value of a RFID system is the most wanted one and why this added value is wanted. These analyses will be used as a starting point for the chapter hereafter in which the determination will be made about which RFID system should be applied for under certain project circumstances in order to obtain the most added value, see *Chapter 5 RFID systems for non-residential construction projects.* The following scheme will clarify this chapter' position in the research.



Scheme 6 Research model - Result data collection

4.1 Within-case analysis

In each case study, two experts (see *Table 8 Experts interviews* on page 19) are questioned about the project circumstances in the project of concern, the wastes in current logistics and they are asked about which added values of the RFID system are wanted in their project (see *Scheme 3 Fourteen added values of RFID in Construction* on page 13). A summary of the interviews and the motivations of each expert has been given in *Appendix F Results interviews*. This paragraph will describe the outcome of these interviews, relevant for this study. Since it can be hard for the experts to indicate all added values during the first interview, potential extra added values are indicated by use of the literature analysis of research question one after the first interview and submitted to the same expert for validation. These new additional added values are indicated by the words '*2nd feedback*' throughout this paragraph. Each within-case analysis starts with a description of the most important project circumstances mentioned by the experts in the interview. This will be followed up by an comparisons between the findings of the expert of Heijmans and the expert of the subcontractor. After the five within-case analyses, the most important added values will be listed, followed up by the cross-case analysis.

4.1.1 Schiphol Lounge 2 Amsterdam

The project site was located at the high secured airside of Schiphol airport. Everything which had to be delivered on site had to pass through Customs, which checked everything (man, machine and materials). Due to the restrictions related to the airside, the last-mile transport was fulfilled by an external logistic service provider (which was experienced in transportations on this airside). This last-mile transport was done during the night from a consolidation centre outside the airside, without a quantity list attached to the deliveries, without control of the main contractor in these deliveries. The intended Just-In-Time deliveries were not fulfilled by the subcontractors since they took out the flexibility in the execution processes of jobsite workers and it was experienced cumbersome due the many checks and restrictions of the Customs. A detailed description of this within-case analysis has been given in *Appendix F Results interviews*.

Cross Comparison between experts Schiphol Lounge 2

The problems the expert of Heijmans recognized (such as the security checks by the Customs, the amount of re-handling products and a loss of products) were not recognized by the expert of the subcontractor in the first place. Therefore, one can clearly see that the coordinating role Heijmans has and the subcontractor does not have. The contract value of the subcontractor is low compared to the contract value of Heijmans (€17.000.000, - compared to €650.000, -). Heijmans recognized that many subcontractors had problems with the delivery of man, machines and materials to the project site via the consolidation centre and the security checks by the airport, the subcontractor does not shared these problems. Possibly, this can be explained by the low contract value and the limited products flows to the project site. The findings are summarized in the following table.

	Heijmans Non-Residential	Subcontractor (Interior)
1. Localize Products on Site	**Project circumstance:** long searching time for products, Long temporary storage of products, A lot of re-handling of products, Limited control in supply and storage of products on site **Motivation**: more control in the location of products on site and productivity is of concern	**Project circumstance:** limited control in supply and storage of products on site, Products are moved by other parties (clean-up) **Motivation**: The productivity of jobsite workers was of concern since they searched for product on the project site (*2nd feedback*)
2. Unique Product Identification	**Project circumstance:** limited control in supply and storage of products on site, It is hard to identify products which are delivered without any delivery note, Handling with reusable products **Motivation**: reused products are stored and transported to a consolidation centre, coordinated by an external logistic company without control of Heijmans (*2nd feedback*)	**Project circumstance:** limited control in supply and storage of products on site, It is hard to identify products which are delivered without any delivery note **Motivation**: the 'last-mile' transport is done by external company. It was difficult to identify the delivered products since there was no quantity list and control over this logistic process (*2nd feedback*)
3. Automate Goods Receiving	**Project circumstance**: limited control in supply and storage of products on site, No idea which products are on the project site **Motivation**: the Customs checked everything, leaving out the need for the main contractor to know what is delivered on site or not. Heijmans did not had any clue and control over what was delivered and stored on the project site	n/a

Table 10 Within-Case Analysis Schiphol Lounge 2 Amsterdam

4.1.2 Telecity AMS1 Amsterdam

This small project site has forced the main contractor to come up with a well-thought logistic plan. A combination of a logistic website (logistic service providers can book a time slot for entering the project site), a ticket system (the entrance evidence of the logistic website) and the on-site logistic was of responsibility of a technical wholesaler, should ensure a smooth construction logistic. However, this was not the case. Although the project value accounts for 80% for installations and just 20% for structural activities, the unexperienced technical wholesaler was the cause for many wastes on-site according to the experts. Besides, many products were ordered in advanced by purchasing departments due to economies of scale and minimal transportation costs, resulting in a lot of storage on site. Also, a suddenly closure of one of the two lifting openings in the façade has forced many subcontractors to store most of their needed products on the storey floors. See *Appendix F Results interviews* for a detailed description of this within-case analysis.

Cross Comparison between experts Telecity AMS1

Both experts share the meaning that execution and logistic plans were not well worked out. They believe if these plans were better worked out and communicated to subcontractors and logistic service providers, many of the resulting logistic' problems would not exist in this project. Both experts think RFID can have an advantageous effect in many construction projects but at the same time, they think the added value of a RFID system in this project will be limited. Only the expert of the subcontractor, Schneider Electric, guesses RFID can be of added value in his situation in the first place since a lot of re-handling of products has taken place on the storey floors whereby jobsite workers have lost products out of sight, reducing the productivity of his jobsite workers.

	Heijmans Non-Residential	Subcontractor (Energy Management provider)
1. Automate Goods Receiving	**Project circumstance:** time consuming to identify delivering products and packages **Motivation:** receiver was often 'Heijmans', not specified who and which company of Heijmans. More control in the arrival process was wanted in order to increase the productivity on site. (*2nd feedback*)	
2. Localize Products on Site	**Project circumstance:** limited control in supply and storage of products on site, Long searching time for products, Long temporary storage of products, A lot of re-handling of products, **Motivation:** the productivity was of concern since many materials were lost on site and unnecessary time was needed to find back products (*2nd feedback*)	n/a
1. Localize Products on Site		**Project circumstance:** limited control in supply and storage of products on site, A lot of re-handling of products on the floor levels **Motivation:** more control in the location of products on the floor levels is wanted to increase the productivity on site
2. Automate Goods Receiving	n/a	**Project circumstance:** time consuming to identify delivering products and packages Limited control in supply and storage of products on site, **Motivation:** multiple (small) products are delivered in a single shipment. They are transported in a box or on a pallet. It takes (unnecessary) time to identify all products delivered whereby more control is wanted in the arrival process of products on site (*2nd feedback*)

Table 11 Within-Case Analysis Telecity AMS1 Amsterdam

4.1.3 Eurojust The Hague

This project was recognized by its international character, located in the international zone of The Hague (the Netherlands). Many embassies are located in the direct surroundings. This in combination with an Elementary school and a small project site has forced the main contractor to come up with a well thought logistic plan. The use of logistic website (the transporter can book a time slot for entering the project site), a ticket system (the actual access by this logistic website) and Just-In-Time deliveries (a buffer location just around the corner of the project site) has smoothen this logistical process. However, the project was recognized by a delay in the superstructure, changing the planning and site lay-out almost weekly. A BREEAM Very Good[1] certificate was of responsibility of the main contractor, so is the 15 years of maintenance as well. See *Appendix F Results interviews* for a detailed description of this within-case analysis.

<u>Cross Comparison between experts Eurojust The Hague</u>

Both experts rank 'Information Upstream – Execution' as the most wanted added value of a RFID system due to the 15 years maintenance responsibility in this project, but, for a different reason. The motivation for the subcontractor is to have all product related information on-the-spot and to keep record of the maintenance activities which has been executed on a specific product. This is a matter of proof of liability in case of a product is malfunctioning. The motivation from the expert of Heijmans to rank 'Information Upstream – Execution' as first is to provide quick access to all product related information. In this way, RFID will be used in order to identify unique products fast and therefore, it has been seen as a more easy way to obtain product related information compared to the already existing BIM2Field system, wherein all related product information is stored in a complex BIM model. RFID could be complementary to this BIM2Field system. Besides, expert 1 (consisting of the main site manager and the project leader of Heijmans), do have a need to see from the site office the fabrication status of a certain products, without the use of communication (by e-mail / telephone) to the manufacturer or the supplier. This will provide quick up-to-date information about the deliveries which can be used to minimize uncertainty in the supply of products and therefore, it will minimize waiting time of jobsite workers.

[1] BREEAM (Building Research Establishment Environmental Assessment Method) is the world's longest established method of assessing, rating, and certifying the sustainability of buildings in five levels: 'Pass', 'Good', 'Very Good', 'Excellent' and Outstanding

	Heijmans Non-Residential	Subcontractor (Façade)
1. Information Upstream – execution	**Project circumstance**: it is hard to look up product' information (in current BIM models or asset list maps), A requirement in the availability of the building, There is a need for more efficient maintenance **Motivation**: fast & easy provision of product' information on-the-spot in utilization phase	**Project circumstance**: there is a requirement in preventive maintenance, A requirement in the availability of the building There is a need for more efficient maintenance **Motivation**: fast & easy provision of maintenance history is wanted in this case
2. Monitoring Building Performance	**Project circumstance**: there is a need for a more proactive maintenance phase, A requirement in the availability of the building **Motivation**: optimizing maintenance activities by obtaining more information from sensors in order to ensure full availability of the building	n/a
3. Visibility Products upstream Supply Chain	**Project circumstance**: uncertainty in the delivery process **Motivation**: maximizing productivity on site by taking out uncertainty in the delivery process	n/a
4. Shipment Visibility of Goods	**Project circumstance**: kilometre record needed for 'BREEAM' credits **Motivation**: sustainability credits of BREEAM requires a kilometre record for onus (*2nd feedback*)	

Table 12 Within-Case Analysis Eurojust The Hague

4.1.4 Hart van Zuid Rotterdam

This project is recognized by its diversity in its multiple sub projects. Every subproject will be managed as a project on its own, resulting in a combination of multiple small projects. Only in two sub projects is a maintenance responsibility (20-24year) incorporated.

Cross Comparison between experts

Although it is hard to point out the added value for a project which is not under construction yet, both experts do see added values in a RFID system in the future for multiple construction projects. The first expert (the integral design manager of the overall 'Hart van Zuid' project) believes RFID can be an added value in the supply of products which are critical to the productivity on site. The continuity of jobsite workers is sometimes strongly depending on the continuous inflow of products, in case of critical shipments. The second expert (project leader of subprojects Ahoy and ICC) does see the added value of a RFID system in projects with a maintain responsibility. This expert assigns the highest priority to *'Information Upstream – Execution'* to projects with a maintain component like the Swimming Pool (20 years) and the new Art House (24 years). The simplicity of a RFID systems is the key motivation for this expert. In comparison with a BIM model (used for the maintenance phase in a project), RFID looks a lot more easier to obtain product life cycle information of a certain product to the expert.

	Heijmans Non-Residential sr. design coordinator	Heijmans Non-Residential Project leader Ahoy & ICC
1. Shipment Visibility of Goods (Arrival)	**Project circumstance**: uncertainty in the delivery process , Continue installation cycle present **Motivation**: ensure continuity of jobsite workers' productivity in case of a (critical) material flow	n/a
2. Information Upstream – Execution*	**Project circumstance**: it is hard to identify products after the realization phase, A requirement in availability of the building There is a need for more efficient maintenance **Motivation**: Fast & easy identification of products on-the-spot (*2nd feedback*)	
3. Monitoring Building Performances	**Project circumstance**: presence of flexible lay-out rooms, Need for higher quality indoor environment **Motivation**: better match between the actual occupancy of a room and the HVAC installations (*2nd feedback*)	
1. Information Upstream – Execution*		**Project circumstance**: it is hard to look up product' information (by BIM or asset list maps) A requirement in availability of the building, There is a need for more efficient maintenance **Motivation**: fast & easy provision of product' information on-the-spot

Table 13 Within-Case Analysis 'Hart van Zuid' Rotterdam

4.1.5 National Military Museum Soesterberg

This project was unique for the main contractor since it was a Design Build Finance Maintain and Operate DBFMO (25 years) contract (in a Public Private Partnership) with many other partners. This has changed the mind-set of the involved partners, which was unique compared to other projects according to the experts. The diversity of the working activities (renewal buildings, new construction, demolition old buildings and infrastructural activities) resulted in many different companies working together on-site. Due to the huge project site (45 ha.), there was a lot of space available for temporary storage of ordered products. For a detailed description of this within-case analysis, see *Appendix F Results interviews.*

<u>Cross Comparison between experts</u>

As expected, the huge project site is a determining factor for the added value of a RFID system in this project by both experts. The expert of Heijmans sees RFID also as a complementary technology to a BIM model (BIM2Field). Especially, the simplicity to obtain product related information is wanted due to the maintenance responsibility of Heijmans in this project. The expert of the subcontractor sees RFID as a means for process optimization during the realization phase. Although the huge project site looked beneficial in the first place to both experts, they believe if there was more control over the arrival and storage of products, there would be less waste on this project site.

	Heijmans Non-Residential	Subcontractor (Finisher)
1. Information Upstream – Execution	**Project circumstance**: it is hard to look up product' information (by BIM or asset list maps), There is a requirement in the availability of the building, There is a need for more efficient maintenance **Motivation**: fast & easy provision of product' information on-the-spot	n/a
2. Automate Goods Receiving	**Project circumstance**: no control in the delivery of products, No idea which products are on the project site **Motivation**: due to the large project site, a lot of products were ordered and delivered in advance. The limited control in the arrival resulted in no idea what was delivered on site.	n/a
3. Storage (in general)	**Project circumstance**: limited control in supply and storage of products on site, No idea which products are on the project site **Motivation**: due to the large project site, many products were stored temporary on site. Which products, which location and how long products were on site was unclear to Heijmans	n/a
1. Minimizing Dwell-time	n/a	**Project circumstance**: limited control in supply and storage of products on site, No idea which products are on the project site **Motivation**: the time difference between the delivery and the processing of products was long due to the large storage opportunity.
2. Localize products on site	n/a	**Project circumstance**: limited control in supply and storage of products on site, Long searching time for products, Long temporary storage of products, A lot of re-handling of products, **Motivation**: more control in the location of products on site is wanted
3. Real-time Stock balances	n/a	**Project circumstance**: no idea which products are on the project site, A lot of re-handling of products on site, **Motivation**: due to the large project site, many products were ordered and delivered, losing sight of the amount of stored products on site. This reduced the productivity by increasing the walking and searching time for products
4. Monitoring Progress / Production	n/a	**Project circumstance**: unclear productivity **Motivation**: the productivity is only based on the daily outcome, not on the time difference between products received and products installed
5. Unique Product Identification	n/a	**Project circumstance**: the use of Custom-made products **Motivation**: it is hard to identify Custom-made products during the arrival process

Table 14 Within-Case Analysis National Military Museum Soesterberg

4.1.6 Prioritization added values

In the table below, the relative score of the added values is determined, indicating the most wanted added values by the different experts across the five case studies.

#	Added value	Phase	Expert prioritization	Relative score
1.	Information Upstream – Execution	Operation and Maintenance Phase	Eurojust Expert Heijmans 1st Eurojust Expert Subcontractor 1st Hart van Zuid Expert Heijmans 1 2nd Hart van Zuid Expert Heijmans 2 1st National Military Museum Expert Heijmans 1st	14 14 13 14 14 + **69**
2.	Localize Products on Site	Production Phase	Schiphol Expert Heijmans: 1st Schiphol Expert Subcontractor 1st Telecity AMS 1 Expert Heijmans: 2nd Telecity AMS 1 Expert subcontractor 1st National Military Museum Expert subcontractor: 2rd	14 14 13 14 13 + **68**
3.	Automate Goods Receiving	Arrival Phase	Schiphol Expert Heijmans 3rd Telecity AMS 1 Expert Heijmans: 1st Telecity AMS 1 Expert subcontractor: 2nd National Military Museum Expert Heijmans 2nd	12 14 13 13 + **52**
4.	Unique Product Identification	Production Phase	Schiphol Expert Heijmans 2nd Schiphol Expert Subcontractor 2nd National Military Museum Expert Subcontractor 5th	13 13 10 + **36**
5.	Minimizing Dwell-Time	Storage Phase	National Military Museum Expert Heijmans 3rd* National Military Museum Expert Subcontractor 1st	12 14 + **26**
6.	Monitoring Building Performance	Operation and Maintenance Phase	Eurojust Expert Heijmans 2nd Hart van Zuid Expert Heijmans 1 3rd	13 12 + **25**
7.	Shipment Visibility of Goods	Arrival Phase	Eurojust Expert Heijmans 4th** Hart van Zuid Expert Heijmans 1 1st	11 14 + **25**
8.	Real-time Stock Balances	Storage Phase	National Military Museum Expert Heijmans 3rd* National Military Museum Expert Subcontractor 3rd	12 12 + **24**
9.	Visibility Products Upstream Supply Chain	Pre-construction Phase	Eurojust Expert Heijmans 3rd	12 + **12**
10.	Minimizing Excess of Stock	Storage Phase	National Military Museum Expert Heijmans 3rd*	12 + **12**
11.	Minimizing Fraud / Theft goods	Storage Phase	National Military Museum Expert Heijmans 3rd*	12 + **12**
12.	Monitoring Progress / Production	Production Phase	National Military Museum Expert Subcontractor 4th	11 + 11
13.	Product Life Cycle Information	Pre-construction Phase	n/a	0
14.	Self-Learning Teams	Storage Phase	n/a	0

Table 15 Most important added value of a RFID system

- This relative score is determined by the priority assigned by each expert, reflecting the importance of added value for the expert. The highest priority (1st) will get '14 point' because there are 14 added values. The second highest priority (2nd) will get '13 points' and so on.

* The expert of Heijmans, in case of the National Military Museum, assigns every added value in the Storage phase (see *Scheme 3 Fourteen added values of RFID in Construction* on page 13)as equal important (third – 12 points), resulting in four times a score of 12 points from this expert.

** This priority is assigned on the basis of the output from an interview with the BREEAM Expert of Heijmans (BREEAM Expert 2016) which is directly responsible for the BREAAM program, the experts of Eurojust are not directly responsible for the BREEAM program in this project.

From this table, it can be seen that 'Information Upstream – Execution' is the most preferable added value of a RFID system in the five case studies by the experts. Hereafter, 'Localize Products on Site' is ranked second, et cetera. In the next paragraph, a cross-case analysis will be used in order to find equal motivations and determining project circumstances across the multiple experts and the five case studies.

4.2 Cross-case analysis

In this paragraph, the cross-case analysis will be made. In comparison with the within-case analysis, this paragraph is subject to the differences and commonalities in different project circumstances across the five case studies and the motivations the experts gave to assign a priority to an added value. This information is needed to understand why a certain added value is desired for different reasons.

During the interviews, all interviewees were curious and interested about the RFID technology. All of them want to know the results of this research, even if they do not see an added value for their project in the first place. This indicates a curiosity or a need from each expert to arrange the construction logistics differently than currently is done. Although the whole RFID system and its fourteen added values were explained in a matter of minutes to the experts, the interviewees were able to understand the technology and the possibilities of RFID in their project. Thereby, they were able to point out why an added value is wanted in their project or not. However, the level of participation of the interviewees differs between the interviewees since some experts did only listen and react on questions asked while others were able to think ahead and came up with practical limitations, new possibilities of the RFID system or even introducing the cost factor of such a new system. Only one expert out of ten did know what RFID is, although, he recognized the technology from a different application (National Military Museum expert Heijmans: RFID is used to localize people and to submit extra information about a museum piece). From the within-case analysis in the previous paragraph, it became clear that the main contractor (Heijmans) seeks most often the added value of a RFID system in the whole life cycle of a project when they are responsible for the maintenance phase as well, while subcontractors seeks the added value of a RFID system in their current daily processes (i.e. during the realization phase of construction projects). They want to optimize their execution processes and they see RFID as an information provider for benchmarking values in order to improve their execution processes. Overall, it can be seen from the within-case analysis, RFID is not wanted for the same reason in every case.

These reasons differ because the project circumstances are different to one other, so was the motivation from each expert to assign a priority to an added value. However, looking at the motivations the experts gave, see within-case analysis, one can see certain recurring motivations across the five case studies. This has to do with a need for an improvement in only a few aspects in current non-residential construction projects, where certain project circumstances forms the basis for the motivation of the experts. It seems that experts believe a RFID system could contribute to these desired improvements. This line of reasoning is visualized as follows:

Project circumstances --> Motivation --> Added value RFID

Following this line of reasoning, the same added value can be desired by two different types of motivations, resulting from different project circumstances. The motivations the expert gave throughout the within-case analyses has to do with *'Sustainability', 'Productivity', 'Control'* or *'Building Management'* improvements (see previous paragraph). These four motivations will be elaborated in this paragraph. Due to these different motivations, different information is wanted from the RFID systems, resulting in a different RFID system' design. These designs will be elaborated in Chapter 5. In this paragraph, only a brief explanation about the motivations for the added values related to the four motivations has been given. In *Appendix G Line of Reasoning,* one can find these line of reasoning's more in detail. Only the most important added values will be treated in this paragraph (see rank 1-8 in *Table 15* on the previous page). Certain abbreviations will be used in this paragraph in order to refer to a specific added value assigned by a certain expert. The following abbreviation technique will be used:

1.1.2
Case study 1
Expert 1
Added value 2

4.2.1 Sustainability

An improvement in sustainability is desired in two case studies. In the Eurojust case, a BREEAM sustainability program was incorporated in the contract. The expert of Heijmans recognizes the need for an improvement in the kilometre records of trucks since the interviewee suspect it will be harder to prove a reduction in kilometre driven by trucks in the nearby future, needed for BREEAM credits. Currently, these kilometres records are based on assumptions made before the start of the realization phase. Therefore, the added value *'Shipment Visibility of Goods'* is wanted here (3.1.4). On the other hand, jobsite workers had problems with the material handling of reusable products, which were deconstructed and installed back again in the Schiphol Lounge 2 case. The added value *'Unique Product Identification'* was desired here in order to simplify the material handling by jobsite workers (1.1.2).

4.2.2 Productivity

In some cases, the productivity of jobsite workers was of concern. Different added values are wanted in these cases. Example given, in order to decrease the uncertainty in the 'last-mile' delivery process, the added value *'Shipment Visibility of Goods'* (4.1.1) was desired in the 'Hart van Zuid' project in order to minimize unnecessary waiting time of jobsite workers on-site. An increase in productivity was desired at the arrival process on-site since it took unnecessary time to control all incoming products: *'Automate Goods Receiving'* (2.1.1, 2.2.2). Besides, an overview of the stock on site is wanted in the National Military Museum case in order to secure the continuity of jobsite workers on site for the subcontractor: *'Real-Time Stock Balances'* (5.2.3). The same expert wants to minimizes the time stock was stored on site since some of his products was prone to damage impact and weather influences: *'Minimizing Dwell-Time'* (5.2.1) was desired. *'Localize Products on Site'* was wanted in multiple cases since it took unnecessary time for jobsite workers to find back products on site (1.1.1, 1.2.1, 2.1.2, 2.2.1, 5.2.2) or on the floor level of Telecity AMS1 (2.2.1). The products were moved by other persons or companies (cleaning company in the Schiphol Lounge 2 case), products were delivered without a delivery note (Schiphol Lounge 2), too much products were delivered (Telecity AMS1 and National Military Museum case) or many products were temporary stored on the storey floors because the lifting opening closed unexpectedly (Telecity AMS1 case), all reasons why products were lost out of sight.

4.2.3 Control

In some of the case studies, a lack of control in the flow of products resulted in various types of wastes on the project site. Due to various causes (the Customs checked everything (1.1.3), receivers of packages were unknown at the arrival process (2.1.1), products were badly controlled due to the long inspection time involved (2.2.2) or there was no need to control these deliveries due to the storage space available (5.1.2)), *'Automate Goods Receiving'* was desired in these cases in order to obtain more control in the arrival process. *'Unique Product Identification'* was desired to increase also this control in the arrival process (1.1.2, 1.2.2, 5.2.5). At the National Military Museum case, the lack of control at the arrival process resulted in a lack of control in the storage on site, resulting in no idea what was delivered and stored on site: *'Real-Time Stock Balances'* (5.1.3, 5.2.3). It was unknown how long products were stored (5.1.3), which became of importance since some products of this subcontractor were prone to damage or weather influences: *'Minimizing Dwell-Time* (5.2.1). There was a need for *'Localize Products on Site'* since it was unknown where stock was located on site (1.1.1, 2.2.1, 5.2.2).

4.2.4 Building Management

Different improvements are wanted during the utilization phase of the case studies. These needs are all subject to the case studies with a maintenance responsibility incorporated in the contract: Eurojust, 'Hart van Zuid' and the National Military Museum case. Experts want a fast and easy identification of products on-the-spot (3.1.1, 4.1.2, 4.2.1, 5.1.1) and a fast and easy obtainment of product related information on-the-spot (3.1.1, 3.2.1, 4.1.2, 4.2.1, 5.1.1), resulting in the added value *'Information Upstream – Execution'.* The subcontractor of the Eurojust had no need to easily identify his products (façade elements) but he sees RFID as an data carrier for maintenance history records (3.2.1). There is also information desired for an improvement in this utilization phase. For example, extra information from sensors is desired in order to optimize the maintenance activities of Heating, Ventilation and Air-Cconditioning (HVAC) installations (3.1.2), resulting in the prioritization of the added value *'Monitoring Building Performances'*. The same added value is wanted in the 'Hart van Zuid' case in order to match the actual occupancy of splitted-up rooms with the output of the HVAC on that spot (4.1.3).

So, the added values are wanted by different type of motivations. This has been visualized below:

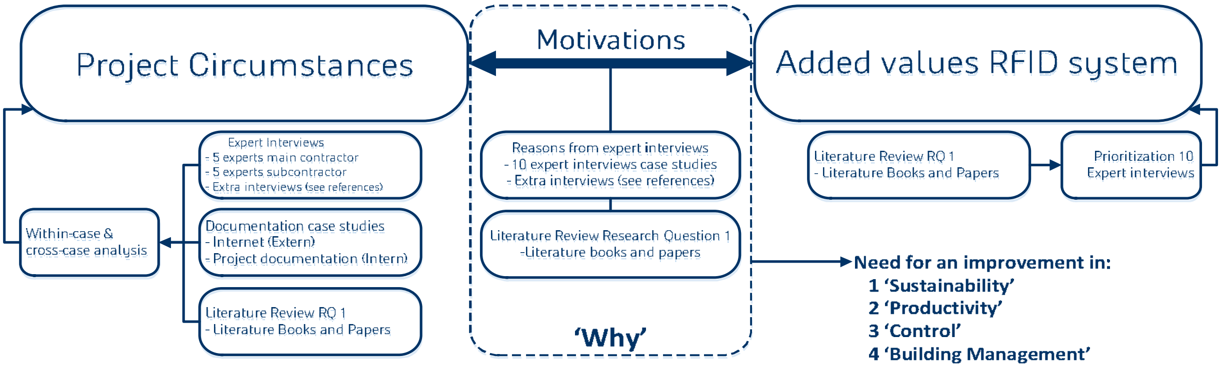
	'Sustainability'	'Productivity'	'Control'	'Building Management'
Shipment Visibility of Goods	x	x		
Automate Goods Receiving		x	x	
Real-Time Stock Balances		x	x	
Minimizing Dwell-Time		x	x	
Localize Products on Site		x	x	
Unique Product Identification	x		x	
Information Upstream – Execution				x
Monitoring Building Performances				x

Table 16 The type of motivation for an added value

It becomes clear by this paragraph that not every added value is wanted for the same reason throughout the case studies. The determining project circumstances and the corresponding motivations of the experts will be set out in the confrontation of the following paragraph.

4.3 The confrontation

In this section, the confrontation will be made in order to determine which added value of a RFID system is wanted under which project circumstances (which will be described in *paragraph 4.3.1 The project circumstances)* and why these added values are wanted (described in *paragraph 4.3.2 The reason why added values are wanted)*. For this confrontation, multiple information resources will be used. Schematic, this confrontation with its corresponding information resources is visualized in *Scheme 7 the confrontation process to be followed*. From the within-case and cross-case analysis, it became clear that experts have four type of different motivations to assign a priority to an added value, namely: *'Sustainability', 'Productivity', 'Control'* or *'Building management'* improvements. These type of motivations are of importance since they will result in different kind of design of RFID systems. To clarify, because the same added value is wanted for a different purpose by two experts, two different type of RFID systems should be implemented here since different type of information is needed. These kind of motivations will serve as the starting point for the RFID system' designs, elaborated in the next chapter. The motivations of the experts will be further explained in the section next by taking a closer look to the added values which are wanted by at least two different motivations.



Scheme 7 the confrontation process to be followed

Shipment visibility of goods

This added value was wanted for sustainability purposes (kilometre record for BREEAM) or it was wanted for productivity purposes whereby operational managers on site can see in real-time where a certain delivery is located. They wanted to decrease the uncertainty in the delivery process (resulting in unnecessary waiting time of jobsite workers) once there is a continuous installation cycle on-going.

Automate goods receiving

This added value was wanted for productivity reasons since it took a while to identify all incoming products or it was time consuming to see what is inside a package without the permission to opening it. In other cases, there was a limited control in the supply and storage of products on site whereby operational managers did not know at one time which products were delivered on site.

Real-time Stock Balances

For productivity reasons, the subcontractor had in one moment no idea what was stored on site whereby jobsite workers were unnecessary searching around for products which were not stored on site. This added value was also wanted to increase the control over the stock on site. Without a time pressure, there was a need to know which stock was stored on site by some operational managers.

Minimizing Dwell-Time

Products of this subcontractor (National Military Museum case) were prone to damage, whereby it is of importance to process these products as fast as possible into the building. Thereby, the subcontractor wanted to achieve an increase in productivity and he wanted to achieve more control in the storage of these type products.

Localize Products on Site

Jobsite workers were unnecessary searching for products on site (a decrease of productivity) or there was no idea at one moment where products are located on site, limiting the control over the storage.

Unique Product Identification

This added value was wanted for sustainability reasons (simplifying and encouraging the material handling of reusable products) or someone wants to identify Custom-made products at the site entrance (control).

4.3.1 The project circumstances

The determining project circumstances under which the experts assigns a priority to an added value of a RFID system, have been given in the table below. This is a complete overview with not only the most important added values which have been used in the cross-case analysis but also the less important added values of the RFID system. This will clarify under which project circumstances which added value is wanted by the experts.

Project Circumstances	Added value RFID
This added value was not wanted in the case studies	1. Product Life Cycle Information
- Time pressure in the realization phase - Lack of continuity jobsite workers - Need for real-time information about manufacturing process - Uncertainty in the delivery process	2. Visibility Products Upstream Supply Chain Overall Priority: 12
- Kilometre record trucks needed (BREEAM) - Uncertainty in the delivery process - Continue installation cycle present	3. Shipment Visibility of Goods Overall Priority: 25
- Limited control in supply and storage of products on site - No idea which products are on the project site - Time consuming to identify delivering products and packages	4. Automate Goods Receiving Overall Priority: 39
- Limited control in supply and storage of products on site - No idea which products are on the project site - A lot of re-handling of products on site	5. Real-Time Stock Balances Overall Priority: 24
- Limited control in supply and storage of products on site - No idea which products are on the project site	6. Minimizing the Excess of Stock Overall Priority: 12
- Limited control in supply and storage of products on site - No idea which products are on the project site	7. Minimizing Dwell-Time Overall Priority: 26
- Limited control in supply and storage of products on site - No idea which products are on the project site	8. Minimizing Fraud / Theft Overall Priority: 12
- Limited control in supply and storage of products on site - Long temporary storage of products on site - Lack of continuity jobsite workers	9. Monitoring Progress / Production Overall Priority: 11
- Handling with reusable products - Limited control in supply and storage of products on site - It is hard to identify products without any delivery note - Use of Custom-made products on site	10. Unique Product Identification Overall Priority: 36
- Limited control in supply and storage of products on site - A long searching time for products - A lot of re-handling of products - Products are moved by other parties (clean-up) - A lot of re-handling of products on the floor levels	11. Localize Products on Site Overall Priority: 68
This added value was not wanted in the case studies	12. Self-Learning Teams
- It is hard to identify products after the realization phase - There is a requirement in the availability of the building - There is a need for more efficient maintenance - It is difficult to look up product' information - There is a requirement in preventive maintenance	13. Information Upstream – Execution Overall Priority: 69
- There is a need for a more efficient maintenance phase (proactive) - There is a requirement in the availability of the building - Presence of flexible lay-out rooms - Need for higher quality indoor environment	14. Monitoring Building Performance Overall Priority: 25

Table 17 The determining project circumstances for added values assigned by experts

On the following page, a summary is given about the motivations of the expert why they assign a priority to a specific added value. These added values are subject to a specific phase of the construction project (arrival – utilization phase).

4.3.2 The reason why added values are wanted

From the within-case and cross-case analysis, it became clear that the added values are wanted for different type of motivations throughout the multiple construction phases. In *Table 18 The motivations for added values by the experts* below, these different type of motivations are given (named domains). Only the most important added values assigned by the experts are given. The line-of-reasoning of the motivations has been given in Appendix G. The abbreviations technique used in 4.2 Cross-case analysis is once again applied. The four domains why the experts assigns a priority to an added value are:

- A RFID system is wanted for <u>sustainability</u> improvements for either minimizing the transport of products or to simplify and encourage the use of reusable products.
- A RFID system is wanted for <u>productivity</u> improvements in order to tailoring the supply of products with the continuity of jobsite workers on site.
- A RFID system is wanted to increase the <u>control</u> over the arrival of product on site and the storage of products on site.
- A RFID system is wanted for an improvement in the <u>building management</u> in order to provide information about products on-the-spot or to provide extra sensory information about HVAC installations and occupancy of a room in order to increase the indoor climate quality.

Construction phase	Most important Added values	Motivations	Reasons	Domain
Arrival Project site	*'Shipment Visibility of Goods'*	Automate kilometre records (3.1.4)	Sustainability, transport BREEAM	Sustainability
		Decrease uncertainty in the delivery process (4.1.1)	Productivity is of concern, supply of products	Productivity
	'Automate Goods Receiving'	More control in the arrival of products to the project site. (1.1.3, 2.1.1, 2.2.2, 5.1.2)	Lack of control in the arrival of products	Control
		Increase time efficiency in checking incoming products (2.1.1, 2.2.2)	Productivity is of concern, supply of products	Productivity
Storage Project site	*'Real-Time Stock Balances'*	Get more control in the storage of products on site (5.1.3, 5.2.3)	Lack of control in the storage of products (5.1.3, 5.2.3)	Control
			Productivity of concern, continuity of jobsite workers on site (5.2.3)	Productivity
	'Minimizing Dwell-Time'	Get insights in how long products are stored on the project site (5.1.3, 5.2.1)	Lack of control in the storage of products (5.1.3)	Control
			Productivity of concern, continuity of jobsite workers on site (5.2.1)	Productivity
		Minimizing temporary storage time of products which are prone to damage (5.2.1)	Lack of control in the storage of products	Control
Production Project site	*'Localize Products on Site'*	More control in the location of products on site (1.1.1, 1.2.1, 2.1.2, 2.2.1, 5.2.2)	Lack of control in the storage of products (1.1.1, 2.2.1, 5.2.2)	Control
			Productivity of concern, continuity of jobsite workers on site (1.1.1, 1.2.1, 2.1.2, 2.2.1, 5.2.2)	Productivity
		More control in the location of products on the floor levels (2.2.1)	Productivity of concern, continuity of jobsite workers on site	Productivity
	'Unique Product Identification'	More control in the handling of products (1.1.2, 1.2.2, 5.2.5)	Lack of control in the arrival of products (1.1.2, 1.2.2, 5.2.5)	Control
			Sustainability, re-use products (1.1.2)	Sustainability
Utilization Phase	*'Information Upstream – Execution'*	Fast & easy identification of products for the maintenance engineer on-the-spot (3.1.1, 4.1.2, 4.2.1, 5.1.1)	Information provision during the maintenance phase	Building Management
		Fast & easy provision of product related information for the maintenance engineer on-the-spot (3.1.1, 3.2.1, 4.1.2, 4.2.1, 5.1.1)	Information provision during the maintenance phase	Building Management
		Fast & easy provision of maintenance history is wanted(3.2.1)	Information provision during the maintenance phase	Building Management
	'Monitoring Building Performances'	Optimizing maintenance activities by obtaining more information from sensors in order to ensure full availability of the building (3.1.2)	Extra information provision, extra information to increase maintenance quality	Building Management
		Better match between the actual occupancy of a room and the HVAC installations (4.1.3)	Extra information provision, extra information to increase quality	Building Management

Table 18 The motivations for added values by the experts

4.4 In conclusion

In this chapter, information from practice and literature has been used in order to give answer on the research question: '*Under which project circumstances is which added value of a RFID system wanted and why?'*. Multiple steps are taken to answer this question. From the literature review of research question one, the documentation about the five case studies and the expert interviews, information about the project characteristics, the wastes in current construction logistics and the motivations why an added value of a RFID system is wanted have been analysed with the use of a within-case and cross-case analysis. With these two analyses, it became clear that the added values the experts want are highly determinative to the project circumstances. Therefore, an overview about under which project circumstances which added value is wanted is given in *Table 17 The determining project circumstances for added values assigned by experts* on page 31.

However, from the analyses in this chapter, it has also been found that the experts have different type of motivations to assign a priority to an added value. The same added value can be wanted for different type of motivations. So, in *Table 18 The motivations for added values by the experts* on the previous page, the reasons why the experts assigns a priority to an added value has been given. It became clear throughout this chapter that the added values are wanted for four type of motivations, namely an improvement in *'Sustainability', 'Productivity', 'Control'* or *'Building Management''*. One can see that the same added value of the RFID system is wanted for different motivations. These two different type of motivations will result in two different kind of RFID systems in practice since different type of information is wanted. These needs will be used for the determination of the composition of components of the RFID system which will be elaborated in the next chapter. The four types of motivations which have been identified in this chapter are:

A. <u>Sustainability</u>
   There is a need to map the kilometres driven by trucks for a project automatically in case of a BREEAM sustainability program is incorporated in the project. Besides, there is a need to simplify the material handling of reusable products inside a project (or in-between projects.

B. <u>Productivity</u>
   In projects where productivity is of concern, experts have a need for more control over the supply of products to the construction site and to secure the productivity of jobsite workers on site.

C. <u>Control</u>
   In some cases, there was a need for more control in the arrival process of products on site and at the same time, there was a need for more control in the storage of products on site.

D. <u>Building Management</u>
   In projects with a maintenance responsibility, there is a need for more efficiency in this phase by simplifying the identification of products or to obtain extra sensory information of Heating, Ventilation and Air-Cconditioning systems (HVAC) and a building' occupancy.

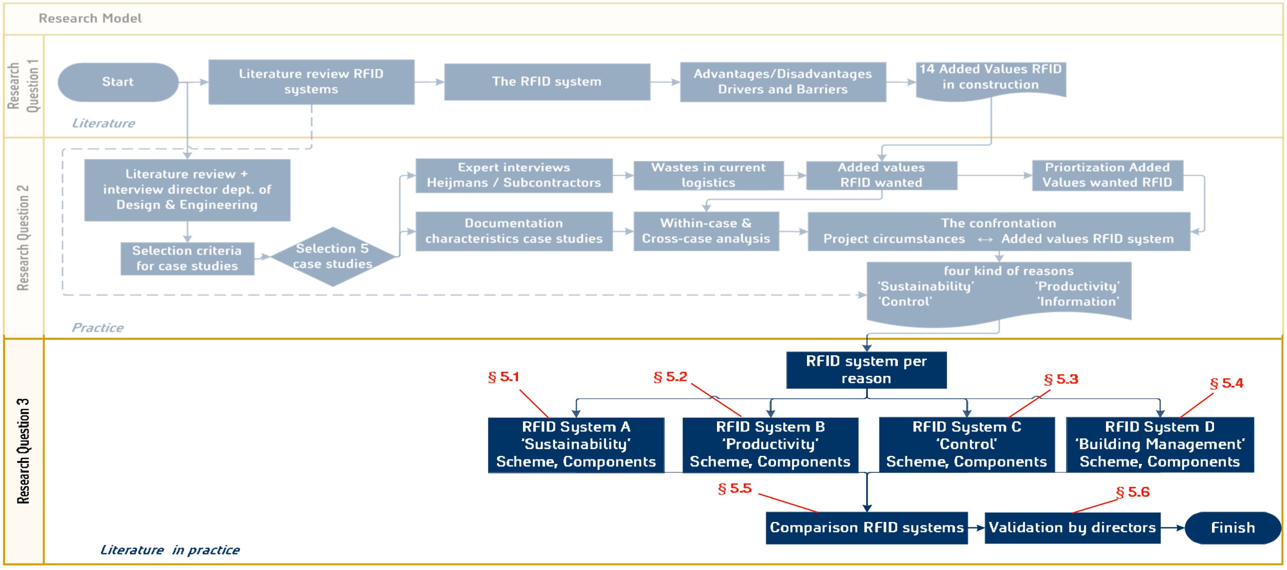
chapter 5

“The simpler, the better. The less choice you give, the more likely someone will do the right thing”

~ Johan Cruijff ~

5. RFID systems for non-residential construction projects

The previous chapter indicates some of the many wastes at current non-residential construction projects today. It is this context wherein RFID is intended to have an added value over the current daily processes. Below, the full research model is given in *Scheme 8 Research model research question 3*. From the literature about RFID, see *Chapter 2 The added value of RFID for the construction sector*, fourteen added values are identified and submitted to experts during expert interviews of the non-residential construction industry in research question 2, which is elaborated in *Chapter 4 Results Interviews*. During these expert interviews, insights in the daily working conditions of jobsite workers were obtained. The bottlenecks about construction logistics are indicated and the needs from each expert has been listed down (see the within-case and cross-case analysis in the previous chapter). It became clear that the added values are wanted for different reasons in each case study, so differs the motivation of each expert. This has resulted in an overview about which added value is wanted under which project circumstances, see *Table 17* on page *31*. The reasons why a certain added value is wanted, has been given in the overview of *Table 18 The motivations for added values by the experts* on page 32. These reasons forms the starting point of the determination of which RFID system should be applied in which situation.



Scheme 8 Research model research question 3

In the analysis of previous chapter, it became clear that the added values are wanted for four different reasons, namely an improvement in:

a. Sustainability
b. Productivity
c. Control
d. Building Management

These four type of motivations will result in four different type RFID systems, which will be named the same from here on. Since the same added value can be wanted for different reasons by two different experts, different type of RFID systems should be implemented in order to meet different needs of these two experts. In this chapter, these RFID systems will be elaborated and explained firstly. Hereafter, a comparison between these systems will be made. Next, these systems will be submitted to three directors of Heijmans non-residential construction in order to find out if these directors see a potential value in these RFID systems in the non-residential construction projects of Heijmans.

After this chapter, it should become clear which RFID system should be applied under which project circumstances in order to obtain the most added value of the RFID system. This will help to answer the main research question: *'which RFID system should be applied under which project circumstances in order to obtain the most added value from a RFID system for non-residential construction projects'.*

For the comparisons between the multiple RFID systems, the following variables will be used in order to differentiate in-between the systems. These variables are indicated by the author as important comparison variables between the multiple RFID systems since they make clear the differences and the impact the RFID systems will have on the non-residential construction projects.

Variables	Measures		
Location of products	Fixed Products (i.e. tags) will not be moved	Flexible Products (i.e. tags) will be moved	
Type of Information	Static information Product life cycle information, such as: name, batch number, dimensions, production date, compositions, manufacturer, warranties (no information will be added to the system)	Dynamic information Product life cycle information which can change such as: last scanned location, environmental measures, added information by actors (maintenance done for example)	
Read Range	Short Tags have to be read from a short distance, approximately from 2metres	Long Tags have to be read from a long distance, over 2metres or between physical locations (inter-company scanning)	
Number of tags	A few Some products have to be provided with tags	A lot Many products have to be provided with tags	
Implementation in Material Supply Chain	Early Attachment of tags to products early in the supply chain (raw material / manufacturer)	Late Attachment of tags to products late in the supply chain (wholesaler / 'last-mile' transportation)	
Implementation in Construction Value Chain	A few subcontractors Only a few subcontractors have to be involved during the realization or maintenance phase	Many subcontractors Many subcontractors have to be involved during the realization or maintenance phase	
Focus RFID System	Money Primary focus: decrease costs	Time Primary focus: time improvement	Quality Primary focus: increase quality

Table 19 Comparison variables RFID systems

5.1 RFID System 'Sustainability'

The first RFID system is 'Sustainability' Sustainability will be of increasing importance for contractors in the construction sector. The amount of BREEAM certified projects has been increased over the years, see Figure 5. Besides, more products should be reused and recycled while emissions (such as CO_2, NO_2, SO_2 and PM_{10}) should be reduced in order to contribute to a corporate social responsibility and a sustainable environment. This RFID system will have two functions, which will be explained next.

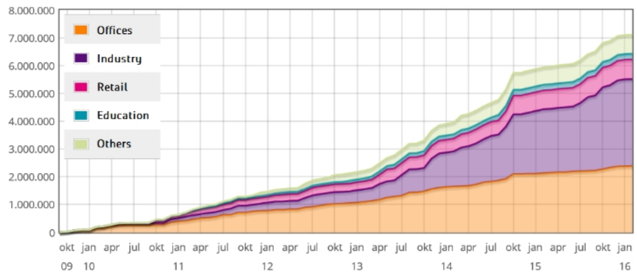
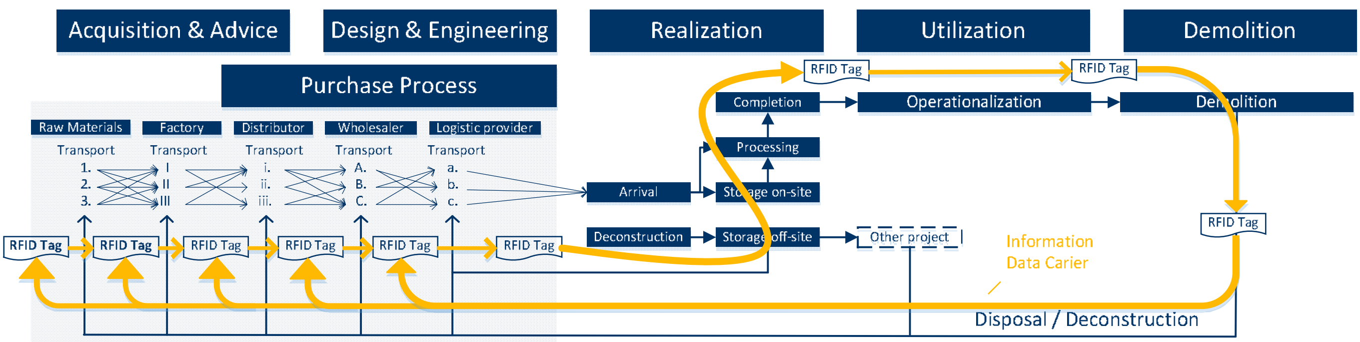


Figure 5 total unique m2 BREEAM certified new construction projects in the Netherlands, source: tps://www.breeam.nl/projecten/statistieken/nieuwbouw

5.1.1 The needs from the experts

There is an increasing need to have information about the origin and composition of products and to get insights in the amount of kilometres driven by the suppliers. The underlying reasons for this is to encourage the reuse of products in new projects, in order to minimize the use of new raw materials. Reduce the amount of kilometres of trucks driven will reduce the nuisance of these trucks to its environment. This nuisance is created by noise and emission pollution, traffic jams and unsafe situations on the streets, all created by trucks. In order to achieve these needs, two different kind of information is needed, resulted in two different RFID systems 1) *Re-use of products* and 2) *Reduce the amount of kilometres* by suppliers' trucks. These two subsystems will be elaborated briefly in paragraph 5.1.2. A detailed description has been given in *Appendix I The RFID Systems in detail*. Below, a schematic visualisation is given about the implementation of such RFID system in the construction value chain. The explanation of this flow chart is given on the next page.



Scheme 9 Flow chart Sustainability

In Scheme 9 on the previous page, one can see the departments of Heijmans non-residential. In this scheme, the tender documents will be worked out in the *'Acquisition & Advice'* – department to a certain level of detail. In the *'Design & Engineering'* - department, these documents will be worked out to executable plans for the *'Realization'* – department. After completion of the realization phase, the building will be operationalized and/or maintain if incorporated in the contract. After this department (i.e. phase), the building will be handed over to the client, redeveloped or demolished. In the construction value chain, the purchase process of products will take place in the '*Acquisition & Advice'* and the *'Design & Engineering'* – departments. The incorporated material supply chain is the chain in which products are manufactured, distributed and transported to its final location. The implementation of the RFID system '*Sustainability'* is visualized in this flow chart.

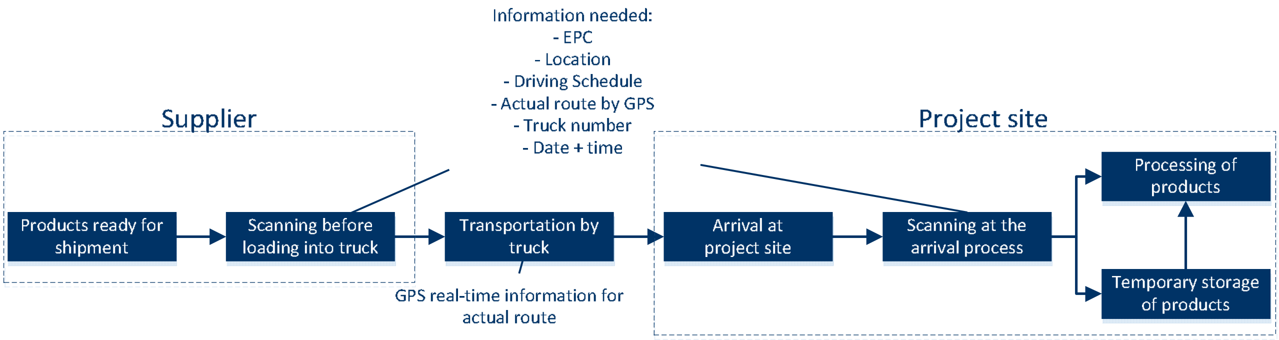
The first function of this RFID system will be the encouragement of the re-use of products. Therefore, existing products have to be provided with an unique code (RFID tag) whereby it becomes possible to link product life cycle information to an existing product and to handle or refer to this unique code (i.e. a unique product). This code will support the material handling by jobsite workers. The second function of this system is to map the kilometres driven for the 'last-mile' transport by trucks to the project site automatically. This subsystem will cover only the last-mile transport to the project site.

5.1.2 The RFID system 'Sustainability'

These two needs of this RFID system result in two type of subsystems. Therefore, a brief explanation about these two subsystems will be given below. An enlarged explanation is given in *Appendix I The RFID Systems in detail, paragraph a) RFID System 'Sustainability'*.

<u>'Re-use of products'</u>
This subsystem will make products unique identifiable instead of identifiable on a SKU-level (like barcodes does). The identification of products becomes problematic after the realization phase due to the damaged barcodes for instance. This subsystem will result in unique product life cycle information, stored on the RFID tag which is attached to (or placed inside) the products. The RFID tag becomes a data carrier. No matter where the product is physically located, everyone should be able to obtain the unique product information. In the case studies, this system could simplify the material handling of fixed signage and furniture in the Schiphol Lounge 2 case.

<u>'Reduce kilometres'</u>
This subsystem will map the kilometres driven by trucks to the project site automatically. Once the logistic flows of products becomes visible, one can optimize the flows by combining shipments or optimize the delivery schedule. Currently, the fragmentation in the construction sector makes this impossible. This subsystem should be implemented firstly for the last-mile delivery and it should be expand upstream the supply chain overtime. A Global Navigation Satellite System (GNSS) should record the actual route and kilometres driven, instead of the suspected kilometres. In Scheme 10 below, the process to map the kilometres automatically has been visualized. This subsystem could contribute to the evidence needed for the BREEAM certificate in the Eurojust case study.



Scheme 10 Process steps RFID subsystem 'reduce kilometres'

5.1.3 Comparison variables

In the table below, an explanation of each subsystem and its impact on construction projects is given with use of the comparison variables of *Table 19 Comparison variables RFID systems* on page 36.

Variables	Re-use of products	Reduce Kilometres
Location of products	Flexible Products will be moved on a project site (deconstruction) or between project sites	Flexible Products will be moved between a distribution centre and a project site
Type of Information	Static information Product life cycle information stored on the RFID tag such as: name, batch number, dimensions, production date, compositions, manufacturer, warranties	Dynamic information Besides the static information, the actual driven route should be linked to the unique code in order to see the kilometres and route driven for a products at a later time
Read Range	Short Tags have to be read from a short distance for handling purposes	Long Tags have to be read at dock doors (approximately 2 meters read distance from at least two sides)
Number of tags	A lot Since it is now unclear which products will need to be re-used in the future, all products should be provided with a RFID tag	A lot In order to see how many kilometres have been driven for each product, all products have to be provided with a RFID tag.
Implementation in Material Supply Chain	Early For new products, the attachment of RFID tags should be done on a source-tagging basis (the manufacturer of the products). For existing products in buildings, products should be provided with a RFID tag as soon as possible	Late For the purpose of this system, products have to be provided with a RFID tag just before shipping to the project site ('last-mile' transport)
Implementation in Construction Value Chain	Many subcontractors All products for a construction project should be provided with a RFID tag, so, all subcontractors have to provide their products with an RFID tag	Many subcontractors Since all products have to be provided with an RFID tag, all subcontractors have to provide their products with an RFID tag.
Focus RFID System	Quality The primary focus is to increase the sustainability of the environment by increasing the re-use of products. A secondary focus is to increase the time efficiency of identifying reusable products and obtain related information.	Quality The primary focus is to reduce the amount of kilometres (reducing the amount of emissions, unsafe situations and congestions) which increases the environmental quality. An incidental benefit will be the reduction of fuel costs.

Table 20 Comparison variables RFID system 'Sustainability'

The key cost-benefit factors of these subsystems are given in the table below.

Variables	Re-use of products	Reduce Kilometres
Costs	- Associated costs (see paragraph 2.4.4) - A standard information lay-out have to be developed / followed by every actor world wide - Information have to be stored on the tags by all actors in the material supply chain	- Associated costs (see paragraph 2.4.4) - A standard information lay-out have to be developed / followed by every logistic service provider - Global Navigation Satellite System-sensor (GPS for example) on trucks - Data interchange between supplier, logistic service provider and (main) contractor
Benefits	- Product life cycle information available anytime and everywhere - Unique product information instead of at SKU-level information - Future proof (application for a 'raw materials passport' for instance, which could be forced by the governments to encourage a circular economy) - Great impact on, and support for, sustainability programs in the future	- Insight in transportation on a fact-basis instead of assumption-basis - Information for benchmark values for reducing kilometres driven over time - Less emission pollutions and unsafe situations and an increase in a sustainable environment

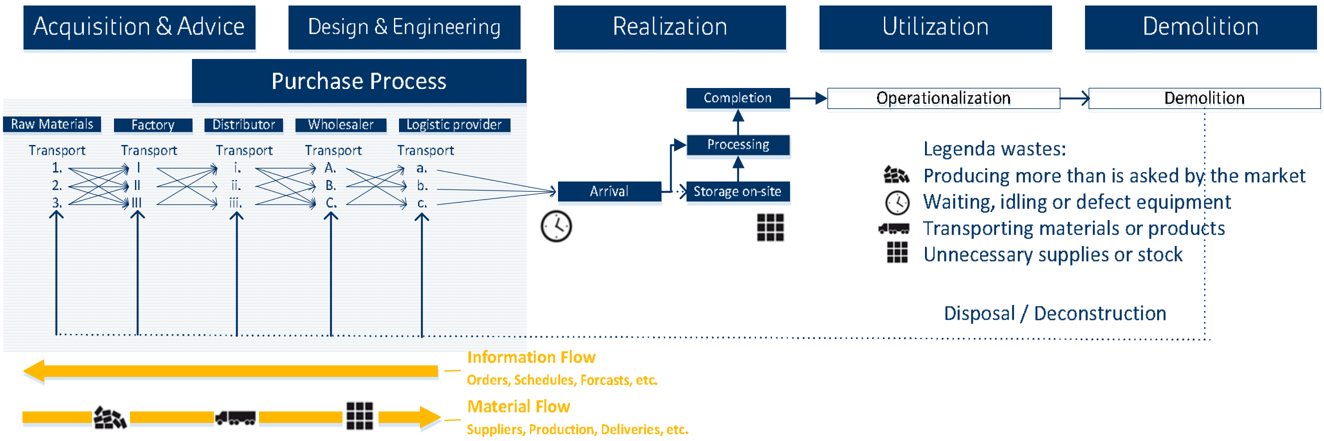
Table 21 Cost & benefit factors RFID system Sustainability

5.2 RFID System 'Productivity'

The second RFID system is 'Productivity'. Experts do have a need for more control over the delivery process when the productivity of jobsite workers is jeopardized. In such a situation, every time delay will have a direct effect on following subcontractors and so, on the total project schedule. For this RFID system, two different subsystems will be proposed for since there are two different kind of information needed. These two subsystems will be explained below.

5.2.1 The needs from the experts

Due to the fragmentation in the construction sector, there is limited control in the supply of products to the project site. In order to ensure that the right products will be delivered at the right time at the right place, two types of information is needed namely: information from the project site (which materials has been processed) and information from the material supply chain (which materials will be delivered when). Therefore, in order to tailor the supply of products with the productivity of jobsite workers on site, information about the shipment of products and information about the productivity of jobsite workers on site is needed. The two subsystems proposed for are 1) *off-site* information and 2) *On-site* information. These two subsystems will be explained in the following section. An explanation about the current flow of materials throughout the construction sector is given in the following scheme:



Scheme 11 Flow Chart 'Productivity'

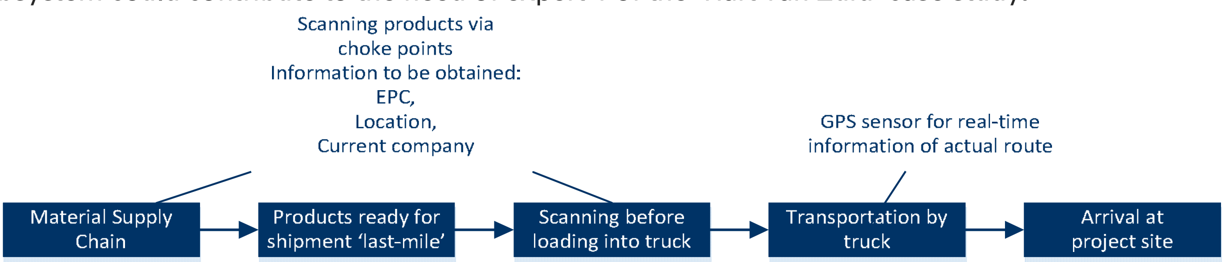
The construction value chain of Heijmans non-residential (from the department *'Acquisition & Advice'* to *'Demolition'*) and the Material Supply Chain (under purchase process: '*Raw Materials'* to '*Logistic Service Provider'*) is given in this scheme. In order to tailor the supply of products with the productivity of jobsite workers on site, insights is needed in this Material Supply Chain and the productivity on site. One can see the fragmentation of the construction sector in the amount of arrows drawn between the stages of the Material Supply Chain. It is currently complicated to obtain the status of certain production and logistic processes throughout the material supply chain due to the fragmentation in this chain.

5.2.2 The RFID system 'Productivity'

The two RFID systems ('*Off-site'* and *'On-site'*) are briefly explained in the following section. An enlarged description has been given in *Appendix I The RFID Systems in detail.*

<u>'Off-site'</u>

This subsystem will create information about the status and location of certain products (i.e. deliveries). The location of products which passes a choke point (a physical location that will be passed through by all products) can be updated in the software systems. These choke points can be located throughout the material supply chain. In order to obtain real-time information about the location of the last-mile delivery, an external Global Navigation Satellite System-sensor (like GPS) should be used. This subsystem could contribute to the need of expert 1 of the 'Hart van Zuid' case study.



Scheme 12 Process steps RFID subsystem 'Off-site'

'On-site'
This subsystem is intended to create information about the productivity on-site. This information is intended to achieved by the processing of products. The moment a product arrived at the project site, the moment the product has been temporary stored on site and the moment the stored product has been processed into the building are valuable time moments which can be used to calculate the productivity of jobsite workers. This subsystem could contribute to the needs of the experts from Schiphol Lounge 2, the experts of Telecity AMS1 and expert 2 of the National Military Museum case.

5.2.3 Comparison variables

The variables for comparison of these two RFID systems are given in the table below.

Variables	Off-Site	On-Site
Location of products	Flexible Products will be moved throughout the material supply chain, also between multiple companies	Flexible Products will be moved from the entrance of the site to the storage area to the installation area
Type of Information	Dynamic Last known location throughout the material supply chain (i.e. products) have to be obtained (with use of the internet for example).	Dynamic the time products will be scanned and the corresponding location changes overtime.
Read Range	Long Tags have to be read from dock doors and choke points(approximately 2 meters read distance from at least two sides of a dock door)	Long Tags have to be read from dock doors and choke points (approximately 2meters read distance from at least two sides of a gate reader)
Number of tags	A few It would be beneficial to provide only products of the so-called '*critical shipments'* with a repetitive installation cycle (often Make-To-Order and Engineer-To-Order products)	A lot All products have to be provided with RFID tags in order to obtain as much reliable data as possible in order to estimate the productivity of jobsite workers / crews properly
Implementation in Material Supply Chain	Early These products have to be provided with a RFID tag as early as possible (source-tagging)	Late For the purpose of this system, only information on the project site is needed
Implementation in Construction Value Chain	A few subcontractors Only products of '*critical shipments'* should be provided with a RFID tag. Therefore, only a few subcontractors need to be involved.	Many subcontractors Since all products have to be provided with an RFID tag, all subcontractors have to provide their products with an RFID tag.
Focus RFID System	Time: The primary focus is to increase the efficiency of the construction supply chain by taking out uncertainty in the delivery process.	Time: The primary focus is to increase the efficiency of the realization phase by increasing the productivity of jobsite workers.

Table 22 Comparison variables RFID system 'Productivity'

The key cost-benefit factors of these two subsystems are given in the table below.

Variables	Off-Site	On-Site
Costs	- Associated costs (see paragraph 2.4.4) - Data interchange between companies	- Associated costs (see paragraph 2.4.4) - Increased infrastructure costs for larger sites
Benefits	- Increase transparency in the supply chain - More insights in the route products have passed throughout the supply chain - Coupling between data and physical objects	- Insights in stock on site - Creating benchmark values for process optimizations (LEAN techniques) - Insights in productivity of certain jobsite workers / crews

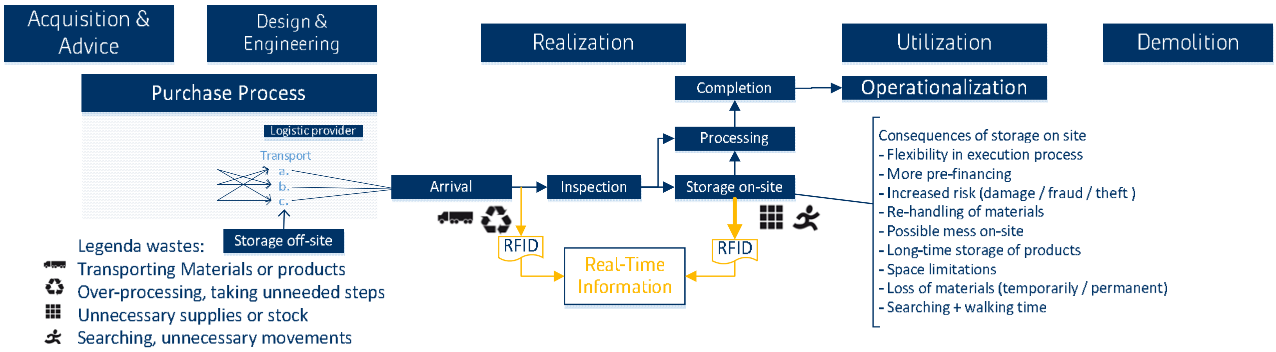
Table 23 Cost & benefit factors RFID system 'Productivity'

5.3 RFID System 'Control'

In some cases, there was a limited control in the arrival of products and thereby often a limited control over the temporary storage of products on site. This is remarkable since (sub)contractors are of increasing risk when products are delivered too early to the project site. There is a risk for damaging and fraud to products for instance. Besides, the project site will be transformed into an unorganized area wherein it is hard to find back products once the storage is not controlled. There will be an increasing safety danger for tripping due to amount of storage on site. It will also increase the walking distances and searching time for products by jobsite workers. So, this RFID system is contemplated to increase the control over the supply and storage of products on site by automatically identify which products have been supplied to the project site and creating information about the location of products on the project site. This will result in the two subsystems,:1) '*Arrival*' and 2) '*Storage*', explained below.

5.3.1 The needs from the experts

In some of the case studies (Schiphol Lounge 2 and National Military Museum), there was a limited control in the arrival of products due to various causes (explained in the within-case analysis of the previous chapter). In the same case studies, there was also a limited control in the storage of products on site. The loss of products increased the walking and searching time of jobsite workers to products. RFID has found to give information about which products are delivered on site and where products are located on site. In the scheme below, one can see the flow chart related to this RFID system and the interference of these two subsystems during the realization process.



Scheme 13 Flow chart 'Control'

In this scheme the logistical process of products from the 'last-mile' transport to the project site and the processing of products on the project site has been visualized. Products stored at distribution centres, wholesalers or consolidation centres are transported by a logistic service provider to the project site. At the arrival process, products will be controlled firstly before they will be temporary stored or processed into the building. This control is currently paper based and often limited done by jobsite workers. It becomes thereby unclear what is delivered and when something was delivered on the project site. In the same case studies, there was a limited control in the storage of products on site. The location of temporary stored products on site was unclear due to various causes, explained in the previous section. There were many movements and a lot of (unnecessary) stock on site.

5.3.2 The RFID System 'Control'

These two type of information needed, checking the products during arrival and localize products on site, results in two kind of RFID subsystems: '*Arrival*' and *'Storage'*, explained here. An enlarged explanation is given in *Appendix I The RFID Systems in detail.*

<u>'Arrival'</u>

The information needed from this subsystem is to provide information about which products have passed the reading zone of the RFID reader, located at the site entrance of construction projects. By multiple researchers (Jaselskis 1995, Demiralp 2012, Sardroud 2012) the following application is proposed for. A truck enters the project site, passes the entrance gate (choke point) and thereby, will pass the reading zone of multiple RFID readers, located at the edges of this gate. Although scanning the products automatically in this way sounds perfect, the steel processed into truck trailers reflects the radio signals, which blocks the readability of the RFID tags inside the trailers, making this application only applicable in the following situations. The loaded products can be scanned at the dock doors of the supplier and can be saved to a RFID tag on top of the truck (outside the trailer). The tag will be read by the readers since there is no steel between the tag and a gate-reader anymore. The use of open trailers is also an option, however, not practical in all situations. Another solution is to read the tags once the products are unloaded on site. This must be done in the reading zone of a fixed reader or the products have to be scanned by a handheld-reader manually. Since it is known what should be delivered (via delivery notes), the checking of products can be done on a management-by-exception basis instead of controlling every product manually (what is currently the case). This will increase the efficiency of the controller on site drastically.

'Storage'

Obtaining information about the localization of products can be done on different manners. One can use active tags with a great read range and a few RFID readers (expensive tags) or one can use passive tags with a short read range. In this last case, the location can be obtained via triangulation of at least three fixed RFID readers (many RFID readers are needed) or by use of localization tags in the floors (only the 'last known' location becomes known). Transport equipment can use these localization tags to navigate and localize the last known position of the stored products. In all these three possibilities (active tags, triangulation or localization tags), the location of products becomes known by which it is possible to 'see' which products are at a storage area and where these products are located in that storage area. This subsystem could contribute to the needs of Schiphol Lounge 2, the Telecity AMS1 and the National Military Museum case study.

5.3.3 Comparison variables

The comparison variables for these two RFID systems are given in the following table.

Variables	Arrival	Storage
Location of products	Flexible Products will pass a choke point, in this case, the arrival gate of the project site	Flexible The stored location of products changes over time by movements or processing of products.
Type of Information	Dynamic The time a certain product (product code) is scanned will be linked to this product code	Dynamic Since the location changes over time, the information have to be updated frequently
Read Range	Long or short Tags have to be read by fixed gate-readers (choke points) with approximately 2metres read-range or by a handheld-reader (short read-range necessary)	Long or short Depending on the localization technique (active tags, triangulation or localization tags), the read range must be long (active tags) or short (use of localization tags on site for navigation)
Number of tags	A lot In order to know which products are delivered on site, all products have to be provided a RFID tags	A lot In order to know which products are where on site, all products have to be provided a RFID tag
Implementation in Material Supply Chain	Late For the purpose of this system, only information on the project site is needed	Late For the purpose of this system, only information on the project site is needed
Implementation in Construction Value Chain	Many subcontractors Since all products have to be provided with an RFID tag, all subcontractors have to provide their products with an RFID tag.	Many subcontractors Since all products have to be provided with an RFID tag, all subcontractors have to provide their products with an RFID tag.
Focus RFID System	Time + money This system results in more control and efficiency in the arrival of products. This will have both an advantageous effect on time (for checking) and money (unnecessary supplies)	Time This system will result in more control over the storage on site. It becomes known where products are located and so, searching and walking time will be reduced.

Table 24 Comparison variables RFID system 'Control'

The key cost-benefit factors of these two subsystems are given in the table below.

Variables	Arrival	Storage
Costs	- Associated costs (see paragraph 2.4.4) - Data interchange between companies (delivery note)	- Associated costs (see paragraph 2.4.4) - Increased infrastructure costs for larger sites (and cases of triangulation / localization tags) - Possible need for a WLAN network on site to send data over a longer range
Benefits	- Control on management-by-exception basis (improving efficiency check-in) - Automatic registration system for all products on site - Decrease human interaction - Control between invoices and actual deliveries (proof of delivery) - Elimination of paper invoices and delivery notes	- Reduce walking and searching time - (real-time) information about stock and location of stock on site - Minimizing dwell-time, lowering the stock on site, lowering pre-investments and minimizing risk of fraud / theft/ damage to products since information of which products are stored when, where and for how long becomes known

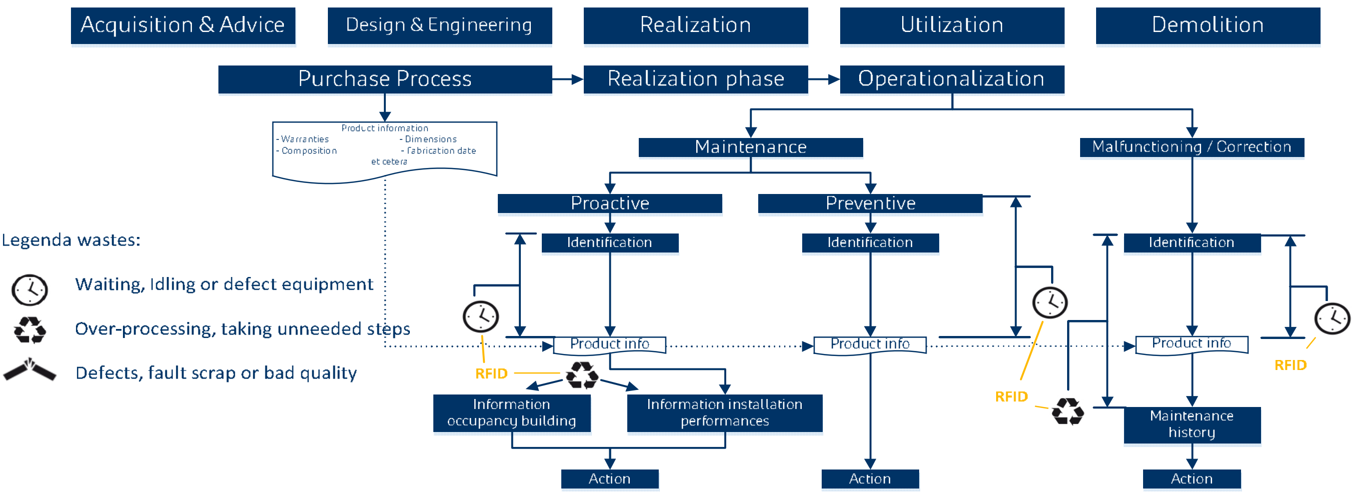
Table 25 Cost & benefit factors RFID system 'Control'

5.4 RFID System ‘Building Management’

The increasing responsibilities of construction contracts to also manage the maintenance phase of buildings (for multiple years) has increased the need for a more efficient maintenance process, expressed in a shorter time needed for activities, less money needed for maintenance or a higher quality as a result. The less efficient maintenance period, the higher the costs for the responsible company will be, the lower the revenues. So, there is an increasing need for a more efficient maintenance phase present by all experts of the case studies dealing with such a responsibility. It has been acknowledged by these experts that a fast and more accurate product identification should improve the speed and efficiency of maintenance activities, improving the quality of the maintenance phase for the client or building users. The product identification and thereby the obtainment of product’ information is currently a very exhausting and error prone process. The benefits are intended to be an improvement in the maintenance quality by minimizing time consuming information retrieval. There are two kind of RFID subsystems needed for this, explained below.

5.4.1 The needs from the experts

During the maintenance phase, it has been recognized by the experts, it is hard and time consuming to identify products and obtain the (unique) product’ information . There is also an increasing need for a pro-active maintenance phase instead of a preventive (or corrective) maintenance phase. Therefore, real-time information about HVAC installation’ performances and the influential occupancy by users should be obtained more frequently in order to optimize the technical life time of HVAC installations and to increase the quality of the utilization phase of buildings. These two types of information can be obtained by two different RFID subsystems: 1) *‘Information from products’* and 2) ‘*information from sensors’*. These two RFID subsystems will be explained below. The current information retrieval during the maintenance phase is visualized in the following scheme.



Scheme 14 Flow chart ‘Building Management’

In this scheme, one can see that static information about the products (the product life cycle information), is being defined in the ‘*Acquisition & Advice’* and *‘Design & Engineering’*- departments, explicitly in the Purchase Process of products. This information is currently stored in (large) documents, complex BIM models and/or huge asset-list maps. During the utilization phase, these information resources will be consulted. In case of product maintenance, there are two types of maintenance identified in this scheme: pro-active maintenance and preventive maintenance. In case of proactive maintenance, information from sensors (environmental values and occupancy) is needed in order to create expectations about the (needed) output of HVAC installations in the future. The applicability of RFID systems in combination with sensors is further elaborated in *Appendix H Interview building management systems*. In case of preventive maintenance and Malfunctioning / Correction, a certain product must be identified first, after which corresponding information can be obtained from a database. Once someone has the needed information, he or she can start with his activity. Currently, this identification of unique products, and the obtainment of unique related life cycle information, is difficult and complicated.

5.4.2 The RFID System 'Building Management'

These two types of information needed results in two type of RFID subsystems, namely *'Information'* and *'Sensors',* explained on the following page. An enlarged explanation is given in *Appendix I The RFID Systems in detail, paragraph d) RFID System 'Building Management'.*

'Information'

This subsystem will make it easier to identify products and obtain its related information. This can be static information (product life cycle information) as well as dynamic (e.g. maintenance records). The RFID tags should be scanned by a maintenance engineer on-the-spot with a handheld reader. Due to the radio waves, it becomes possible to read hidden products and to read products from a distance. This subsystem could contribute to the needs of all projects with a maintenance responsibility.

'Sensors'

This subsystem will create more information about the utilization of a building. With sensors, one can measure the indoor climate (temperature, carbon dioxide and humidity) and a building' occupancy. One can optimize the output of the HVAC installations with use of these two values. Thereby, one can better adjust the output of the installations on a building' occupancy in, for example, splitted-up rooms. The wireless feature of these sensors can create flexibility in Building Management Systems (further explained in *Appendix H Interview building management systems).* This subsystem should contribute to the needs from the Eurojust and 'Hart van Zuid' case study. It must be clear that this subsystem is investigated in the context of this study, whereby the system is not compared to other existing wireless sensor systems.

5.4.3 Comparison variables

The comparison variables for these two RFID systems are given in the following table.

Variables	Information	Sensors
Location of products	Fixed Processed products in buildings have a fixed location, scanned via handheld-readers	Fixed The sensors will be placed on fixed location, so can be the antennas and readers.
Type of Information	Static + Dynamic Product life cycle information will be static information although maintenance history will change over time (dynamic)	Dynamic Real-time information about sensory data should be send to the RFID readers
Read Range	Short Tags should be read from approximately 3 to 5 meters since the maintenance operator hold a handheld reader and moves around	Long In order to minimize the hardware costs, the read-range should be approximately 2 metres (room-level / between rooms)
Number of tags	A lot Every component with a preventive maintenance responsibility should be provided with a RFID tag	A lot The more sensors, the more sensory data can be obtained, the better the harmonisation between HVAC installations and occupancy of a building
Implementation in Material Supply Chain	Early Since information have to be linked to products during the purchase process (source-tagging)	Late For this subsystem, sensors should be placed as late as possible (preventing damaging)
Implementation in Construction Value Chain	Many subcontractors Because every (sub)contractor with a preventive maintenance responsibility should link the relevant information to the RFID tag.	Few subcontractors Only subcontractors related to HVAC installations and building operate should make use of this RFID subsystem
Focus RFID System	Time This system will increase the time efficiency to identify products (uniquely) and obtain related information fast and easily	Quality The primary focus of this system is to increase the quality of the indoor climate and the technical life span of HVAC installations

Table 26 Comparison variables RFID system 'Building Management'

The key cost-benefit factors of these two subsystems are given in the table below.

Variables	Information	Sensors
Costs	- Associated costs (see paragraph 2.4.4) - Coordination costs between companies throughout the construction supply chain	- Associated costs (see paragraph 2.4.4) - Placement of RFID sensor tags - Coordination of obtained information
Benefits	- Fast and easy information obtainment on-the-spot - Improved data integrity - Unique product related information instead of SKU-level	- Very accurate environmental measures - Better match occupancy and indoor climate - Control of design plans (HVAC) and pool for data for optimizations in new projects

Table 27 Cost & benefit factors RFID system 'Building Management'

5.5 Comparison RFID systems

These eight RFID subsystems do have a wide variety of important features for both sub- and main contractor. In each of the previous paragraphs, an explanation is given about the characteristics of these RFID subsystems, with use of the variables from *Table 19* on page 36. The keywords of these variables across the systems are listed in the following table:

Variables	'Sustainability'		'Productivity'		Control'		'Building Management'	
	Re-use	Reduce	Off-site	On-site	Arrival	Storage	Information	Sensors
Location of products	Flexible	Flexible	Flexible	Flexible	Flexible	Flexible	Fixed	Fixed
Type of Information	Static	Dynamic	Dynamic	Dynamic	Dynamic	Dynamic	Static + Dynamic	Dynamic
Read Range	Short	Long	Long	Long	Long or short	Long or short	Short	Long
Number of tags	A Lot	A Lot	A Few	A lot	A lot	A lot	A lot	A lot
Implementation in Material Supply Chain	Early	Late	Early	Late	Late	Late	Early	Late
Implementation in Construction Value Chain	Many sub contractor s	Many sub contractors	Many sub contractors	Many sub contractors	Many sub contractors	Many sub contractors	Many sub contractors	Few sub contractors
Focus RFID System	Quality	Quality	Time	Time	Time + Money	Time	Time	Quality

Table 28 Comparison variables of the RFID systems

As one might noticed, not every RFID subsystem looks equally desirable to implement in the non-residential construction industry. So, the following table judge which RFID subsystem should be implement, elaborated afterwards. These findings are based on the assumptions of the author.

RFID System	Sub system	Priority experts	Applicability	Impact	Costs	Benefits	Total
Subsystem A. 'Sustainability'	Re-use products	3	1	5	2	4	15
	Reduce kilometres	2	5	4	3	3	17
Subsystem B. 'Productivity'	Off-site	2	4	2	3	3	14
	On-site	1	2	1	1	3	8
Subsystem C. 'Control'	Arrival	4	3	5	3	5	20
	Storage	5	4	4	1	4	18
Subsystem D. 'Building Management'	Information	5	3	5	5	4	22
	Sensors	2	2	2	2	3	11

Table 29 Validation RFID systems author

In this table, a '5' means a very good performance and a '1' means a very bad performance. For the sake of this study, each column and each value has been counted as equally important. The column '*priority*' is determined with the use of the priorities of the corresponding added values assigned by the experts, see Table 15 on page 27. The other values are determined by the estimation of the author. The '*total score'* determines which subsystems looks worthwhile to implement by taking all variables (priority, applicability, impact, costs and benefits) into consideration. The four highest scores are considered to be worthwhile to implement in the non-residential construction industry.

1. System D. Building Management: subsystem '*Information' (22)*
2. System C. Control: subsystem '*Arrival' (20)*
3. System C. Control: subsystem '*Storage' (18)*
4. System A. Sustainability: subsystem '*Reduce kilometres'* (17)

Worthwhile to implement

5. System A. Sustainability: subsystem '*Re-use products' (15)*
6. System B. Productivity: subsystem '*Off-site' (14)*
7. System D. Building Management: subsystem '*Sensors' (11)*
8. System B. Productivity: subsystem '*On-site' (8)*

Not worthwhile to implement directly

'Information': This subsystem has the highest priority assigned by the experts due to the simplicity of the system. Since the intended RFID tags (passive) are cheap, the attachment of tags can take place on a mass-scale basis. The information is welcome and simple to obtain during the maintenance phase, so, the author does see a great advantages in this added value. However, the orientation of the tags inside buildings must be well managed due to the presence of steel (which blocks the radio waves).

'Arrival' : More control and efficiency in the arrival process of products is desirable in many projects. However, special attention is needed due to the presence of steel (used in trucks for example). The

impact can be great since it becomes known what is delivered, when and by who. Subsequent processes can benefit from this system (an automatic billing system, a management-by-exception control and a proof of delivery). The costs consist mainly of the data interchange between suppliers and (main) contractor and the standard costs as explained in Paragraph 2.4.4 Associated Costs.

'Storage' : More control over the storage of products on site will have great benefits too. However, the storage area have to be well-organized. With the use of 'localization tags' (explained earlier) costs will drop but the information will not be in real-time. The impact can be great since the searching and walking time for products reduces once it is visible where (certain) products (and how many) are stored on site. Overall, this RFID subsystem is worthwhile to implement due to the contemplated benefits.

'Reduce kilometres': The priority is scored not that high due to only one case study has a BREEAM responsibility. However, the applicability of such a system has found to be high due to the minimal adjustments needed for logistic companies (logistic companies do know the exact location of their trucks in real-time via a GPS sensor on trucks). The impact could be relative high since the information from this system can be used for benchmark values in order to reduce the kilometres driven in upcoming projects. This will reduce noise and emission pollution, traffic jams and unsafe situations on the streets. The costs of the system can mainly be attributed to the changes in the enterprise systems and data interchange between logistic service provider and the main contractor. The benefits should be find in a quality improvement of the environment rather than a reduction of the gasoline cost.

'Re-use products' : The applicability of this system is low due to the needed collaboration with all relevant material supply chain-actors around the world. Due to the diversity of this material supply chain, it is very complicated to achieve collaboration from all actors. Besides, the diversity in products (raw materials, semi- and finished products which also will be cut, sawn and chop into pieces) blocks the wide implementation of such a system. However, the system can have an huge effect on the world' sustainability since it can boost the reuse of products and it lowers the use of new raw materials. Unfortunately, due to the amount of suspected coordination and changes in current business processes, the costs of such a system is expected to be high. The benefits of such a system should be find in the prove a corporate social responsibility rather than a reduction of the costs.

'Off-site' : The applicability of this system is found high since subcontractors have already much of the needed infrastructure in place (e.g. GPS sensors on trucks). Extra RFID readers at choke points in static indoor environment like factories would not result in many problems about the readability of the tags. The impact on the construction sector is not that high since many orders do have a time-buffer incorporated and suppliers are bound to the deliveries dates. Meanwhile, the costs are not that high due to the minimal hardware devices needed. The benefits remain questionable due to the time-buffers.

'Sensors' : Although the quality of the utilization phase can boost for building users, current Building Management Systems can control already the needed environmental values in-side buildings. It is expected that this quality level will not increase in the nearby future. In combination with the presence of steel in buildings (blocking signals), makes this system not that worthwhile to implement.

'On-site' : Calculating the labour productivity only on the time difference between arrival – storage and storage – processing of products, is find not that beneficial. The productivity depends on many more factors than just the processing time of products. So, the applicability and the impact are expected to be low. Besides, the storage area have to be well controlled, otherwise, it is impossible to calculate these time differences. It is impractical to calculate the productivity with only the processing of products on site, making it not worthwhile to implement this system.

5.6 Validating the findings

These eight subsystems were submitted and explained to three directors of Heijmans non-residential during face-to-face interviews. During these interviews, the directors were asked about which RFID systems looks worthwhile to implement in projects, based on the judgement variables *'Applicability', 'Impact', 'Costs'* and *'Benefits'* on a scale from '1' (a very bad performance) to '5' (a very good performance). Therefore, each director fills in an empty version of *Table 29 Validation RFID systems author* on page 45 from his point of view. The directors should be able to judge the potential added values of these systems in non-residential construction projects of Heijmans since these directors covers most of the responsibilities of the projects at Heijmans non-residential. These are the directors of the contemplated departments which should apply these RFID systems. The findings of all the three directors will be interchanged between the directors after the last interview in order to validate the findings, obtain new insights and it will serve as a triangulation feature of the findings to guard the internal validity of this study. The findings will be given below. The directors are:

- Director of 'Design and Engineering'
- Director of 'Projects' (Realization)
- Director of 'Maintenance & Utilization'

5.6.1 Validation by the director of 'Design and Engineering'

This director sees many interesting applications of a RFID system in the projects of Heijmans non-residential. Even, he made the question: *'why do we not apply this technology already?'*. The director sees many advantageous for the main contractor but less for subcontractors, manufacturers and logistic service providers. Therefore, the main contractor should pay companies earlier in the supply chain to attach the RFID tags to their products. The costs of the systems consist mainly of the RFID tags since the other costs can be spread out over multiple projects. For this director, it is of great value to have more information about the performances of the realization phase and the utilization phase since it can help to sharpening the tender price of Heijmans in new projects. Heijmans should become owner of this data, rather than submitted to clients, after a maintenance period, or project partners since this data has a great competitive advantage. The cost/benefit ratio can be expressed as follows:

$$\text{€ Realization phase} + \text{€ Exploitation phase } + \# \, Warranties\ obligations \ = Worthwhile\ to\ implement\ RFID$$

RFID System	Sub system	Applicability	Impact	Costs	Benefits	Total
Subsystem A. 'Sustainability'	Re-use products	4	4	4	4	12
	Reduce kilometres	2	3	3	3	11
Subsystem B. 'Productivity'	Off-site	1	2	1	2	6
	On-site	3	3	2	4	12
Subsystem C. 'Control'	Arrival	5	4	2	5	**16**
	Storage	3	2	2	3	10
Subsystem D. 'Building Management'	Information	3	2	1	4	10
	Sensors	4	3	3	5	15

Table 30 Validation Director of department 'Design and Engineering'

5.6.2 Validation by the director of 'Projects'

This director recognized the differences in the structural part and installation part of non-residential construction projects. Heijmans outsource many of the structural related activities. The activities related to the installation part of a project are different since products are ordered by the internet, there are digital invoices and the products are mainly finished products (compared to the structural activities which mainly order products by phone or fax, uses paper based invoices and products are often composed of multiple other products). The suppliers for the installation part of a project are often only a few big wholesalers, which can perfectly manage the material flows. In case of creating information about the outsourced activities, the director recognized the danger of becoming partly responsible for the outsourced activity once Heijmans has information over it. It is not without a reason that Heijmans outsourced some of his activities. The added values this director recognizes are related to the utilization phase, however, a well-organized BIM model offers already many of these added values.

RFID System	Sub system	Applicability	Impact	Costs	Benefits	Total
Subsystem A. 'Sustainability'	Re-use products	3	1	2	1	7
	Reduce kilometres	4	2	4	1	11
Subsystem B. 'Productivity'	Off-site	1	1	2	1	5
	On-site	1	1	2	1	5
Subsystem C. 'Control'	Arrival	3	1	3	2	9
	Storage	4	3	3	3	13
Subsystem D. 'Building Management'	Information	3	3	3	3	12
	Sensors	5	5	3	5	**18**

Table 31 Validation director department of 'Projects'

5.6.3 Validation by the director of 'Maintenance & Utilization'

This director was apportioned about the RFID system since the director sees only an added value in very specific cases. In general, the products have to be high-value goods (between €25.000, - and €50.000, - a piece). This has to do with its impact on time, quality and budget when such a product is missing. The director mentioned the unwillingness of clients to pay extra for a more sustainable realization phase or a more sustainable building. A contractor cannot bring in extra sustainable measures since they cost extra money while the contracting authority during a tender mainly is focussed on the project price. This director sees a great value in the subsystem *'Information'* since the tags can store locally as-built drawings, leaving the multiple revision drawings apart. However, the revenue model of Heijmans will change once subcontractors uses the right information, lowering the proportion of work Heijmans has to do for them. The director also recognized that more information is not always better for a project team.

RFID System	Sub system	Applicability	Impact	Costs	Benefits	Total
Subsystem A. 'Sustainability'	Re-use products	4	1	4	4	13
	Reduce kilometres	5	1	1	1	8
Subsystem B. 'Productivity'	Off-site	1	1	5	1	8
	On-site	2	3	4	3	12
Subsystem C. 'Control'	Arrival	5	4	3	4	16
	Storage	2	2	4	2	10
Subsystem D. 'Building Management'	Information	5	4	4	4	**17**
	Sensors	3	3	3	3	12

Table 32 Validation director department of 'Maintenance & Utilization'

5.7 In conclusion

In this chapter, eight RFID subsystems were identified and explained. These subsystems are conceived, based on the findings from the within-case and cross-case analysis, made in *Paragraph 4.1* and *Paragraph 4.2* of *Chapter 4 Results Interviews.* The eight identified RFID subsystems are:

Subsystems	Group	Subsystems	Group
* Re-use products * Reduce kilometres	Sustainability	* Arrival * Storage	Control
* Off-site * On-site	Productivity	* Information * Sensors	Building Management

These eight subsystems are compared in paragraph 5.5 with the use of comparable variables (see *Table 19 Comparison variables RFID systems* on page 36). Afterwards, each subsystem has been judged, based on the findings obtained in this study so far, on the subjects *'Applicability', 'Impact', 'Costs',* and *'Benefits'.* Simultaneously, these 8 RFID subsystems were submitted and explained to the following directors:

- Director of 'Design and Engineering'
- Director of 'Projects' (Realization)
- Director of 'Maintenance & Utilization'

These directors have judged the eight subsystems on these four judgement variables as well. The findings of the directors has been given in *Paragraph 5.6*. One can see the variation in the findings between the three directors and the findings of this research in this paragraph. The most remarkable findings in these judgements are coloured in the table below:

Validators
A = Director of Design & Engineering
B = Director of Projects (Realization)
C = Director of Maintenance & Utilization
D = Researcher of this study

RFID System	Sub system	Applicability				Impact				Costs				Benefits				Total			
	Validator:	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D*
Subsystem A. 'Sustainability'	Re-use products	4	3	4	1	4	1	1	5	4	2	4	2	4	1	4	4	12	7	13	15
	Reduce kilometres	2	4	5	5	3	2	1	4	3	4	1	3	3	1	1	3	11	11	8	17
Subsystem B. 'Productivity'	Off-site	1	1	1	4	2	1	1	2	1	2	5	3	2	1	1	3	6	5	8	14
	On-site	3	1	2	2	3	1	3	1	2	2	4	1	4	1	3	3	12	5	12	8
Subsystem C. 'Control'	Arrival	5	3	5	3	4	1	4	5	2	3	3	3	5	2	4	5	16	9	16	20
	Storage	3	4	2	4	2	3	2	4	2	3	4	1	3	3	2	4	10	13	10	18
Subsystem D. 'Building Management'	Information	3	3	5	3	2	3	4	5	1	3	4	5	4	3	4	4	10	12	17	22
	Sensors	4	5	3	2	3	5	3	2	3	3	3	2	5	5	3	3	15	18	12	11

Table 33 Summary of the findings of the validators
(*findings of the total score are included the priority of the experts from the case studies)

Based on the total score of all validators, see total score in Table 29 until Table 32 and the relative score assigned by the experts of the case studies (*Table 15 Most important added value of a RFID system* in *Paragraph 4.1.6 Prioritization added values* on page 27), the following RFID subsystems are considered to be worthwhile to implement to improve the construction logistics of non-residential construction projects (the total score has been given between brackets):

1. System C. Control: subsystem '*Arrival' (61)*
2. System D. Building Management: subsystem '*Information' (61)*
3. System D. Building Management: subsystem '*Sensors' (56)*

Worthwhile to implement

4. System C. Control: subsystem '*Storage' (51)*
5. System A. Sustainability: subsystem 'Re-use products' (47)
6. System A. Sustainability: subsystem '*Reduce kilometres' (47)*
7. System B. Productivity: subsystem '*Off-site' (37)*
8. System B. Productivity: subsystem '*On-site' (33)*

Not worthwhile to implement directly

Although the three subsystems *'Arrival', 'Information'* and *'Sensors'* are considered worthwhile to implement, the diversity in the findings of all validators visualizes the differences in the level of support by these validators, which will obstruct the implementation of a RFID subsystem in practice. Conclusions will be drawn upon in the following chapter.

chapter 6

*"It is not the strongest or the most intelligent who will survive,
but those who can best adapt to change"*

~ Charles Darwin ~

6. Conclusion and recommendations

This chapter will outline the research' limitations, the conclusion and recommendations. First, some points of discussion have to be made here.

There is a mismatch present between the operational managers (i.e. the experts of the case studies) and the managers from the head office of the host company (Heijmans non-residential construction). The operational managers mentioned the importance of only the result (i.e. the output, defined in time, money and quality) of outsourcing working activities to subcontractors, whereas managers from the head office mentioned the importance of also the processes of these subcontractors. This could be explained by the changing responsibilities for the main contractor. Currently, the role of the main contractor is shifting from a building constructing company to a manager of the total life cycle of construction projects, an increase in the responsibilities for the main contractor that previously only constructed a building.

This increase in responsibilities forces the main contractor to operate more efficiently throughout the whole life cycle of the project instead of only the realization phase. In an attempt to achieve more efficiency, insights in each partner' processes is needed. RFID can offer information about the logistic flows, however, a sense of untrustworthy collaboration can rise at a partner once he will be controlled by such a system. In a healthy collaboration, project partners should trust each other and they should be able to rely on the reliability of information each project partner (can) offers to the main contractor. Therefore, it should be clear that RFID is not meant to control a project partner' processes but to achieve more efficiency in between each other' processes (a win-win situation). A strong collaboration between the partners must be in place for a successful applicability of RFID systems in practice therefore.

6.1 Limitations

The research limitations are set out in this paragraph with the use of eight different topics.

1. The technology
   Different types of technologies to identify and localize products have been investigated, see *Appendix A Why RFID?*. In this analysis, RFID is find to be the best technology, however, it could be possible that not all relevant technologies were examined. Evenly, developments in this field recur rapidly, changing the capabilities and the performances of the technologies over time, changing also the added values of a RFID system. The fourteen added value which have been subtracted from the literature, see *Scheme 3 Fourteen added values of RFID in Construction* on page 13, could therefore be incomplete or they could have been changed over time during this study. Scientific meta studies (like Muthukrishnan 2005, Sardroud 2012, Nasr 2013 and Li 2016) are used in order to identify all possible technologies.

2. Case study
   The use of case studies in this research resulted in limitations in the data collection method. Only five case studies were investigated, either was the objective to select the case studies on a maximum variety basis, see *Paragraph 3.1 The selection of the case studies* on page 17. It should be clear that these five case studies are not the five common projects for the whole non-residential construction industry world-wide. Even, these are not all types of projects (or related market segments) Heijmans non-residential is working with. However, despite only five different case studies have been analysed during research question two, the wide variety selection criteria should give an impression about the possibilities of RFID systems in practice.

3. Interviews
   The use of face-to-face interviews with the experts of the case studies *(Paragraph 3.2)* and the three validation interviews with directors *(Paragraph 5.6)* has resulted in limitations of this research as well. These limitations will be explained by the following topics:

   - Only 10 experts (two experts in each case study) and 3 directors interviewed
   - Biases of the experts
   - Time differences between first and second feedback moment
   - Not all construction supply chain partners included

For the within-case analysis, only ten experts from 5 different case studies were interviewed. Also, three directors of Heijmans non-residential were used to judge the potential added values of the RFID systems. Although the interviewees received the same explanation of the RFID system, differences could occur because of the interviewees' background and understanding.

This was reflected in the answers of the interviewees (some only react on questions asked while others introduces, for example, a cost factor as well, resulting in more profound motivations of the interviewees). These biases, an interviewee' knowledge and experiences, was of great importance in this study since the potential added value of the RFID system has been based on the opinions of the experts in the case studies (see *Paragraph 4.1 Within-case analysis*), which ultimate resulted in the design of eight RFID subsystems. In general, the whole study is based on the opinions of experts, leaving out real-case scenarios.

There was a time gap of approximately three months between the first and second contact moment of the expert interviewees. The new identified added values are indicated throughout this study by the words *'2nd feedback'*. The case studies were further completed, which can result in new type of wastes and different motivations for the added values by the experts.

During this study, interviews have been conducted with a great diversity in persons in the construction sector (see *Paragraph 7.1.3 Interviews).* Although many different professions and types of companies are contacted, these are not all relevant professions and companies in the construction sector. However, this variety should give a broad view from multiple perspectives.

4. Project circumstances
   With the selection of only five case studies, not all relevant project circumstances are incorporated. Since certain project circumstances can change the added value of a RFID system drastically, one cannot generalize this study's findings for the whole non-residential construction industry. For example, no projects in the Health Care or High Tech Clean market have been analysed. Example given: the (limited) ionizing and magnetic feature of radio waves may not be applied in ATEX environments (Explosive Atmospheres). Since such type of project has not been investigated, it remains unknown if RFID may be applied in such projects.

5. Construction supply chain
   The tagging of products throughout the material supply chain will have great consequences on how businesses will work in the construction supply chain. Many questions are of importance for contractors but are not covered in this study due to a time limitation, such as: 'who has the responsibility over the management of the information', 'who is responsible for the tagging of the products', 'who bears the costs' and 'who has access to the information linked to the EPC'? Evenly, 'how integral is the system in practice', 'how does the devices work in real-life (different tags / different readers of different manufactures)' and 'which company can obtain what information of the products throughout the supply chain', are not answered. These questions remains open after this research, which limits the applicability of a RFID system in practice for Heijmans, its subcontractors and other (main / sub) contractors.

6. Practical knowledge and experience
   Two companies have been found (Inotec and FermRFID) that have experiences with implementing RFID in real case scenarios. However, they have mainly experiences in the retail, transport and the food sector (a controllable and static environment) instead of the construction sector (an uncontrollable and dynamic environment).

7. Type of products
   There is a wide variety of different (types of) products in the non-residential construction industry. Products which are used are: raw products, semi-finished or finished products. Even, the decoupling point can be different ('Make-to-Stock', 'Assembly-to-Order', 'Make-to-Order' or 'Engineer-to-Order' products) and products can be edited in size, shape and composition by cutting, drilling and sawing for example. Therefore, due to this variety in products, no product can be treated the same, resulting in different set-ups of the RFID systems. This has not been investigated by this study, limiting the practical value of this study for contractors.

Due to time restrictions, not all limitations could have been prevented. Nevertheless, the amount of literature analysed, the selection criteria 'maximum variety' for the 5 case studies and the variety in the experts which are interviewed, should give a broad data analysis from multiple perspectives.

6.2 Conclusion

In order to achieve more control in the construction logistics, the *'Control Tower'* concept has been proposed for in *Chapter 1 Introduction*. This Control Tower is a fictive control tower, like an air traffic control tower, which manages and coordinates the flows of man, machine and materials, and the corresponding information flows, throughout the supply chain and thereby, is capable of optimizing processes between the multiple actors involved (Vries de A. et al 2015). This Control Tower is contemplated to, among other things, optimize the construction logistics (which is the flow of man, machine and materials and its corresponding information flows) during the realization and utilization phase of multiple construction projects. The Control Tower has to know the real-time location of specific products in order to achieve this optimization. Radio Frequency IDentification (RFID) is found to be a possible technology to achieve this information. However, RFID has been rarely implemented in the construction sector whereby it remains unknown what a RFID system is, what it can do and when a contractor should apply such a RFID system. The main research question of this study is:

Which RFID system should be applied under which project circumstances in order to obtain the most added value for non-residential construction projects?

Since three topics are incorporated in this main research question (RFID Systems, Project Circumstances and Added Values), three research questions are established and answered in *Chapter 2 The added value of RFID for the construction sector, Chapter 4 Results Interviews* and *Chapter 5 RFID systems for non-residential construction projects*.

In Chapter 2, an explanation about what a RFID system is has been given in *Paragraph 2.2 The RFID system*. The advantages and drivers of RFID systems in the non-residential construction industry are given as well (see *Paragraph 2.3 Advantages of a RFID system)*. The disadvantages and barriers to implement such a system are given in *Paragraph 2.4 Disadvantages of a RFID system*. From the literature analysis, a list of fourteen possible added values for construction contractors have been identified in *Paragraph 2.5 Added value RFID systems for the construction sector*, which includes:

1. Product Life Cycle Information	2. Visibility Products Upstream Supply Chain	3. Shipment Visibility of Goods
4. Automate Goods Receiving	5. Real-Time Stock Balances	6. Minimizing the Excess of Stock
7. Minimizing Dwell-Time	8. Minimizing Fraud / Theft of Goods	9. Monitoring Progress / Production
10. Unique Product Identification	11. Localize Products on Site	12. Self-learning Teams
13. Information Upstream – Execution	14. Monitoring Building Performance	

Subsequently, experts interviews have been conducted in order to achieve information from practice during *Chapter 4 Results Interviews.* Two experts in each of the five case studies (Schiphol Lounge 2, Telecity AMS1, Eurojust The Hague, 'Hart van Zuid' Rotterdam and the National Military Museum) were asked about which kind of wastes in construction logistics are present at their projects, why they think these wastes occur and if some of the fourteen added values is wanted in their project and why, all given in *Paragraph 4.1 Within-case analysis*. In *Paragraph 4.2 Cross-case analysis*, these findings were compared to each other, in order to identify certain shared motivations across the case studies. Hereby, it became clear that the added values are wanted by the experts for four different kind of motivations, namely: 'Sustainability', 'Productivity', 'Control' and 'Building Management', explained in *Paragraph 4.2 Cross-case analysis* and *4.3 The confrontation*. Once the same added value is wanted by the experts for two different motivations, the information needed from the RFID system will be different, so will the RFID systems be different. Therefore, these different motivations have been used to identify different RFID systems during research question three.

In Chapter 5, eight RFID subsystems have been identified, covering these four types of motivations. These eight RFID subsystems are explained throughout Paragraph 5.1 until Paragraph 5.4. In Paragraph 5.1, the RFID system 'Sustainability' have been explained, including the two subsystems '*Re-use products'* and *'Reduce kilometres'.* Paragraph 5.2 outlines the RFID system 'Productivity', including its two subsystems *'Off-Site'* and *'On-Site'*. In Paragraph 5.3, the RFID system 'Control' have been explained, including the two subsystems *'Arrival'* and *'Storage'*. At last, 'Building Management' and its two subsystems *'Information'* and *'Sensors'* have been explained in Paragraph 5.4. The differences between these eight subsystems have been given in *Paragraph 5.5 Comparison RFID systems.* In the same paragraph, the researcher has judged these eight RFID subsystems, based on the variables: 'Priorities of the Experts' (see Paragraph 4.1.6), 'Applicability', 'Impact', 'Costs' and 'Benefits' for an implementation of these RFID systems in projects of Heijmans non-residential.

Simultaneously, these eight RFID Subsystems were submitted and explained to three directors of Heijmans non-residential in order to let them judge the systems by the same variables. These directors (director of 'Design & Engineering', 'Projects' and 'Maintenance & Utilization') do have a final responsibility over these departments which are contemplated to work with RFID at Heijmans non-residential. They findings differ greatly in-between the directors and the researcher of this study, see *Paragraph 5.6 Validating the findings*. This can be explained by the different responsibilities each director does have and his / her knowledge and experiences in construction projects. The biases and the responsibility for only one single department could declare the diversity in these findings, compared to someone who has an overall responsibility over the whole life cycle of projects, and thereby, has the responsibility over multiple departments. According to the results of this research, the following RFID subsystems are considered worthwhile to implement in the following order to add value to the construction logistics of non-residential construction projects (total score has been given between brackets):

1. System C. Control: subsystem '*Arrival' (61)*
2. System D. Building Management: subsystem '*Information' (61)* — Worthwhile to implement
3. System D. Building Management: subsystem '*Sensors' (56)*
4. System C. Control: subsystem '*Storage' (51)*
5. System A. Sustainability: subsystem 'Re-use products' (47)
6. System A. Sustainability: subsystem '*Reduce kilometres' (47)* — Not worthwhile to implement directly
7. System B. Productivity: subsystem '*Off-site' (37)*
8. System B. Productivity: subsystem '*On-site' (33)*

With the information obtained by Chapter 2 until Chapter 5, the main research question can be answered. The following RFID systems should by applied under the defined project circumstances to obtain the defined added value in non-residential construction projects.

rank	RFID system	Subsystem	Score	Project Circumstances	Added value
1	Control	'Arrival'	61	- Limited control in supply and storage of products on site - It is hard to identify products without any delivery note - Use of Custom-made products on site	Unique Product Identification
				- Limited control in supply and storage of products on site - No idea which products are on the project site	Automate Goods Receiving
2	Building Management	'Information'	61	- It is hard to identify products after the realization phase - There is a requirement in the availability of the building - There is a need for more efficient maintenance - It is difficult to look up product' information - There is a requirement in preventive maintenance	Information Upstream – Execution
3	Building Management	'Sensors'	56	- There is a need for a more efficient maintenance phase (proactive) - There is a requirement in the availability of the building - Presence of flexible lay-out rooms - Need for higher quality indoor environment	Monitoring building performance
4	Control	'Storage'	51	- Limited control in supply and storage of products on site - No idea which products are on the project site - A lot of re-handling of products on site	Real-time stock balances
				- Limited control in supply and storage of products on site - No idea which products are on the project site	Minimizing Dwell-Time
				- Limited control in supply and storage of products on site - A long searching time for products - A lot of re-handling of products - Products are moved by other parties (clean-up) - A lot of re-handling of products on the floor levels	Localize Products on site
5	Sustainability	'Re-use Products'	47	- Handling with reusable products	Unique product identification
6	Sustainability	'Reduce kilometres'	47	- Kilometre record trucks needed (BREEAM)	Shipment Visibility of Goods
7	Productivity	'Off-Site'	37	- Uncertainty in the delivery process - Continue installation cycle present	Shipment Visibility of Goods
				- Time pressure in the realization phase - Lack of continuity jobsite workers - Need for real-time information about manufacturing process - Uncertainty in the delivery process	Visibility Products Upstream Supply Chain
8	Productivity	'On-site'	33	- Time consuming to identify delivering products and packages	Automate Goods Receiving
				- Limited control in supply and storage of products on site - No idea which products are on the project site - A lot of re-handling of products on site	Real-time stock balances
				- Limited control in supply and storage of products on site - No idea which products are on the project site	Minimizing Dwell-Time
				- Limited control in supply and storage of products on site - A long searching time for products - A lot of re-handling of products - Products are moved by other parties (clean-up) - A lot of re-handling of products on the floor levels	Localize Products on site

Table 34 Which RFID system should be applied under which project circumstances in order to obtain the most added value for non-residential construction projects?

6.2.1 Contribution to the host company

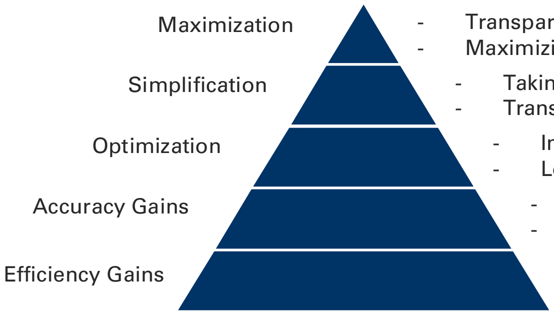
During the expert interviews (operational managers of non-residential construction projects), all interviewees were curious and interested in the RFID technology. All of them want to know the outcome of this research, even if they do not see an added value for their project in the first place. This indicates a curiosity or a need to arrange the construction logistics differently than currently is done.

It became also clear that most of the experts of the main contractor are looking for improvements in the utilization phase (in case of a maintenance responsibility) while the experts of the subcontractors are mainly looking for improvements in their execution activities. They see RFID as an information provider for benchmarking values for execution activities while the main contractor sees RFID more as a tool to obtain more data from the whole life cycle of non-residential construction projects and thereby improving the efficiency for the whole life cycle of a project.

From the data analysis in this study, it has been identified that the added values the experts want is highly determinative to the project circumstances of the project of concern. The great diversity in construction projects in the non-residential construction industry makes RFID in one project desirable while in another project not desirable. The diversity in the projects and the diversity in the products which are used in this industry makes that a RFID system is not suitable in every environment (also confirmed by Sarac 2010 and Li 2016). RFID will be custom-made and it will be desirable in some very specific cases only.

As explained at the beginning of this chapter, there is a mismatch present between the operational managers (i.e. the experts of the case studies) and the managers from the head office of the host company (Heijmans non-residential construction). At the beginning of this research, the goal was set to improve the construction logistics in general. Hereby, the supply of products to the construction site was considered to be inefficient, causing disturbance to the direct environment, many shipments of products to the construction site, multiple backorders and the missing of products on site for example. However, instead of looking for added values of the RFID system in the whole construction supply chain, experts are mainly looking for added values in their processes, resulting in added values related to their processes only. This indicates an attitude to improve only someone’s own responsibility instead of looking for improvements in the whole construction supply chain.

Hereby, it has been acknowledged that most of the interviewees are focussing on the short-term gains which can be achieved by the implementation of RFID systems. This could be explained by the low margins, the low turnover and the competitive environment of non-residential construction projects. The experts wanted to achieve a quick win. This was reflected in the motivations the operational managers and the three directors gave, which were almost all related to achieve efficiency and accuracy gains (see pyramid below, based on Flederus M. 2016). So, there seems to be a lack of understanding about what could be possible with a 100% transparent construction supply chain, wherein every actor sees exactly the flow of specific products. With this, a contractor can achieve an improvement over an improvement, offering much more gains in the long-term than is currently visible in the short-term.



- Transparency in operational processes throughout supply chain
- Maximizing turnover of the whole supply chain
- Taking out the unnecessary steps (non-value added activities)
- Transacting more direct by using reliable data
- Improve effectiveness of the operational processes
- Lowering inventory, improve time plans, improve forecasting
- Improve accuracy of the operational processes
- Less disputes, less rework, first time right in operational processes
- Improve efficiency of operational processes
- Faster identification, reduction human actions and reduction manual steps

In the end, it remains questionable if RFID is the appropriate technology to implement in this industry and if the industry is ready for such a transition. More research is needed in this area. Nevertheless, the information which can be obtained by such a technology can have a tremendous effect on the way contractors organize their supply chains (100% transparent supply chains). Not without a reason are additional benefits discovered every day in other sectors (which have already implement RFID for over ten years). It can be concluded that in a dynamic and fast changing sector, which works with prototype projects: *‘Information will be the new added value’*.

6.2.2 Contribution to the literature

The use of RFID systems in the non-residential construction industry has been investigated in this thesis. Although there are researchers who investigated the possibilities of RFID systems in the construction sector (e.g. Jaselskis (1995), Lu (2011), Demiralp (2012) and Sardroud (2012)), no research have been made towards the non-residential construction industry yet. It is assumed that the amount of waste regarding the construction logistics in non-residential construction projects is more compared to residential or infrastructural projects. This has to do with the complexity of the projects and its direct surroundings. This results in differences in: type of projects (different market segments), differences in building' design and its purpose (different materials, subcontractors and companies involved) and differences in clients (public and private clients). It is for sure that the diversity in RFID systems (and its components) and the diversity in the non-residential construction projects will have its influence on the applicability of RFID systems in non-residential construction projects.

In comparison with other researchers who investigated the possibilities of RFID systems in the construction sector, like in workforce, equipment and materials tracking (Cheng 2010), reducing life cycle costs of buildings with RFID (Heller 2014), concrete processing and handling, cost coding for labour and equipment and materials control (Jaselskis 1995), engineering/design, material management, maintenance and field operations (Jaselskis 2003), labour attendant and ready mixed concrete management (Kim S. 2013), man, machine and materials tracking (Lu 2011), tracking of assets and people, quality and productivity management, site safety and document management (Nasr 2013), construction time and schedule management, construction quality management, construction supply chain management, construction safe management, construction document management and construction waste management (Sun 2013), this study was focused on how RFID systems can add value in the construction logistics of products and its corresponding information flows.

Although some comparable added values (see *Scheme 3 Fourteen added values of RFID in Construction* on page 13) are mentioned by other researchers such as Jaselskis (2003), Tajima (2007), Lu (2011), Hinka (2013), Kasim (2013) and Sun (2013), no other researcher has made this list of these fourteen added values (related to the construction logistics of products and its corresponding information flows only). Hereby, the timeline proposed by Sardroud (2012) is focused on the flow of products throughout the different construction phases. The proposed fourteen added values by this study are related to a specific construction phase only, instead of one single added value related to all these construction phases (like in case of Sardroud (2012)).

These added values are considered to be wanted for different reasons, set out in the within-case and cross-case analysis of this research. These reasons have been served as the starting point for the determination of the four RFID systems: Sustainability, Productivity, Control and Building Management, in which these RFID systems are supposed to have an advantageous effect on construction logistics of products under the identified project circumstances. These four RFID systems (in total eight RFID subsystems) have not been explicit identified until now. Even, the purpose of the RFID systems in this way to improve the construction logistics, has not been investigated yet.

The decision to design the RFID systems based on the needs from practice and the possibilities from literature, has resulted in realistic RFID systems for (sub and main) contractors in the construction sector. If the RFID systems were designed based on literature or only practice, it would have resulted in perfect designs which were not applicable in real life. With this approach, it has been found that, for example, the application of automatic checking-in products once a truck enters the project site (proposed by Jaselskis (1995), Demiralp (2012) and Sardroud (2012)) is partly implementable. This is caused by the steel in closed truck trailers, which will block the radio waves, sent by RFID tags inside the truck' trailer. With this approach, this application has been sharpen since it is only implementable in case of open-trailer trucks. Solutions for this reading problem are mentioned in the explanation of the RFID system (see *Chapter 5 RFID systems for non-residential construction projects*). One can see by this example how the needs from practice could be achieved by the possibilities from literature, resulting in realistic RFID systems.

In the end, it has been found that the practical relevance has a great stake in the determination of a RFID system' applicability. Besides, the purpose of the RFID systems (desirable by the experts) is highly determinative to the project circumstances of the project. So, designing and implementing RFID systems only based on literature or on the needs from practice, will result in unrealistic RFID systems, which will not be implemented by contractors in the non-residential construction industry.

6.3 Recommendations

In this last paragraph, recommendations for further research have been outlined.

<u>New added values</u>

Many (digital) innovations occur in the construction sector (see for example 'industry 4.0'). Since RFID is rarely applied into practice, further research should be performed about possible applications of RFID systems in the construction sector. RFID can be complementary to many new upcoming technologies like IOT (Internet of Things / Big Data), applications with BIM (Building Information Modelling), VR (Virtual Reality) and AR (Augmented Reality) in multiple ways since RFID can form a direct link between digital information and a real-life setting. Clearly, many opportunities will occur with these innovations, which can consequentially be an added value for the construction sector as well. Extensive research in this area should indicate what the opportunities of RFID in combination with these technologies are for contractors in the (non-residential) construction sector.

<u>Project Circumstances</u>

Due to the time limitations and the diversity of the non-residential construction industry, only five case studies, ten experts from these case studies and a few additional experts have been used to identify relevant project circumstances. In order to get to know under which project circumstances a RFID system can also be an added value for (main or sub-)contractors, more case studies should be investigated, increasing the amount of different project circumstances and perspectives of the applicability of RFID systems in the non-residential construction industry.

<u>Real-case scenarios</u>

In order to get to know how different RFID systems will perform under different products and different environments (RFID is no in-the-box solution), real-case scenarios should be tested which give insights in the readability and applicability of RFID systems in specific real-case scenarios.

<u>Implementation</u>

Such a new technology, where employees are not convinced yet and its benefits have not been proven yet, should cost a minimal effort (in time to implement and in costs of the system) and should result in a maximum yield in the beginning of implementation (greatest cost/benefit ratio). Thereby, once a system has proven its usefulness and achieves support from employees, one can extend the scope of the system and scaling up its functions. Since a RFID system always starts with the identification of products, it should be recommended to contractors to implement first RFID subsystem 'Information' (total score of 61, see *Paragraph 5.7*, and afterwards extending its functions and the devices needed for the other subsystems. In sequential order, the following subsystems should be applied in a real-case setting: *'Information' (61), 'Arrival' (61), 'Sensors' (56), 'Storage' (51), 'Re-use products' (47), Reduce kilometres' (47), 'Off-site' (37)* and *´On-site' (33).* More research should be done on all these RFID subsystems in order to investigate their actual cost/benefit ratio in the construction logistics.

<u>Cost/benefit</u>

The diversity of the products used in the construction sector (explained in limitation 7 under *paragraph 6.1 Limitations*) limits the generalizability of the application of RFID system. RFID systems should only be implemented in some very specific cases on specified products due to technical and practical limitations (readability for instance). The determination of which products should be tagged should be based on a cost/benefit ratio. This can either be cost driven (*'from a certain cost price, every product should be tagged')* or either be risk driven ('*what will be the impact if some specific product' information is missing').* To clarify, examples are present to provide a €1,- product with a tag of €0,50 since the costs of missing that specific product' information once needed, like in case of malfunctioning for example, can be higher than the €0,50 tag costs for that single product (Flederus M. 2016). Although some indication about cost/benefit factors are given in *Chapter 5 RFID systems for non-residential construction projects* and *Appendix I The RFID Systems in detail*, more research should be done on this cost/benefit ratio in order to investigate the applicability of RFID systems in the industry.

<u>Human interaction</u>

Such RFID system will have a great impact on the construction supply chain. Since the construction sector is a labour intensive industry, the willingness of employees in the construction supply chain to work with RFID systems should be investigated. A sense of untrustworthy collaboration can rise at other parties, explained at the introduction of this chapter. Without the support of the involved employees, a RFID system is doomed to fail in practice. Research should be performed about the willingness of persons throughout the construction supply chain to implement such a RFID system.

chapter

7

"Information will be the new added value"

R. J. H. (Rens) van den Hurk

7. References

7.1.1 Papers

Cheng, T. , Yang, J. , Teizer, J., Vela, P.A. (2010), 'Automated Construction Resource Location Tracking to Support the Analysis of Lean Principles In 18th Annual Conference of the IGLC (p. 643 - 653)

Davenport T.H., Prusa K.L., (1998) 'Working knowledge: How organizations manage what they know', Boston: Harvard Business School Press. In: Laak, M. van (2004). Knowledge management at Siemens VDO. Unpublished manuscript. Eindhoven: TU Eindhoven

Demiralp G., Guven G., Ergen E. (2012) 'Analysing the benefits of RFID Technology for cost sharing in construction supply chain: A case study on prefabricated precast components', Automation in Construction 24 (120-129)

Deshmukh P.S., More A.B., Chavan S.A. (2014) 'Supply Chain Management in Residential Construction Sector', International Journal of Engineering and Advanced Technology vol. 4 (2)

Eisenhardt K.M. (1989) 'Building Theories from Case Study Research', The Academy of Management Review, Vol. 14 (4) (pp 532-550)

Flyvbjerg B. (2006) 'Five Misunderstandings About Case-Study Research', Qualitative Inquiry vol. 12 (2)

Grau D., Caldas C., Haas C., Goodrum P., Gong J.(2009) 'Assessing the impact of materials tracking technologies on construction craft productivity', Automation in Construction 18 (903-911)

Heller A., Orthmann C. (2014) Wireless technologies for the construction sector - Requirements, energy and cost efficiencies, Energy and Buildings 73 (212-216)

Hinkka V., Tätilä J. (2013) 'RFID tracking implementation model for the technical trade and construction supply chains', Automation in Construction, 35 (405-414)

Holness G. (2008) 'BIM building information modelling: Gaining momentum' ASHRAE Journal; 50(6)

Jaselskis E.J., Anderson M.R., Jahren C.T., Rodriguez Y., Njos S.(1995) 'RFID applications in construction sector', Journal of Construction Engineering Management, Vol. 121 (2)

Jaselskis E. J., El-Misalami T. (2003). Implementing radio frequency identification in the construction, Journal of Construction Engineering Management 129(6) 680-688

Karim L., Nasser N., Mahmoud Q.H., Anpalagan A., Salti T.E. (2015) 'Range-Free Localization approach for M2M communication systems using mobile anchor nodes', Journal of Network and Computer Applications 47 (pp. 137-146)

Kasim N., Latiffi A.A., Fathi M.S. (2013) 'RFID Technology for Materials Management in Construction Projects - A Review', International Journal of Construction Engineering and Management, 2(4)

Kim S., Kim S., Tang L.C.M., Kim G-W. (2013) 'Efficient Management of Construction Process Using RFID+PMIS System: A Case Study', International Journal Applied Mathematics & Information Science, Vol. 7, No. 1 (19-26)

Kini, D. (1999) 'Materials Management: The Key to Successful Project Management', Journal of Management in Engineering, Vol. 15 Issue 1 (30-34)

Li S., Visich J.K. (2006) 'Radio frequency identification: supply chain impact and implementation challenges' International Journal of Integrated Supply Management 2 (4) (407–424)

Li H., Chan G., Wong J., Skitmore M.(2016) 'Real-Time Locating Systems applications in Construction', Automation in Construction 63 (37-47)

Lu W., Huang G.Q., Li H. (2011) 'Scenario's for applying RFID Technology in Construction Project Management', Automation in Construction 20 (101-106)

Love P.E.D., Irani Z., Edwards D.J.(2002) 'A rework reduction model for construction projects' Transactions on engineering management. Vol. 51. No 4. (426-440)

Michael K., McCathic L, (2005) 'The pros and cons in supply chain management', Proceeding of the international Conference on Mobile Business, Copyright IEEE (pp 623-629)

Mingxiu Z., Chunchang F., Minggen Y. (2012) 'The application used RFID in Third Party Logistics', Physics procedia 25 (2045-2049)

Mohsen A. (2012) 'Critical Success Factors and Challenges of Implementing RFID in Supply Chain Management', Journal of Supply Chain and Operations Management, Volume 10, Number 1

Muthukrishnan K., Lijding M.E.M., Havinga P.J.M. (2005) 'Towards Smart Surroundings - Enabling Techniques and Technologies for Localization', in 1st Int. LoCA

Muya M., Price A.D.F., Thorpe A. (1997) 'Construction Materials Supply Logistics', Loughborough University vol. 10

Nasr E., Shehab T., Vlad A. (2013) 'Tracking Systems in Construction Applications and Comparison', 49th ASC Annual International Conference Proceeding, Associated Schools of Construction

Parikh M. (2001) 'Knowledge management framework for high-tech research and development', Engineering Management, 13, (pp. 27-33)

Persson F., Bengtsson J., Gustad Ö. (2010) 'Construction Logistics Improvements Using the SCOR Model - Tournet Case' IFIP International Federation for Information Processing vol. 338, 8

Ramanathan R., Ramanathan U., Lorrain L. (2014) 'Adoption of RFID Technologies in UK Logistics - Moderating roles of size, barcode experience and government support', Elsevier, Expert Systems with Applications 41 (230-236)

Sarac A., Absi N., Dauzère-Pérès S. (2010) 'A literature review on the impact of RFID Technologies on Supply Chain Management', International Journal Production Economics 128 (77-95)

Sardroud J.M. (2012) 'Influence of RFID technology on automated management of construction materials and components', Sharif University of Technology, Scientia Iranica Transaction A: Civil Engineering Vol. 19 (3), pp 381 – 392

Safa M, Shahi A., Haas C.T., Hipel K.W. (2014) 'Supplier selection process in an integrated construction materials management model', Automation in Construction Vol. 48, pp 64-73

Serpell A., Venturi A., Contreras J. (1997) 'Characterization of waste in building construction projects', Lean Construction ed. L. Alacón Balkema Rotterdam, The Netherlands

Shou-Wen J. Ying T. Yang-Hua G. (2013) 'Study on Supply Chain Information Control Tower System', Information Technology Journal 12 (8488-8493)

Song J., Haas Caldas C., Ergen E., Akinci, B. (2006) 'Automating the task of tracking the delivery and receipt of fabricated pipe spools in industrial projects', Automation in Construction 15 (2)

Sun C., Jiang F., Jiang S. (2013) 'Research on RFID Applications in Construction sector', Journal of networks, vol 8. no. 5

Thunberg M., and Persson F. (2013) 'A logistics framework for improving construction supply chain performance', In: Smith S.D., Ahiaga-Dagbui D.D., Procs 29th Annual ARCOM Conference 2013, Reading, UK, Association of Researchers in Construction Management, 545-555.

Tajima M. (2007) 'Strategic value of RFID in supply chain management', Journal of Purchasing and Supply Management, 13(4), 13. doi: 10.1016/j.pursup.2007.11.001

Vries de A., Rinsma R., Ludema M. (2015) 'TKI Project '4C in Bouwlogistiek', WP2.1 Control tower

Watson L.S., Miller D.L., Walton C.M., Skinner R.E. (2007) 'Research Opportunities In Radio Frequency Identification Transportation Application', Transportation Research Board, E-C114

Yagi J., Arai E., Arai T. (2005) 'Parts and packets unification radio frequency identification (RFID) application for construction', Automation in Construction 14 (4) 477–490.

Yan C., Zhangong X. (2013) 'Study on the Information Technology-based Lean Construction SCM Model', In G. F.L. (Ed.), Recent Progress in Data Engineering and Internet Technology (Vol. 2, pp. 499-505). Berlin: Springer

Yin R.K. (2014) 'Case Study Research: Design and Method' (L. Bickman and D. J. Rog, Eds.). Sage Publications

Yin S., Tserng H., Wang J., Tsai S. (2009) 'Developing a precast production management system using RFID Technology', Automation in Construction 18, pp. 677-691

7.1.2 Other

Australian Seafood Cooperative Research Centre (2007) 'Review of Traceability and Product Sensor Technologies relevant to the Seafood Industry' (pp. 48)

Barthorpe S., Sullivan G., Robbins S. (2010) 'Managing Construction Logistics', Wiley Blackwell Ebook

BREEAM-NL (2014) Beoordelingsrichtlijn Nieuwbouw en Renovatie 2014 v1.01

Bouwkennis (2014) 'Faalkosten - Uiting, Oorzaken, Preventie en remedies', Rapport Faalkosten, in Dutch, Available at: http://www.bouwkennis.nl/wp-content/uploads/2014/03/Faalkosten.pdf (07-03-2016)

Christopher M. (2011) 'Logistics & Supply Chain Management' 4th edition (Ebook): Pearson

EIB (2014) 'Bedrijfseconomische kerncijfers b&u en gww bedrijven', Visser N.R.L

EraBuild (2006) 'Review of the current state of RFID technology, its use and potential future use in Construction', Report, a Co-operation between 'National Agency for Enterprise and Construction, Tekes, Formas and DTI, pp 100

Heijmans 2015 Annual Report

OECD (2008), 'Construction sector report'

USP Marketing Consultancy B.V. (2009) 'Documentatie over faalkosten in de bouw' commissioned 15-01-16: http://uspdate.usp-mc.nl/uspdate.php?maand=mrt&jaar=2011&page=Faalkosten-door-de-jaren-heen

Teicholz P. (2000) 'Productivity trends in the construction sector', Presentation to the 2000 AISC Annual Convention, San Francisco, California, 2000

7.1.3 Interviews

Preparation:

Bloemendaal J. (Project Manager Business Development & Legal) interview Technische Unie (wholesaler), Alphen aan den Rijn: 11-01-2016

Bodegraven van S. (Project Manager), Interview Heijmans non-residential, Rosmalen: 07-03-16

Broek van den E. (Director until dec. 2015), Interview Heijmans non-residential, Rosmalen: 03-12-2015

Dijkstra J. (Purchage manager), Interview Heijmans non-residential, Rosmalen: 30-11-2015

Donders E. (Director), Interview Heijmans NV dept. Purchaging, Rosmalen: 09-12-2015

Fleuren T. (Director) and Mertens B. (Programma Manager) Interview Heijmans non-residential, dept. Business Development, Rosmalen, datum: 06-10-2015

Geus R. (Director until aug. 2016), Interview Heijmans non-residential, dept. Design & Engineering, Rosmalen: 04-12-2015 & 22-04-2016

Giorgi San M. (Director), Interview Heijmans non-residential, dept. Acquisition & Advice, Rosmalen: 04-12-2015

Jochems J. (Manager), Interview Heijmans NV. Dept. Facility, Rosmalen: 26-11-2015

Lock D. (Project Director), Interview Heijmans non-residential, Rosmalen: 27-11-2015

Tuuk van der B. (Manager) Interview DHL NL Business Development, Rosmalen, datum: 04-11-2015

Expert Interviews:

Heijmans non-residential construction:

Project leader, Schiphol Lounge 2: 03-06-16, 2nd feedback: 05-09-16

Main site manager, Telecity AMS1 Amsterdam: 24-05-16, 2nd feedback: 05-09-16

Main site manager, Eurojust The Hague: 25-05-16, 2nd feedback: 05-09-16

Project leader, Eurojust The Hague: 25-05-16, 2nd feedback: BREEAM Expert M.: 08-09-16

Senior Design Manager, Hart van Zuid Rotterdam: 31-05-16, 2nd feedback: 05-09-16

Project leader, Hart van Zuid: 15-06-16, 2nd feedback: 13-09-16

Project director, National Military Museum Soesterberg: 23-05-16, 2nd feedback: 05-09-16

Subcontractors:

Project leader, Schiphol Lounge 2, Verwol Interior Realisation: 04-07-16, 2nd feedback: 05-09-16

Project leader, Telecity AMS1 Amsterdam, Schneider-Electric: 21-06-16, 2nd feedback: 07-09-16

Main site manager, Eurojust, TGM: 06-06-16, 2nd feedback: 05-09-16

Project coordinator, National Military Museum, Kwakman Finishing, 14-06-16, 2nd feedback: 06-09-16

Validation Interviews:

Director Department of 'Design and Engineering', Heijmans non-residential construction: 27-10-16

Director Department of 'Maintenance & Utilization', Heijmans non-residential construction: 01-11-16

Director Department of 'Projects', Heijmans non-residential construction: 03-11-16

Extra:

BREEAM Expert (Advisor / BREEAM Expert Heijmans): 15-07-16 & 08-09-16

HVAC Experts (Advisor and Advisor Sr. HVAC Heijmans non-residential construction): 28-07-16 & 15-08-16

Mr. Bulent S. (Project Leader Heijmans Big Projects non-residential construction Eindhoven) & Mr. Velden J. v.d. (Project Leader Heijmans non-residential construction Eindhoven): 08-07-16

Geertsema E.M. (2016) Country Manager Inotec Barcode Security GmbH Wijchen, Interview, Rosmalen: 27-01-2016 & 17-08-16

Flederus M. (2016) Director Solutions: Ferm RFID Solutions BV Zaltbommel, interview Zaltbommel: 26-08-2016, 12-09-16, 28-10-16

7.1.4 Quotes:

L. Bernstein (1918-1990) "To achieve great things, two things are needed: A plan and not quite enough time" in: Preddy S. (2011) How to Run a Successful Design Business: The New Professional Practice, Burlington, VT: Gower Publishing Company (P. 189)

J. Cruijff (2010) "Hoe simpeler hoe beter, want hoe minder keuze je een speler laat hoe meer kans dat hij het juiste doet" in book: 'Voetbal is oorlog, Bijzondere Uitspraken Over Voetbal' (Gerd de Ley) ISBN: 9460680232

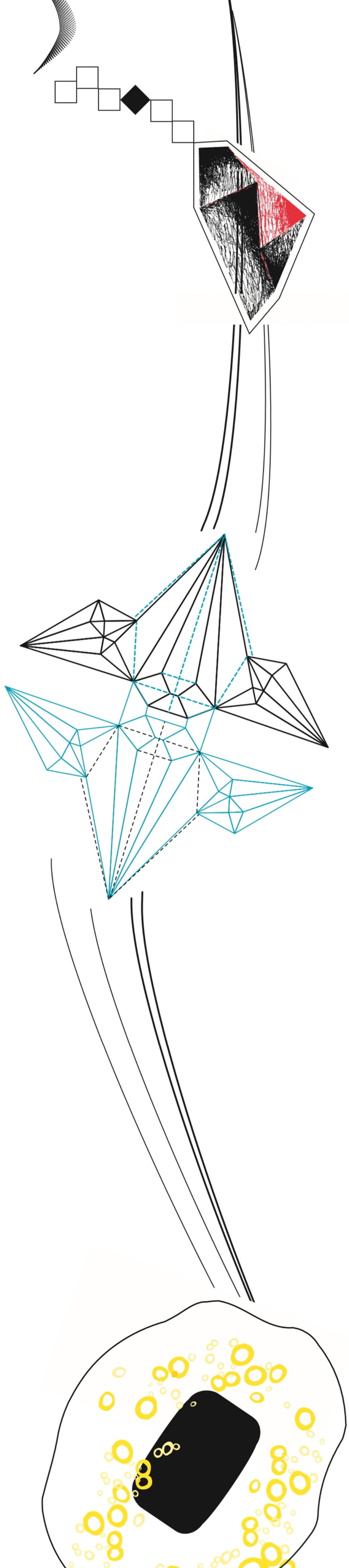
C.R. Darwin (1859) "It is not the strongest or the most intelligent who will survive, but those who can best adapt to change" in book: 'On the origin of species by means of natural selection, or the preservation of favoured races in the struggle for life' London: John Murray [1st edition]

W.R. Emerson (1984)"Nothing great was ever achieved without enthusiasm", Essay: 'Circles' (last paragraph) in source: http://www.emersoncentral.com/circles.htm (28-03-2016)

H. J. Harrington (1991) "If you cannot measure it, you cannot control it. If you cannot control it, you cannot manage it. If you cannot manage it, you cannot improve it" in book: 'Business Process Improvement: The Breakthrough Strategy for Total Quality, Productivity, and Competitiveness' (p. 82), McGraw-Hill Education, ISBN: 9780070267688

Quantified Self (2015) "Zelfmeten leidt tot zelfkennis en dat is de eerste stap naar gedragsverandering", Quote on website: http://www.quantifiedself.nl/

P.J. van der Ven (2015) "Bouwen is transporteren" Lunch presentation Heijmans, 22-10-2015



heijmans

UNIVERSITY OF TWENTE.

RFID SYSTEMS IN THE NON-RESIDENTIAL CONSTRUCTION INDUSTRY

Improving construction logistics

Appendices Master's thesis (public)

By R.J.H. (RENS) VAN DEN HURK (BASc.)

Size: 84 pages

Date: 15 Dec. 2016

FACULTY OF ENGINEERING TECHNOLOGY
(CONSTRUERENDE TECHNISCHE WETENSCHAPPEN)
3TU FEDERATION – IN COOPERATION WITH TU-DELFT & TU-EINDHOVEN
DEPT. CONSTRUCTION MANAGEMENT AND ENGINEERING
UNIVERSITY OF TWENTE, THE NETHERLANDS

APPENDIX A – APPENDIX I

heijmans

UNIVERSITY OF TWENTE.

Appendix A. Why RFID?

In this appendix, the reason why to consider RFID as the best suitable technology to identify and localize individual products will be explained. First, a comparison will be made between RFID and other identification technologies. Hereafter, multiple localization technologies will be examined. Thereafter, communication technologies will be discussed. Since the data (identification and localization) must be send to enterprise systems, a communication feature is needed as well. At the end, the conclusion will be drawn about why to consider RFID as the most favourable solution for the construction sector.

The three features of the technologies (Identification, Localization and Communication) will be compared by use of the variables given in *Table 35 Explanation of comparison variables*. These variables are based on Sardroud 2012 comparison variables, with the addition of the possibility to identify, localize and communicate between other devices.

Variables	Explanation	scale
Identification	Possibility to identify	Yes / No
Localization	Possibility to localize	Yes / No
Communication	Possibility to send data	Yes / No
Accuracy	The precision of the system to exactly localize a product	1: 0-5m 2: 5-20m 3: >20m
Affordability	Initial costs (such as hardware, software, implementation costs)	1: Low (€0-€1000) 2: Medium (€1000-€10.000) 3: High (>€10.000)
Data Storage Capacity	The ability to store information locally without an extra data storage device	1: yes, >1mb 2: yes, < 1mb 3: no data storage capacity
Ease of Use	User friendly and simplicity of use	1: Most easy (well known) 2: Medium easy (some training) 3: Least easy (much of training needed)
Fast Read Rates	The speed in which the technology is able to localize a product	1: Fastest (< 1 sec/item) 2: Medium (1-10 sec/item) 3: Slowest (> 10 sec/item)
Read Range	The range in which the technology is able to localize a product.	1: Worldwide 2: Project site (10 – 500m) 3: Locally (<10m)
Resilience to harsh environments	Performance in harsh environments and dense areas	1: Good (no interference) 2: Medium (some interference) 3: Bad (Susceptible to its environment)

Table 35 Explanation of comparison variables

a) Identification Technologies

In order to identify products, multiple technologies exists, all have their own performances and capabilities. The investigated identification technologies are Smart Cards, Biometric Systems, Optical Character Recognition (OCR), Barcodes and RFID.

Smart Cards

Smart cards (i.e. chip cards) are made of plastic and have an embedded integrated circuit. This circuit contains encrypted digital information about the user of the card and are widely used in credit cards, public transport and door accesses. Due to the mechanical contact in the card, this system remain impractical for the construction sector because of its weakness to wear, corrosion and dirt. The cards could be contactless but therefore, industry wide adapted readers first have to be developed. These are not applied in the construction sector yet making the smart cards not interesting.

Biometric Systems & Optical Character Recognition OCR

These systems make use of individual characteristics in order to identify people, in this case products. This can be done by people (based on senses) or by machines like computers (based on algorithms). If the recognition is done by machines, special fonts are developed for Optical Character Recognition (OCR) in order to identify a person, a document or a certain product (Sardroud 2012). The product do not need to carry any device or label to identify products and the system can cover a relatively large area, making the technology interesting. However, there are some limitations. Due to the uncontrolled environment, it is a very expensive system because the system needs complicated readers to obtain the visualizations (Li 2016). Due to the wide variance of products in the construction sector, the complicated readers, and the dynamic environment, this is not a very favourable system for the construction sector.

Barcodes

Barcodes are the most famous identification system in the world. It is widely adapted in multiple sectors due to its cheapness. The barcode is printed on the packing of a product and scanned by an optical reader. *Table 36 Comparison multiple barcodes* gives an overview of multiple barcodes which exists.

Type	1D Linear	2D (e.g. QR code, website links)	3D (e.g. QR code + colour, e.g. Rabobank Scanner)
Symbol			
Capacity	EAN-13: 13 digits: 1012 combinations	Up to 5.016 bits/square inch[2]	Up to 16.000 bits/square inch[2]
Regulation	ISO/IEC 15426-1	ISO/IEC 15426-2 ISO/IEC 18004 (QR)	ISO/IEC 18004 (QR/ High Capacity Coloured 2-Dimensional

Table 36 Comparison multiple barcodes

Due to its cheapness and widely adopted technology, barcodes provide sufficient benefits.

Radio Frequency IDentification RFID

RFID is relatively similar to barcode but have some conceptual differences. Barcodes are scanned by optical readers. RFID is scanned by radio waves. Besides, each RFID tag (see *Figure 7 Components of a RFID* system *on page 9)* contains an unique number instead of a number for a certain product like a barcode has (they make use of a Stock Keeping Unit SKU-level).

Comparison barcodes and RFID

Due to the characteristics of each identification technology, the barcode and RFID provide the best solutions for the construction sector in the field of identification technologies. However, some clear limitations and benefits make in one case the barcode beneficial over RFID, and in the other case make the RFID beneficial over the barcode. The following reasons indicate why RFID is preferable over barcodes.

According to Tajima (2007) and Yin (2009), RFID does not need physical contact between tags and readers which barcode does need. Barcodes need a clear Line-of-Sight in-between. Secondly, the radio waves of RFID tags can be read through layers of packaging materials without undoing the packaging. Thirdly, multiple products can be scanned simultaneously and automatically. Fourthly, products can, with limitation due to some composition of materials, be scanned in all direction and therefore, the positioning of the products is no longer of concern. Lastly, RFID is more robust in the harsh environment of the construction sector (e.g. resistant to snow, dust, mud, rain) than barcodes are. These advantages eliminate human errors and the unnecessary time to check associated product for a barcode. Other advantages are also recognized by other researchers as well: all tags are unique (Hinka 2013), tags can be used inside (concrete) products and becomes irremovable (Lu 2011), some tags are thin and flexible (they are called 'inlayers') and thereby very cheap to produce. Sardroud (2012) recognized that RFID can hold greater amounts of data than barcodes can, the data on RFID tags can be updated, RFID tags can be reused and therefore are more durable than barcodes are. Besides, the efficiency of barcodes is limited because they suffer from the problem of having a short read range, limited durability, vulnerable to scratches and dirt, they require a clear Line-of-Sight and barcodes are hard to read in bright sunlight. In *Table 37 Advantages and Disadvantages Barcode and RFID, Source: Sardroud 2012* is the comparison between barcodes and RFID summarized.

[2] Querini M. et al. (2011) 2D color barcodes for mobile phones, International Journal of Computer Science and Applications © Techno mathematics Research Foundation Vol. 8 No. 1, pp. 136 - 155, 2011

	Advantages	Disadvantages
Barcode	Affordable Easy to use Mature and proven technology Established quality standards Reliable and accurate	Optical Line-of-Sight scanning Limited visibility Restricted traceability Incapable of item level tracking Labour intensive Susceptible to environmental damage Prone to human error Limited memory
RFID	Non- line-of-sight scanning Simultaneous automatic reading Labour reduction Enhanced visibility and forecasting Item level tracking Traceable warrantees Reliable and accurate Information rich Enhance security Robust and durable	Cost of tags and new infrastructure Lack of training and limited knowledge Immature technology Concern of return on Investment Lack of ratified standards

Table 37 Advantages and Disadvantages Barcode and RFID, Source: Sardroud 2012

Based on this comparison, it is worthwhile to consider RFID as the appropriated Identification Technology. In the section next, multiple localization technologies will be examined.

b) Localization Technologies

The localization technologies described below are divided into two categories: radio frequency based and non-radio frequency based systems. First the non-radio frequency systems will be examine, afterwards the radio frequency based systems will be discussed. The full electromagnetic spectrum (radio and non-radio frequencies) is given at page 7 in order to see the difference in wave lengths of each technology.

Vision Based Analysis

Like the biometric systems for identification, vision based analysis does not need any device to localize a product. This technology can cover a relatively large area but is also limited by the surrounding environment (Li 2016). It is based on vision and thereby visible light. The human interaction is huge, hence, they have to recognize a certain product by predetermined factors or a machine have to recognize 'something' by use of a camera and algorithms. This technology is nog favourable in the construction sector due to the huge amount of (different) products involved and the uncontrolled environment of the project site.

Infrared

Infrared is the light which operates at the spectrum of 300GHz until 430 THz of the electromagnetic spectrum. Infrared is widely used in order to see temperature differences in environments. In order to localize a product, the hardware device needs to have a clear Line-of-Sight. The technology can be very accurate (Li 2016) but is limited due to its relatively short read range. For the construction sector, the dynamic and uncontrolled environment, the movement of the products, the temperature fluctuations and the erection of buildings make an infrared system impractical.

Ultrasound

Ultrasound are sound waves at frequencies of 20KHz to several GHz. (American National Standards Institute) of the electromagnetic spectrum. This technology is used, for example, by bats to navigate in dark environments, by animals to communicate like dolphins, echoes for pregnant woman and radar systems. This technology uses the Time of Flight (TOF) measurement to localize an object. Due to the difference in time between the sending and receiving sound wave, the system can localize a certain distance between the speaker and an object. Although this technology is very accurate (Li 2016), it suffer in the construction sector because the sound waves cannot penetrate walls and objects without sufficient power, the waves are sensible for fluctuation in case of temperature changes and the ultra sound can be distorted by reflected signals and noise caused by metal objects for example. Besides, the ultra sound wave cannot carry (digital) information which make it impractical to localize a certain product in the construction sector (Sardroud 2012).

Machine-to-Machine

It has to be noted that new technologies in the Machine-to-Machine (M2M) communication domain offers organizations a range-free, energy efficient and an easy scalable solution to communicate with individual products (i.e. sensors) throughout a grid. Comparable technologies includes Internet-of-Things and LoRa[3]. However, in current scientific researches, M2M is most often considered to implement only for sensor communication, collecting environmental values of a sensor' surrounding. The use of M2M technologies to localize individual products is not found in the literature analysis, sensors are often a static anchor node (Karim 2015) and therefore, will not be investigated anymore.

The above four technologies represents the non-radio frequency based systems category. These operate at the electromagnetic spectrum from 20Khz (ultrasound) until 770 THz (Vision Based Analysis). Machine-to-Machine makes use of the internet to communicate in-between systems. Below, radio frequency based systems will be discussed, which operates at the radio spectrum of the electromagnetic spectrum with frequencies of 3Hz until 3 THz in general.

Ultra-Wide Band (UWB)

This technology is a radio transmission technology that utilizes low power levels for short range high-bandwidth communication. This will be achieved by using a wide portion of the radio spectrum (>500 MHz) at the time. It is an extremely low energy system and very precise (Nasr 2013). However, the accuracy may drop when it is deployed in a large area such as a 65.000m^2 or a 100.000m^2 lay down yard (Li 2016) or with the presence of obstacles such as boxes (Li 2016). The distance between tags, as well as the operating frequency level have its influences on the performance of an UWB-system, thereby, UWB-systems are currently used for short ranges only (Rodriquez 2010, Li 2016) e.g. ergonomic analysis for installation handling processes at project sites. UWB does not have an on-board memory capacity and there is only one single UWB frequency at the time, only one tag can be located at a time (Rodriguez 2010). UWB is a new, upcoming technology with some good performances but suffer currently due to lacking research and limited real-case scenarios in the construction sector.

Bluetooth

Bluetooth operates at a 2.4 GHz frequency of the radio spectrum and is a technology for wireless short range links between portable handheld devices like mobile phones and Personal Computers. Currently, the read rang is around 10m (Sardroud 2012). Li 2016 search in the period of 2005 – 2014 (75 articles) for real-time location systems in construction, non-research has been done with Bluetooth applications in the construction sector. Probably due to its short read range of the technology.

Wireless Local Area Network (WLAN)

Another technology which operate at the 2.4GHz radio band is ZigBee, also known as 802.11b a, 802.15.4, and Wireless Fidelity, Wi-Fi (Sardroud 2012). Due to the deployment of many devices locally in a network, such as routers, modem and end-devices, the communication range can be much larger than Bluetooth. WLAN usually calculates the position of an object according to the signal strength. Because of the use of many devices, the network can be extent for a wide area, making this technology affordable for large project sites (Li 2016). However, the products needs to be connected with the WLAN, whereas each connection is relatively expensive due to the amount of connections needed. Due to the needed connection, the system is considered only applicable for indoor environments since it is not a very portable system and suffers flexibility for outdoor environments (Sardroud 2012).

Wireless Wide Area Networking (WWAN)

This technology is widely used for telecommunications like mobile phone internet. WWAN make use of a mobile telecommunication cellular network to transfer its data. Thereby, it can cover a widespread area (Sardroud 2012). Where the Global System for Mobile Communication (GSM) uses this network for mobile phone calls, the General Packet Radio Systems (GPRS) uses this network to send and receive data across the mobile telephone network. Multimedia Messaging Service (MMS) and Internet Communication Service (ICS) are the most famous mobile internet applications of GPRS. GPRS can send any sort of message without a limitation to the amount of data (Sardroud 2012). GPRS uses the same protocols as the internet, thereby, the network can be seen as a subset of the internet. Based on triangulation, it can detect a device' location if receivers are located at known positions. The accuracy is not that high due to the initial function of the WWAN network (telecommunication purposes).

[3] LoRa stands for Long Range, it is a wireless telecommunication network for machine-to-machine communication. Due to its long range, low power and thereby long life expectancy, the network is considered to use for Internet-of-Things purposes.

Global Navigation Satellite System (GNSS)

A widely used localization technology are systems based on satellites which orbits around the earth at high altitudes every day of every week. This system, in comparison with other localization technologies, only sends its location. A secondary device has to translate this signal into a usable digital format. Often, a wired of wireless communication technology (like LAN or WLAN) is used in order to communicate this signal. The network of satellites transmit radio signals and uses a Time of Flight (TOF) measurement in order to provide reliable location and time information to identify geographic locations (longitude, latitude and altitude) of any user, at anytime, anywhere around the world under any weather condition (Sardroud 2012). The most famous GNSS systems are the Global Positioning System GPS (developed by the United States' Department of Defence), Galileo (developed by the European Union) and GLONASS (Developed by Russia). The precision of the system is not that accurate since it cannot provide, for example, lane-level positioning in urban areas (Watson 2007). Because the systems are developed by a country, it may occur that a certain system is not as precise as in its home country somewhere else in the world. In order to increase the precision of satellites in foreign countries and in, e.g., in urban areas and blind spot areas like a tunnel, a combined global navigation satellite system can provide a solution. A combination of the GPS, Galileo and GLONASS systems together should greatly increases the visibility everywhere in the world, a constellation of about 75 satellites of these three systems. However, this is not current practice yet. Its market availability and user-friendly features makes GNSS a desirable system for individuals and organizations. Unfortunately, the high initial investment costs make construction practitioners, suppliers and contractors reluctant to widely adopt this technology for every single product (Nasr 2013).

Radio Frequency IDentification RFID

Radio Frequency IDentification is based on radio waves. Due to the radio waves, positioning methods for RFID can be either Received Signal Strength (RSS), Time Of Arrival (TOA) or Time Difference Of Arrival (TDOA). The Received Signal Strength (RSS) make use of the effect that power drops of signals. Because the power level at the start of the transmission is known, the RSS can be used to estimate the distance the signal has travelled. Time of Arrival (TOA) focusses on the time differences between signal leaving and signal receiving because the speed of the signal is known, this is around the speed of light. With Time Differences of Arrival (TDOA), the same technique is used as in Time of Arrival. The only difference is that the location sensors must be exactly time synchronized in order to prevent ambiguity, which creates false data. Not a round trip is calculated but a single trip (Munoz 2009). In comparison to WLAN, RFID tags does not have to be connected to the LAN whereby RFID tags are portable and so, a much more flexible system than WLAN can be deployed. Depending on its composition, a RFID system can have a huge range indoor and outdoor.

Comparison localization technologies

The above explained non-radio frequency based systems (Vision Based Analysis, Infrared, Ultrasound and Machine-to-Machine) are considered to be not suitable for the construction sector. Vision Based Analysis requires a clear Line-of-Sight, they suffer from illumination, occlusion and scale variation and the system can lose track of an object when its appearance changes to much or is strongly shadowed (Li 2016). Infrared requires also a clear Line-of-Sight. Besides the system does not have a long read range. Ultrasound can provide highly accurate results but cannot penetrate objects without sufficient signal strength. A clear Line-of-Sight is desirable but this cannot be guarantee in the construction environment. In all, these three technologies require a huge amount of human import, high initial investment costs are associated and they cannot work in uncontrolled and dynamic environment since they require a clear Line-of-Sight. Machine-to-Machine communication is a bit different since it makes use of the internet in order to communicate, instead of the electromagnetic spectrum like Vision Based Analysis, Infrared and Ultrasound. A lack of scientific evidence to localize individual products with Machine-to-Machine technology in the construction sector has lowered the creditability of the technology. Therefore, it will not be considered as an appropriate localization technology for the construction sector. Therefore, these non-radio frequency based systems are not suitable for the construction sector in order to localize products efficiently.

Other investigated systems are radio frequency based systems like Ultra-Wide Band (UWB), Bluetooth, Wireless Local Area Network (WLAN), Wireless Wide Area Network (WWAN), Global Navigation Satellite System (GNSS) and Radio Frequency IDentification (RFID). Bluetooth can only work for indoor applications since its short read range of approximately 10m. GPS, the most famous GNSS system, does not work in indoor environments and its accuracy decreases in highly dense areas when signals are blocked (Li 2016). Although the combination of multiple satellite systems can increase its accuracy in highly dense areas, still, there would be limitations due to the long travel distance between a GPS tag and the antenna and the resulting minimal accuracy. WLAN-based systems are the most inaccurate systems compared to the other system according to Li 2016. WWAN-based systems also suffers in accuracy compared to the other technologies due to its initial purpose: telecommunication.

UWB and RFID are two, relatively comparable systems but a lack of UWB-related research and practical experiences makes RFID more eligible than UWB. Besides, UWB needs an additional storage capacity which RFID has on-board up to several megabytes. Looking at the characteristics of common project sites: an uncontrolled, unprepared and a dynamic environment (Sarac 2010), it should be worthwhile to consider a RFID system as an appropriate system since it accomplished until so far the functions: it can identify a product and to localize a product, a combination other technologies cannot accomplish. In *Figure 6 The Electromagnetic Spectrum* on *page 7*, the electromagnetic spectrum is given in order to give an overview of the wavelength and frequencies of the different localization technologies. In *Figure 15 The Electromagnetic Spectrum, including a detailed Radio Spectrum* on *page 14*, a larger graph is visualized.

c) Communication Technologies

The information obtained from the identification and localization feature of a technology has to be send to another device or enterprise systems in order to make value of the data. The feature communication will be examined below.

Most of the localization technologies can also communicate between devices. The examined technologies are Bluetooth, RFID, UWB, WLAN and WWAN. An Explanation of each technology can be find on the previous pages. Extra information will be described here.

Wireless Local Area Networking (WLAN)

WLAN, known from Wi-Fi ("Wireless Fidelity") and ZigBee, in technical terms 802.11b and 802.15.4 can act on a 2.4GHz radio band (Sardroud 2012). For the communication, multiple devices are needed, such as coordinators, routers and end-devices. Because of the possibility to change devices, the communication range can be up to 1000m in general.

Wireless Wide Area Networking (WWAN)

As mentioned above, WWAN is generally known for its telecommunication feature. It can cover the whole globe by use of satellites and masts. Back in 1982, the Groupe Spécial Mobile (GSM) has been formed during the Conference of European Posts and Telecommunications to develop a pan-European mobile cellular radio system, later called Global System for Mobile GSM (Sardourd 2012). With this technology, it became possible to send messages by GPRS. Practical examples of this function is Multimedia Messaging Service MMS and Internet Communication Service ICS. The protocols of GPRS are the same as the protocols used for the internet of today. So, in order to send data by a WWAN network, a contract with an internet provider is needed.

d) Comparison matrix

Throughout this appendix, multiple different technologies were introduced which can identify and localize unique products, and communicate this information. Thereby, on multiple aspects, RFID is considered to be worthwhile to investigate in this study. In the table on the next page, Table 38 Comparison matrix localization Technologies, a summary has been given about all pros and cons of the different technologies examined.

	Barcode	Bluetooth	GNSS	RFID	UWB	WLAN	WWAN
Identification	Yes	n/a	No	Yes	No	No	No
Localization	No	Yes	Yes	Yes	Yes	Yes	yes
Communication	No	Yes	No	Yes	Yes	Yes	Yes
Accuracy	n/a	10-15m[9] 2-10m[11]	10m[4] 5-10m[10, 11]	0.86-2.6m[5] 5cm-5m[11]	0.3m[5] 6-10cm[11]	50-100m[9] 50-1000m[15]	100-150m[9] 50-100m[11]
Affordability	Very low[15]	Relatively cheap (Bluetooth modules €10,-)	Very high[12] >$50.000[12] $24.485[13]	Relative expensive[6] $55.000[13] ±€0,80 / 1 tag[21]	Expensive[9] €3.833,50-$12.000[22]	± €10/ 1tag[21]	Contract costs service provider
Data Storage Capacity	Low, compared to RFID[15]	Additional capacity needed	Additional capacity needed	Great amount[15] < 8MB[19]	Additional capacity needed	Additional capacity needed	Additional capacity needed[15]
Ease of use	Really easy in use[15]	Yes, mobile phones	Most used[13] Very easy[15]	Automate[15] Easy[6]	Easy to install[9]	After set-up, training needed to localize	After set-up, training needed to localize
Fast Read Rates	One item at the time	24Mbit/s v.3.0	<1time/sec [17]	High[19] >60 tags/sec[1]	Several GB/sec[5, 15]	15,3MB/sec[2] [3]	5,5MB/sec[23]
Read Range	By a scanner locally (<10m)	10m[15]	Worldwide (except blind spots)	Passive:6-180m[7] Passive: 15m[20] Active:>100m[7] Active:>100m[20]	Short-/medium range: 10-30m[20]	Locally, depending on routers	Almost worldwide (network availability)
Resilience to ambient noise and interference	Sunlight, rain, dirt, damage by impacts[15]	Metal + heavy materials interference	Dense Areas/GPS blind spots[15]	No influences harsh conditions, metal + liquid inlvuences[2, 6, 15,18]	Metal influence[4] Almost none[4] Less affected[9]	Metal + heavy materials interference	Metal + heavy materials interference
Typical Use	Retail sector, products	Mobile phone, laptop	Outdoor[12]	Indoor/ outdoor[12]	Indoor[12]	Wi-Fi access	Mobile phone

Table 38 Comparison matrix localization Technologies

1 Bank (2007)
2 Finkenzeller (2010) Table 1.2
3 Garmin, Kenwood
4 Li 2016
5 Li (2016) Table 6, Best result Construction publication
6 Lu (2011)
7 Malik A (2009), Table 2-1
8 Malik A (2009), Table 11-1
9 Muthukrishnan (2005), Table 1
10 Muthukrishnan (2005), Table 2
11 Muthukrishnan (2005), Table 4
12 Nasr (2013)
13 Nasr (2013), Table 1 (Case Example)
14 Rodriguez (2010)
15 Sardroud 2012
16 Lee (2007)
17 Source: https://learn.sparkfun.com/tutorials/gps-basics (19-04-16)
18 Source: https://rfidinschools.files.wordpress.com/2013/01/rfidjournal-article9476-1.pdf (19-04-16)
19 Sweeney (2005), Table 2-1
20 Tajima (2007)
21 Yu (2009): Price for full operating system
22 Yavari (2014)
23: http://cloudworks.nu/2015/06/25/nederland-loopt-achter-met-mobiele-internetsnelheid/ 2015 Netherlands

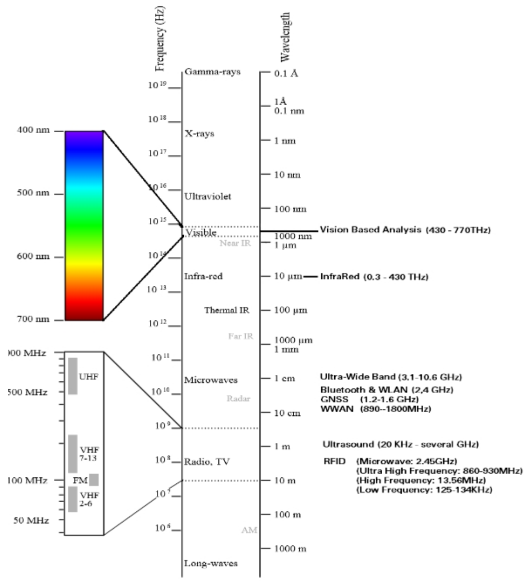


Figure 6 The Electromagnetic Spectrum

References

Finkenzeller K. (2010) RFID Handbook - Fundamentals and applications in Contactless Smart Cards, RFID and NFC, Wiley Ebook

Hinkka, V., & Tätilä, J. (2013). RFID tracking implementation model for the technical trade and construction supply chains. Automation in Construction, 35, 405-414. doi: 10.1016/j.autcon.2013.05.024

Karim L., Nasser N., Mahmoud Q.H., Anpalagan A., Salti T.E. (2015) Range-Free Localization approach for M2M communication systems using mobile anchor nodes, Journal of Network and Computer Applications 47 (pp. 137-146)

Lee J-S., Su Y-W., Shen C-C. (2007) A comparative study of Wireless Protocols Bluetooth, UWB, ZigBee and Wi-Fi, the 33rd Annual conference of the IEEEE Industrial Electronics Society (IECON)

Li H., Chan G., Wong J., Skitmore M.(2016) Real-Time Locating Systems applications in Construction, Automation in Construction 63 (37-47)

Lu W., Huang G.Q., Li H.(2011)Scenario's for applying RFID Technology in Construction Project Management, Automation in Construction 20, 101-106

Malik A. (2009) RTLS for Dummies, Wiley Publishing, Inc

Munoz D., Bouchereau F., Vargas C., Enriquez R.(2009) Position Location Techniques and Applications, Elsevier, Ebook

Muthukrishnan, K. and Lijding, M.E.M. and Havinga, P.J.M. (2005) Towards Smart Surroundings - Enabling Techniques and Technologies for Localization. In 1st Int. Workshop Location- and Context-Awareness (LoCA),

Nasr E., Shehab T., Vlad A. (2013) Tracking Systems in Construction Applications and Comparison, 49th ASC Annual International Conference Proceeding, Associated Schools of Construction

Rodriguez S., Shang C., Hammad A.(2010) Feasibility of location tracking of construction resources using UWB for better productivity and safety, Computing in Civil and Building Engineering 52

Sarac A., Absi N., Dauzère-Pérès S. (2010) A literature review on the impact of RFID Technologies on Supply Chain Management, International Journal Production Economics 128 (77-95)

Sardroud J. M. (2012) Influence of RFID technology on automated management of construction materials and components, Sharif University of Technology, Scientia Iranica Transaction A: Civil Engineering 19 (3), pp 381 – 392

Sweeney P. (2005) RFID For Dummies

Tajima M. (2007) Strategic value of RFID in supply chain management. *Journal of Purchasing and Supply Management, 13*(4), 13. doi: 10.1016/j.pursup.2007.11.001

Watson L.S. et al, (2007) Research Opportunities In Radio Frequency Identification Transportation Application, Transportation Research Board, E-C114

Yavari M., Nickerson B.G. (2014) Ultra-Wide Band Wireless Positioning Systems, University of New Brunswick Canada

Yin S., Tserng H., Wang J., Tsai S. (2009) Developing a precast production management system using RFID Technology, Automation in Construction 18, pp. 677-691

Yu K., Sharp I., Guo Y.J. (2009) Ground-based Wireless Positioning, IEEE, A John Wiley and Sons Book

Appendix B. The RFID system

This appendix will describe the technology behind a RFID system. The complete system consists of several components. Each component will be described below. Characteristics, regulation and properties will all be discussed. After reading this appendix, one should be able to understand the basic principles of common RFID systems. One should find out that the applicability of a RFID system does not depend on the characteristics of a components itself but on the characteristics these components have in a specific environment. A read range of 5m could be achieved both by a passive and an active RFID tag. It is the environment and the purpose of the system what determines which component (and characteristics) will fit best in this specific situation: the passive or the active tag. First, the history of RFID will be given. Afterwards, the system will be explained by the hardware components from the point of use (RFID tag) up to the enterprise system.

a) History

Radio Frequency IDentification (RFID) is based on electromagnetic energy and thereby, its ancestry can be traced back to the very first moments of 'everything'. Scientists and religion believed that electromagnetic energy was the beginning of everything due to the formation of protons, neutrons and electrons. When photons, the quantum element of electromagnetic energy, collided, they converted energy into mass, which creates protons, neutrons and electrons. It was this collision which forms the origin of the 'Big Bang' and afterwards, the four fundamental forces of nature: gravity, strong and weak nuclear forces and electromagnetic energy. This last fundamental force, electromagnetic energy, is the source of RFID. Research from the 1800s and on examine the use of this energy but, according to AIM, the "Identify Friend or Foe" system, developed to differentiate friendly airplanes from enemy airplanes during the second World War, was the first application of what we call today 'RFID' (Landt 2001). With RFID, one can identify an unique code. To make this identification worthwhile, an underlying RFID system is needed to add information, and thereby a meaning, to this identification.

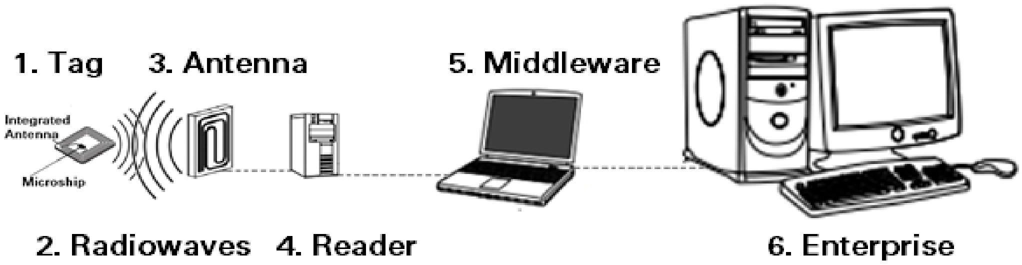


Figure 7 Components of a RFID system

A typical RFID system contains several components which will be briefly discussed below. First of all, the system includes a RFID tag (consisting of an internal microchip and an antenna) which is the identification device of the system. Secondly, radio waves are used to communicate this identification with the RFID reader. This RFID reader can be divided into an antenna and the actual reader. Mostly, these components are combined in one single device, a handheld RFID reader for example. Fixed readers (with an on-board or external antenna) also exists. Hereafter, the RFID middleware is the component which collects the information from the RFID readers and process this obtained information between the RFID reader and other applications of an enterprise system. Normally, this middleware is linked to the Enterprise Resource Planning system, an internal and/or an external database. Below, each component will be explained in detail. Next to each section, the corresponding component is given in the margin of the page[4].

b) RFID tag

The RFID tag (i.e. transponder) consist of two main substitutes: the internal antenna and the microchip. The RFID antenna is the conductive element that enables the RFID tag to send and receive data[5]. The microchip is the element which transforms the incoming signals and sends at least, its unique number back via the tag' antenna to the RFID reader. RFID tags can be placed on single products, a box of product or a pallet with multiple boxes of products.

[4] Pictograms are based on Sweeney J.P. (2005)
[5] RFID Journal-The Basic of RFID Technology [22-04-16]. Available: http://www.rfidjournal.com/articles/view?1337

Active, Semi-passive and Passive tags

There are three types of RFID tags: active, semi-passive and passive RFID tags. With passive RFID tags, the electromagnetic energy derived from the RFID reader contains all the energy needed for the microchip in the RFID tag in order to react on the incoming signal. This electromagnetic field of the reader can be modulated or the RFID tag can intermediately store, for a short time, the energy from the electromagnetic field. This means that the energy emitted by the reader is used for data transmission both from the reader to the RFID tag and back to the reader. Therefore, when a passive RFID tag is outside the range of the reader, it obtains no electromagnetic energy and thereby, it has no ability to send radio waves back to the reader. In case of active tags, an on-board energy supply provides the power for the microchip in order to operate. Because active tags do not need the energy from the electromagnetic field, the absorption power of the RFID tag' antenna can be much weaker than in case of passive tags. This substantially increases the reading distance of active RFID tags. The most basic active tag sends out a signal at a regularly predefined rate. This is known as the beacon rate of the RFID tag (Bank 2007). The life span of the battery, and thereby the active RFID tag, is bound by three variables: the beacon rate of the tag, the strength at which the tag transmit radio waves and the maximum shelf life of the battery. Unfortunately, the life span of an active tag is relatively short due to these variables, compared to passive RIFD tags which have no on-board power source. Semi-passive tags are a combination of passive and active tags. The passive element of the tag gets energized by the incoming electromagnetic field of the reader. This energy activate the internal power source. This power source sends the signal back to the reader what results in a longer life span than active tags and a much further reading range than passive tags. The on-board power (active and semi-passive tags) can also be used in combination with external sensors (e.g. temperature, carbon dioxide, humidity). In general, active tags have larger memory, longer reading ranges, and better noise protection from interference than passive tags. However, active tags are larger and heavier, more expensive and have a shorter life (3-10 years) than passive tags but offers the possibility for a more flexible system since the transmission strength is higher and therefore better applicable in harsh environments (Sun 2013). Semi-passive tags is a combination of both type of RFID tags.

Memory banks

The microchip in the RFID tag contains the data capacity with at least four key memory banks. The first reserved bank (00) contains access protocols, the second (01) contains a Protocol to be followed for reading the tag' data, the third bank contains the unique Tag ID (10) and the last bank contains a possible user memory (11), see *Table 39 Typical memory banks RFID tags,*
source Bank 2007. In 2005, there were only four primary manufactures of these RFID chips worldwide: Philips, Texas Instruments Fairchild and St Micro (Sweeney 2005). When a coupling (a connection) is established, the memory will be read from Bank 00 to Bank 11. If passwords are predefined, they are located in Bank 00 'Kill & Access Passwords'. If no password is in place, the tag must treat this memory bank as zero values which is permanently locked to read and write operations. The following bank (bank 01) determines the protocol to be used. This consist of a 16-bit Cyclic Redundancy Check (CRC-16). This value is a computed quantity that is used to validate the integrity of the rest of the data found on this bank. In this bank, a EPC code can be defined. However, it must be noted that the EPC in this context does not refer to the unique Electronic Product Code, developed by EPCglobal/GS1 explained later in this paragraph. In the third memory bank (10), the unique Tag ID is located, regulated by the ISO/IEC 15963. In memory bank 11, an optional user memory is located. This data-capacity range from a few bits, to multiple kilobytes and even multiple megabytes. It is the only bank where read/write activities can take place (Bank 2007).

Reserved (Kill & Access)	Bank 00
Protocol	Bank 01
Tag ID	Bank 10
User memory	Bank 11

Table 39 Typical memory banks RFID tags, source Bank 2007

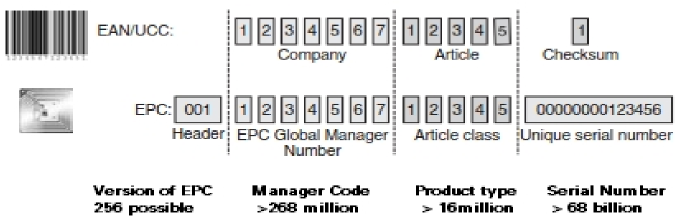


Figure 8 Comparison UPC and EPC

Unique Tag ID

The Unique Tag ID (TID), located in memory bank 10 is the number where RFID is all about. This bank cannot be written. Many organisations plead for standards of this unique number. The GS1, the most famous example, is an international operating non-profit organization that develops and maintain standards for electronic communication between different companies. The GS1 organization formed in 2003 'EPCglobal Inc', specifically for RFID standardisation and assignment of unique identifiers for RFID tags (Bank 2007). The standard format developed, the Electronic Product Code (EPC), is a meta-coding scheme which is designed to meet the needs of many different sectors. This EPC is located on bank 01 (Protocol). The combination of the EPC and a tag' TID is unique in the world since the TID cannot be adjusted by anyone (the TID is incorporated into the tag during chip manufacturing and this bank cannot be alter this number, nor any data can be changed on this memory bank). The EPC on the other hand, (Bank 01) can be adjusted or copied. This combination is a widely accepted standard in many sectors. The difference with the well-known Universal Product Code (UPC), which defines one code for a certain product (SKU) whereas the EPC + TID defines one code for every single article, thereby, non-duplicate codes exists in the world. The difference between UPC and EPC are shown in *Figure 8 Comparison UPC and EPC* on the previous page. The UPC is known for its use by barcodes and thereby requires a clear Line-of-Sight between the barcode and a scanner. A RFID tag does not require a Line-of-Sight because a RFID tag is based on radio waves instead of optical vision. The UCC, Uniform Code Council, is the organization in charge of assigning UPC manufacture codes.

Read-Only, WROM/RW

The user memory (bank 11) of the RFID tag can be either Read-Only (RO), Write-Once-Read-Many (WORM) or Read-Write (RW). In case of Read-Only applications, the reader only can read the data placed on the tag, nor it can adjust data on this tag. Because of this simple system architecture, Read-Only tags can be manufactured extremely cheaply. Writeable RFID tags are more complex and therefore, more expensive. Write and Read access to the transponders take often place in blocks of data. In order to change the data content of an individual block, first the entire block must be read before the modified bytes can be written back to the RFID tag. In some application, the RFID tag is only used as an identifier where in other applications the RFID tag is used in an more dynamic way wherein the tag is updated with new information, so, writeable functionalities are needed in this case.

Classes

RFID tags can be classified. The GS1 classified the type of RFID tags, as one can see in *Table 40 Classes Source: GS1 US.*

Class	Power	Range	Memory	Communication	Peripherals	Cost	Type
0	None	<3 m	1 to 96 bits, Read Only	Backscatter	None	Low	Passive
1	None	<3 m	1 to 96 bits, Read/Write Once	Backscatter	None	Low	Passive
2	None	<3 m	1 to 96 bits Read/Write	Backscatter	Security	Medium	Passive
3	Battery Assisted	<100 m	<100 Kilobytes Read/Write	Backscatter	Security, Sensors	High	Semi-passive
4	Battery Assisted	<300 m	<100 Kilobytes Read/Write	Active Transmission	Security, Sensors	High	Active
5	Battery Assisted, AC/DC Connection	Unlimited	Unlimited, Read/Write	Active Transmission	Security, Sensors can communicate with other tags	Very High	Active

Table 40 Classes Source: GS1 US

Only beyond class 0, the tags are user-programmable. From class 2 and on, a read-write memory is added, including an encryption functionality. From class 3, a power source is included. From class 4 and on, peer-to-peer communication and additional sensing are possible. Class 5 tags contain enough power to activate other tags, they can be classified either as reader.

Security

With the possibility to read the user memory, and to write data to the RFID tag, the need for cryptologic authentication has been risen. One of the simplest mechanisms for protection is the use of a password. In this case, the microchip corresponds the transmitted password from the reader with the stored reference password on the chip and permits access or not (Finkenzeller 2010). This password is located in bank 00 of the tag' memory. Another mechanism is by use of an authentication procedure. With this procedure, two secret keys are involved. The secret key is written to the key memory by the manufacture before the tag is supplied to the Customer. This key memory cannot be read by reader whereby the key is not accessible by readers or other devices. This is a more advance, and thereby a more expensive, procedure.

Antenna

In general, how bigger the RFID Tag, how bigger the size of the antenna, how more energy could be obtained by the antenna and therefore, more energy can be broadcast back to the reader (so, a longer read distance). There are two components in the electromagnetic field of the reader which broadcast power to the RFID tags: the magnetic component (H-field) and the electric component (E-field). A passive tag antenna is designed to power themselves of one of these two fields only. If the tag is designed to operate in a spectrum less than Very High Frequency (30 – 299MHz), a coil type antenna will be used, see *Figure 9 NXP Ntag203 Coil inlay.* When a tag operates at Ultra High Frequency or higher (300 – 2999MHz), tags derives its power from the electric component in the electromagnetic field and therefore, have antennas which are based on a linear design (mostly straight tags). These tags are known for its 'far field' use and are often called radiative tags see *Table 41 Overview of Tag Antenna Types (source: Bank 2007).* Both the orientation of the antenna, as well as the width of the antenna (surface), helps to couple the tag' antenna with the reader (Bank 2007). When objects being tracked may be set at different orientations, 'squiggle tags' are often used because these type of tags consist antennas which can receive waves at all possible angles, see *Figure 10 ALN-9440 Squiggle from Alien Technology inlay (source: Bank 2007)*.

Frequency	Field	Tag Type	Antenna Type
LF	Near	Inductive	Coil
HF	Near	Inductive	Coil
UHF	Far	Radiative	Linear

Table 41 Overview of Tag Antenna Types (source: Bank 2007)

Figure 9 NXP Ntag203 Coil inlay

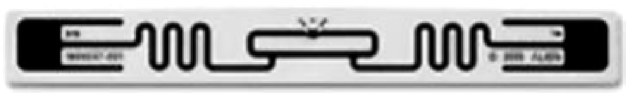


Figure 10 ALN-9440 Squiggle from Alien Technology inlay (source: Bank 2007)

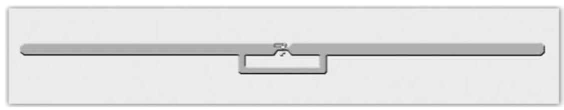


Figure 11 Single-dipole inlay (source: Bank 2007)

In applications where the tag orientation can be controlled, often a dipole antenna will be used. This type of antenna have two poles, separated by a small gap in which the tag' microchip, is placed, see *Figure 11 Single-dipole inlay (source: Bank 2007)*. Dipole antennas should be approximately half as long as the carrier wave frequency for optimal coupling. This means, a 15cm long dipole antenna is used to couple a 915MHz radio wave because a 915MHz radio wave have a wavelength of ± 33cm. These three types of antenna are so called 'inlays', i.e. printed passive RFID tags. Active RFID tags are not printed but fabricated and thereby, they cannot be an inlay. The active RFID antennas comes in a wide variety of designs, from actual (radio) antennas to small, on board antennas captured in a hard protection shelf.

Wattage

The wattage of high-frequency tags is regulated by telecommunication regulations in almost every country around the world. However, some variation in the wattage exists around the world. In Brazil and the United States for example, the wattage of the tag is limited to 4Watt. In China and in the Netherlands, this limitation is set on 2Watt (Bank 2007). This wattage has influences on the range of the RFID tag. There are two separate power ratings for broadcasting expressed in watts, type and size of the antenna. The first power rating, 'Effective Isotropic Radiated Power' (EIRP), is a measurement of the power which is based on an isotropic antenna. This antenna broadcast evenly in all direction to create a sphere around the antenna, see *Figure 12 Isotropic Pattern*. The other power rating is 'Effective Radiated Power' (ERP), which is a measurement based on a dipole antenna. These dipole antennas cannot emit electromagnetic radiation from the ends of these dipole. As a result, a donut-shaped area around the dipole antenna evolves, see *Figure 13 Dipole Pattern*.

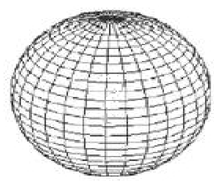


Figure 12 Isotropic Pattern

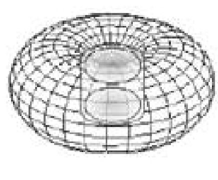


Figure 13 Dipole Pattern

Substance

Depending on the size, type and characteristics of the above described features, a certain substance holds the elements of the tag in place. This is most often a Mylar or plastic film. Glass is mostly used in case of capsules and hard cases are mostly used in combination with active RFID tags. A very flexible, mostly printed passive RFID tags are known as 'inlays'.

Printers

Since most passive tags are cheap and easily to produce, special RFID printers are used to print these tags, they are often called inlay-tags. Because this cheap variant of RFID is mostly used for high volume purposes, the speed of which a printer can produce inlays becomes important. The speed of a printer is measured in inches per second (IPS). A standard RFID inlay printer has a speed of 6 to 12 IPS (15.2 to 30.5 cm/sec). Extremely high-speed printers can achieve a speed of 24 IPS (61 cm/sec) (Bank 2007).

In summary

It has to be noted that the use of a certain type of tag has huge influences on the readability in a certain environment and thereby, the usability of the underlying system and the way how data is to be captured. Besides the accuracy, reading range, lifetime of a RFID tags, the manner how a coupling takes place in a certain environment, what functionalities the RFID tag has and what data is stored on the RFID tag, or online, are all contributing factors to the usability of a RFID system. In the next paragraph, the communicating technology between RFID tags and RFID readers will be explained: radio waves.

c) Radio waves

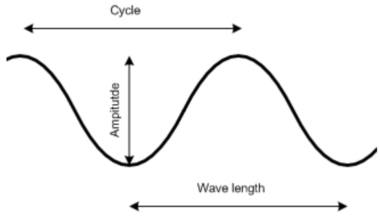


Figure 14 a Radio Wave

The radio waves forms the actual communication between the RFID tag and the RFID reader. A full wavelength is the linear measurement in meters, of one wave. The amplitude is the strength or width of one wave. A radio wave cycle is the interval between two points that measures the completion of one radio wave.

Frequency

The electromagnetic energy is send by radio waves. The frequency of a radio wave is the number of radio cycles per second, expressed in Hertz (Hz). The wavelength can be calculated by $\lambda = c\,/\,f$ whereas c = the speed of light (299.792.458$^{m}/_{s}$ i.e. 300.000.000 $^{m}/_{s}$) and f= frequency of the radio wave. A frequency of 10kHz (10.000 Hz) has a wavelength of ± 30.000m (30 km). The frequency depends the intensity of the radio waves used to transmit the data and thereby, is a key-factor in determining performance levels and applications of a RFID system (Tajima 2007). Normally, RFID systems operates at one of the following four different frequency categories: Low Frequency (125–134 kHz), High Frequency (13,56 MHz), Ultra High Frequency (860–930 MHz) and sometimes Microwave Frequency (2,45 GHz). See *Figure 15 The Electromagnetic Spectrum, including a detailed Radio Spectrum* for an overview of the full electro-magnetic spectrum. Next, see *Scheme 15 Operating frequencies and performance characteristics* for an overview of differences between the frequencies and performance of RFID tags.

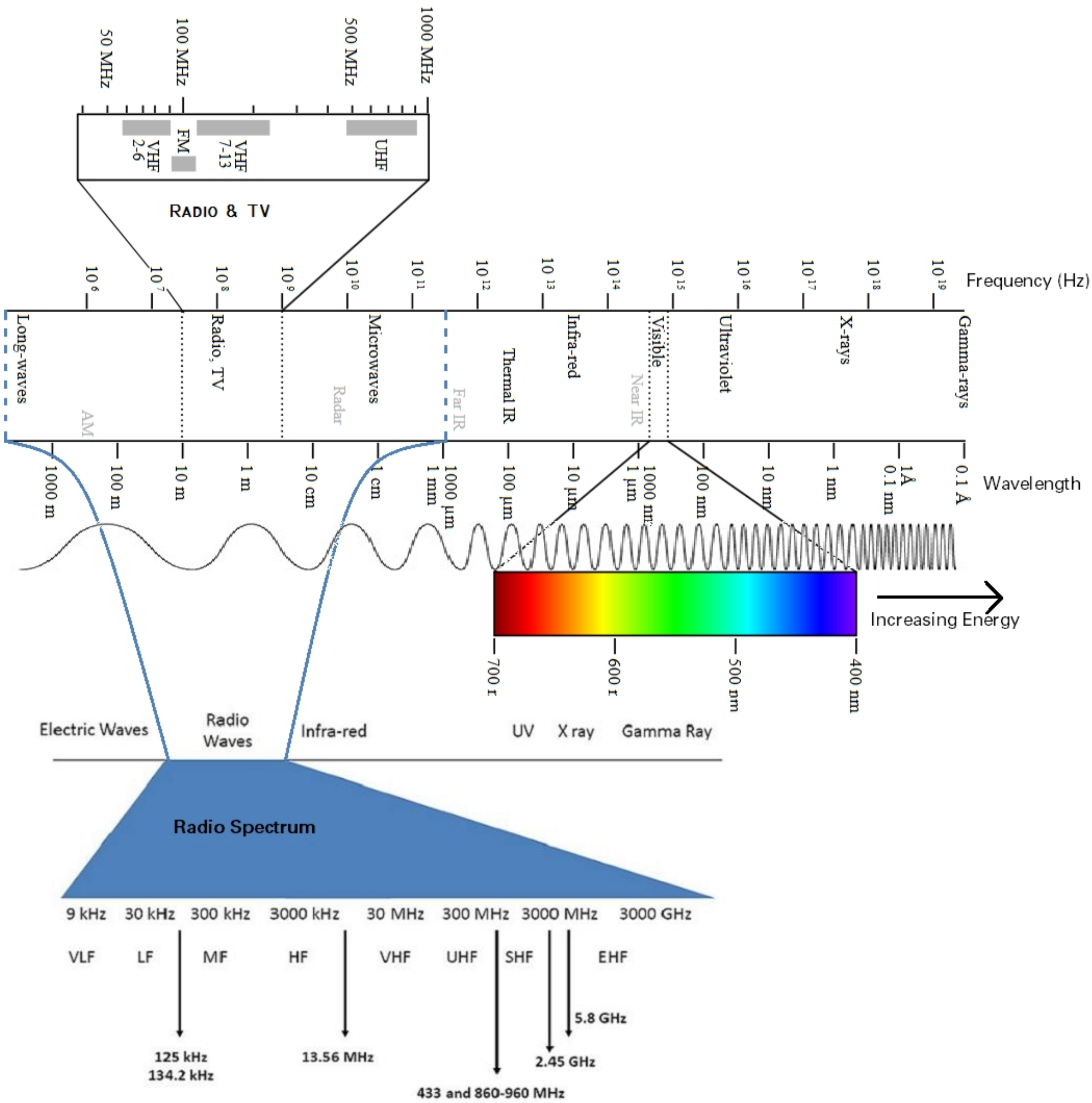


Figure 15 The Electromagnetic Spectrum, including a detailed Radio Spectrum

	Low frequency (LF)	High frequency (HF)	Ultra high frequency (UHF)	Microwave frequency (MF)
Frequency range[a]	125–134 KHz	13.56 MHz	860–930 MHz	2.45 GHz
Tag type*[b]	Passive	Mainly passive	Active and passive	Active and passive
Read range (passive*)[a,b,c]	<0.5 m	1.0 m	3.0 m	10 m
Tag size (passive*)[c]	Larger	Larger	Smaller	Smaller
Data transfer rate[a,b,c]	Slow	Medium	Fast	Fastest
Ability to read near metal or wet surface[a,c]	Best	Better	Worse	Worst
Tag cost[c]	High	Lower than LF tags	Lowest	High
Typical application[a,c]	Livestock tracking, card-key access control, beer keg tracking, Exxon Mobil Speedpass	Airline baggage handling, library book tracking, electronic article surveillance	Supply chain tracking, warehouse management	Electronic toll collection, railroad monitoring

*See Table 2 for more details.
[a]Source Wyld (2006).
[b]Source Kabachinski (2005).
[c]Source SAMSys Technologies (2006).

Scheme 15 Operating frequencies and performance characteristics, source Tajima M. 2007

Coupling

Coupling is the connection of the tag and the reader in a way that they can communicate effectively together at the same frequency. In case of an inductive coupling antenna, there is a large area coil or conductor loop in place which functions as the antenna, see *Figure 9 NXP Ntag203 Coil inlay* on page 12 for an example. This method is frequently used in case of passive tags due to the maximization of the (relatively short) reading range. Another method to couple between tags and readers is the Electromagnetic Backscatter Coupling method (sometimes called 'propagation coupling'). With this method, the tag collects the inbound energy from the electromagnetic field, changes the properties of that energy and then reflecting it back to the receiving device (the RFID reader). Passive and semi-passive tags uses this method due to the cheapness of manufacturing. Another coupling method is the capacitive coupling method. In this case, the antenna of the transponder is made up of two conductive surfaces lying in a plane (electrodes). If the tag is placed within the electrical field of the reader, an electric voltage arises between the two transponder electrodes, which is used to supply power to the microchips (Finkenzeller K. (2010), p. 68). It will only works if the reader is located correctly to the tag and therefore, its application is mostly find in close-coupling environments like smartcards. *See Figure 16 Inductive, Backscatter and Capacitive Coupling Method* for differences between the coupling methods.

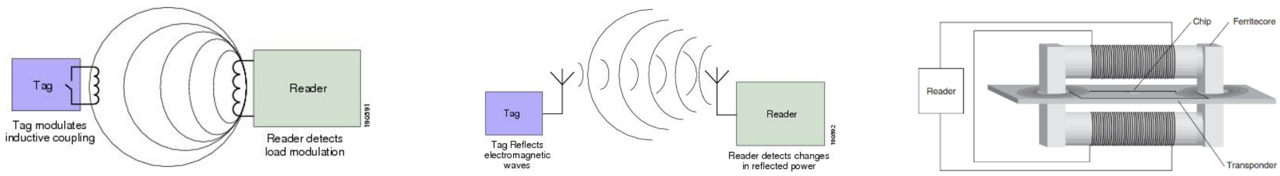


Figure 16 Inductive, Backscatter and Capacitive Coupling Method

Main Characteristics

A radio wave has three main characteristics to keep in mind: 1. The data rate: the amount of data that can be encoded into an radio frequency transmission, 2. Permittivity: the types of materials through which a radio wave is able to propagate and 3. Distance: the maximum distance that a tag can be energized (Bank 2007).

1. Data Rate.
The data rate becomes important when the tag has a great amount of data to be send. It is also called 'throughput'. The amount of data that can be send via a radio wave increases when the frequency increases because more cycles will come in contact with the receiving antenna at higher frequencies. Each wave length in a wave can encode a single piece of data (Bank 2007). Therefore, when a reader obtains more waves in a shorter period of time, it will be able to decode more data. Another factor of influence is the field of use (electric or magnetic), see characteristic '2. Permittivity'. Next, the data rate becomes determinative in applications where the RFID tags will be moving at a high velocity, like at a conveyor belt in a factory. In this application, the data rate must be sufficiently high enough in order to transmit all of the tag's data in the short reading period of time. Thereby, the available bandwidth of the radio frequency spectrum has also its impact on the maximum attainable data rate. The maximum data rate increases when the bandwidth increases. With a higher bandwidth, more devices are able to

communicate at the same time with a RFID Reader at a specific frequency. When the number of tags trying to couple with a RFID reader increases, the reader must determine which single tag is allowed to couple and which tags have to wait. This interferences of multiple tags is called ‘jamming’ or ‘collision’. Communication algorithms provide a solution for this. The United States’ ‘Frequency Hopping Spread Spectrum’ (FHSS) and the European ‘Listen Before Talk’ (LBT) algorithms will be discussed later in this paragraph under the section ‘regulation’.

2. Permittivity.
Due to the atomic structure and density of materials, each type of material will absorb a certain amount of frequencies which results in a retardation of the wave’s propagation through the material (Bank 2007). For example, a RFID system that operate at microwave frequencies (>1GHz) should not be deployed into environments which operates near liquids due to the absorption of a liquid material at this frequencies. Not all liquids absorb the same amount of energy. A metallic object, on the other hand, creates reflection, therefore, metallic objects are considered to be RF-opaque see *Figure 18 Signal Flows, source Malik A. 2009*. Precise tuning of the antennas or tags mounted on a foam platform, which avoids direct contact with the metal offers a solution to this opaque problem i.e. reflection of RF waves. In general, the impact of absorption and opaque materials is higher when a higher frequency is in place. This is due to the ratio of the wavelength to the object size (Bank 2007).

Material Composition	Effect on RF Signals
Glass	Attenuation (weakening)
Groups of cans	Multiple propagation effects, reflection
Human body and animals	Absorption, detuning, reflection
Metals	Reflection
Plastics	Detuning (Dielectric effect)

Table 42 Material Effects on RFID Communications, source: Sweeney J.P. 2005

The RFID Expert Group (REG) came up with a so-called ‘RFID friendliness pyramid’ in order to classify materials and their impact on radio waves. The pyramid can be used to determine the way a material should be tagged, taken into account the material permittivity. The higher the classification in the pyramid, the more stable the RFID performance should be.

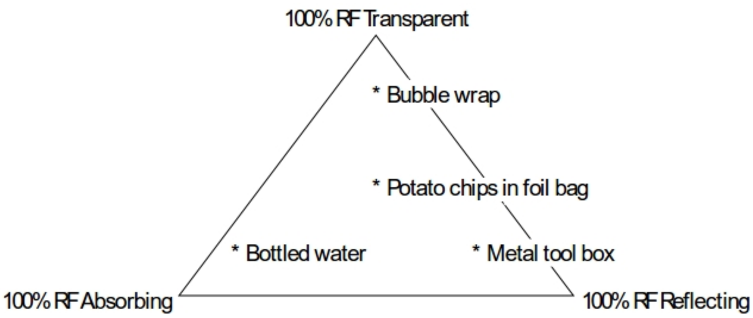


Figure 17 The RFID Friendliness Pyramid, source Sweeney J.P. 2005

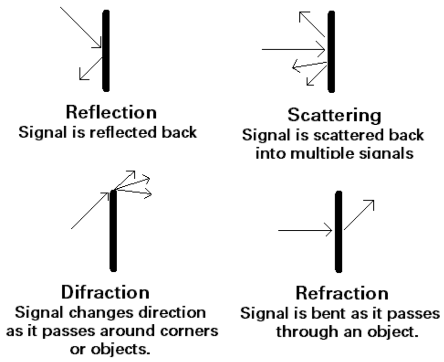
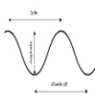


Figure 18 Signal Flows, source Malik A. 2009

3. Distance.
The amount of energy that can be absorbed from an electromagnetic wave is directly proportional to its frequency. Because of this, RFID systems that operate at higher frequencies have, in general, greater read ranges. The more static the environment is, the better the performance of the RFID system can be, regarding the influences of the environmental factors.



Regulation
Many frequencies are nowadays regulated and differ unfortunately from country to country. In the United States of America for example, highly publicized mandates in the past had required suppliers to use the Ultra High Frequency at the frequency of 902 – 928 MHz. The reason for this bandwidth is largely due to work at MIT’s Auto-ID Centre in early 2000. Innovations in the Ultra High Frequency’ ability to read tags at greater distances than other frequencies made the UHF category desirable. This is the reason why UHF is favourite in the supply chain world and made it popular in many sectors around the globe. However, looking at the characteristics and performance of the UHF band, research and investment also take place in the HF and microwave frequency band. For example, the pharmaceutical industry is deploying 13.56 MHz (HF) systems since HF performs better than UHF within close-range liquid items. HF has a better ability to accurate read a wide variety of materials in a small space. It could become a problem when multiple devices are attempting to send data at the same

frequency. This interference is called ‘jamming’ or ‘collision’. In *Figure 19 ISO standards for RFID system, Source Bank* 2007, an overview given of ISO standards for a RFID system. In Europe, the bandwidth for UHF is regulated at a 865.6 – 867.6 MHz whereas in Australia the bandwidth of UHF is regulated at 918 – 926 MHz (Sweeney J.P. 2005).

The USA has allocated a fairly large range (26 MHz) for UHF band RFID compared to Europe (865.6 MHz to 867.6 MHz: 2 MHz). There are two methods for utilizing the allocated bandwidth efficiently. In the United States, a method known as Frequency Hopping Spread Spectrum (FHSS) is employed. Applications with less bandwidth use the method known as Listen Before Talk (LBT), Bank 2007.

‘Frequency Hopping Spread Spectrum’ (FHSS)
FHSS changes frequencies randomly through the allocated spectrum while broadcasting at a predefined statistical randomness. The RFID tag and RFID reader must change to the same frequency at the same time in order to couple. This method helps to minimize the interference of multiple tags’ frequencies. FHSS facilitates also some way of security since the reader need to know the frequency hopping algorithm. This method is for example used in the USA for due to its broad bandwidth (26 MHz) of the UHF band.

‘Listen Before Talk’ (LBT)
This method is not as advanced as FHSS, but it works well when there is limited bandwidth allocation, like the 2MHz in Europe. This algorithm mandates that each RFID tag must ‘listen’ to the frequency it wishes to use prior to broadcasting. If another tag is communicating on that frequency, the transmitter (RFID tag) must either wait until the other use transmission is finished or the tag has to move to another frequency. This method is very slow compared to FHSS because of the listening time required before the transmitter can safely broadcast its information.

Below, an overview of RFID related standards is given in *Figure 19 ISO standards for RFID system, Source Bank* 2007 and *Table 43 Overview ISO Standards RFID Related*.

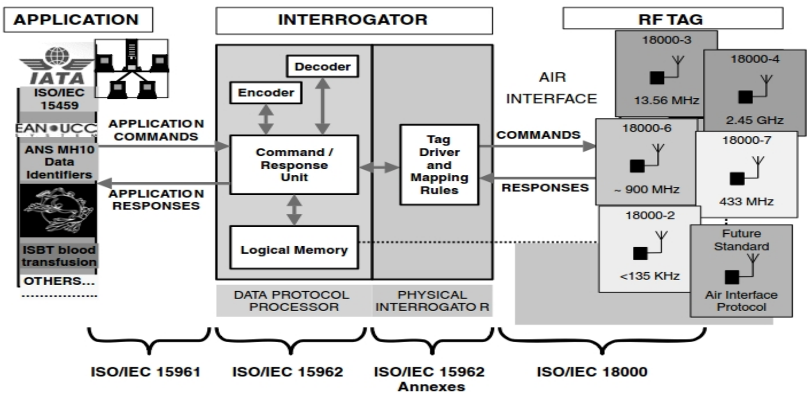


Figure 19 ISO standards for RFID system, Source Bank 2007

Full Name Standard	Standard Code
Radio frequency identification of animals -- Code structure	ISO 11784: 2010
Radio frequency identification of animals -- Technical concept	ISO 11785: 2008
Information technology — Radio frequency identification (RFID) for item management — Data protocol: application interface	ISO 15961: 2004
Information technology — Radio frequency identification (RFID) for item management — Data protocol: data encoding rules and logical memory functions	ISO 15962: 2013
Information technology -- Radio frequency identification for item management -- Unique identification for RF tags	ISO 15963: 2009
Information technology -- Radio frequency identification device conformance test methods	ISO 18047: 2010
Information technology -- Radio frequency identification device performance test methods	ISO 18046: 2012
Generic parameters for air interfaces for globally accepted frequencies	ISO 18000–1: 2008
Air interface for 135 KHz, 13.56MHz, 2.45GHz, 5.8 GHz (withdrawal due to insufficient global interest), 860 – 930MHz, 433.92MHz	ISO 18000 2-7

Table 43 Overview ISO Standards RFID Related

Security & Privacy

With common standards (e.g. ISO norms) in place, the rise of security and privacy of the data on RFID tags has risen as well. Three security and privacy threats will be discussed here in order to give an idea of threats which can become reality in practice (Bank 2007 P. 292).

Eavesdropping
RFID tags are designed to transmit stored information to an inquiring reader. The threat is that this function allows unauthorized users to scan tags and obtain the data on a RFID tag.

Spoofing
If no security protocol is used on the RFID tag, attackers can write blank RFID tags with the same formatted data that has been collected earlier. The possibility to write data on a RFID tag replaces product' information and thereby, other data will be used. For example in a shop where a cheaper price will be scanned by the cashier.

Relay attack (i.e. cloning)
Unsecured RFID tag data could be copied to another tag by attackers. The advantage for attacker to have the RFID data is the possibilities with that RFID data. For example, the encrypted code can be copied from one car's license plate to the other in order to obtain 'free' access on an automatic toll payment road.

To protect data on a RFID tag, mostly the use of a password (memory bank 00) or an authentication procedure has to be followed, see paragraph 'Security' in the RFID tag' section.

d) Reader

The third component of a RFID system is the RFID Reader & antenna. The RFID reader (i.e. interrogators) are classified by the EPC as a class 5 device (*Table 40 Classes Source: GS1 US*). Once there is a coupling, i.e. a connection, between the tag and the reader, the tag signals data back to the reader. One can compare this connection with the game tug-of-war, where both devices pull on the rope. Each 'pull on the rope' sends 1 bit of data. The tag strings together a series of these bits to form bytes (consist of 8 bits) of data (Bank 2007). These bytes of data forms the actual data which will be send. Since readers have a power source, they can pull exponentially harder on the tag than the tag can on the reader can. A RFID reader can be divided into two different modules, namely the antenna, i.e. 'High Frequency Interface' and the reader, i.e. 'Control System' (Bank 2007). See *Figure 20 Sub block Reader Diagram, source Bank* 2007 for a schematic overview of a RFID reader.

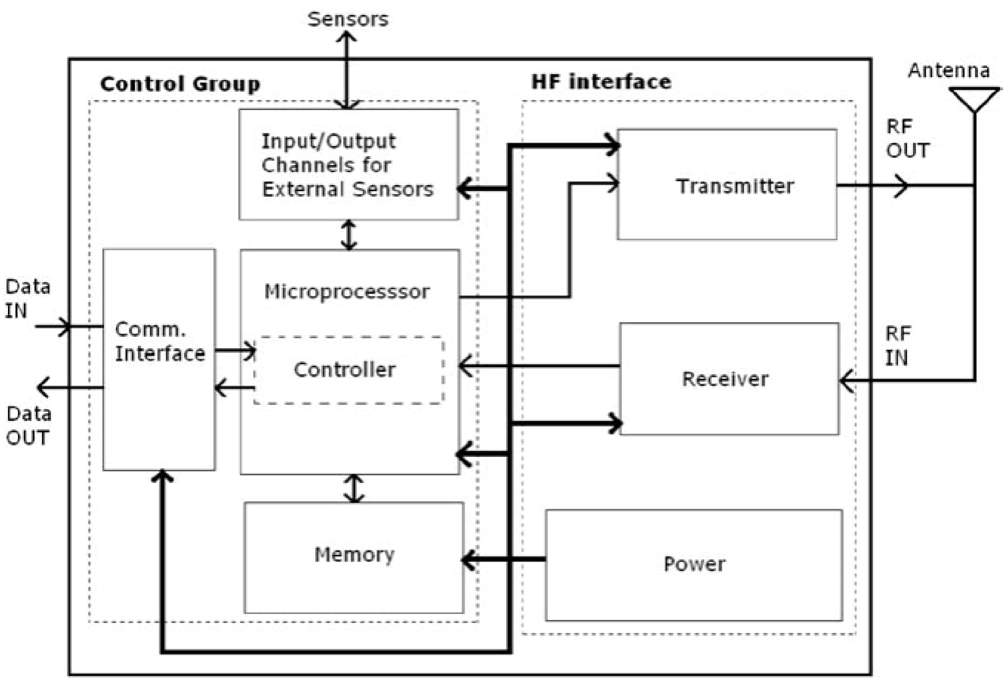


Figure 20 Sub block Reader Diagram, source Bank 2007

High Frequency Interface

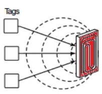
This module performs the function of 1) Demodulating and decoding the date retrieved from the tag and 2) Energizing of RFID tags, in the case of passive and semi-passive tags. Elements of this modules includes the transmitter, the sender of the radio waves, the receiver which receives the signals from the tags and pass them to the microprocessor and the power elements which supplies all adequate power for the whole reader.

Like RFID tag' antennas, RFID reader antennas comes in a wide variety of designs for different purposes. The Squiggle form antenna displayed *in Figure 10 ALN-9440 Squiggle from Alien Technology inlay (source: Bank 2007)* is also used in RFID Reader' antennas, in order to couple with radio waves at any opportunity. These antennas are called orientation-insensitive antennas. Long straight antennas are designed to perform well on flat, directionally sensitive applications like a factory' conveyor belt. The signal from the RFID tag comes from a continue, predetermined direction whereby the reader can locate the tag easily with little preparation. In general, the straighter the antenna, the greater the size of the conductive plane, the greater this plane is, the better the tag' performance i.e. readability. If a tag antenna curves in many directions, only a part of the antenna will be used by the reader since only a part of the radio waves coming from the tag will be 'hit' by the reader. To read passive RFID tags, the RFID reader must be very sensitive in order to recognize the small changes in the magnetic field around the reader' antenna created by the tag's backscattering method (Bank 2007).

Control Group

This modules performs the function of 1) decoding, 2) error checking and 3) communication with an external system, the middleware explained in section '*e) Middleware*'. The 'Control Group' module has to transform the signal coming from the receiver into a understandable binary code which will be used by the microprocessor. The second element is the microprocessor, which follows a predefined protocol (Memory bank 01). The microprocessor receives a digital signal from the receiver and by use of the memory, this element performs also the error checking in the messages. The third element is the memory of the reader which stores the data received from the RFID tags and transmit them to the middleware if demanded. The fourth element, communication interface, is used to interact with an external host system to send and receive the data. The last element of the reader is the input/output channels for external sensors. This element is not always in place because it is only beneficial in specific environments. Its main function is to save energy by shutting down the power element if no tags are in the read range of the reader. This can be performed in a conveyer belt environment where an item passes the reading zone of the reader at a non-simultaneous interval for example.

Tag density



One of the most important characteristic of a RFID reader is the metric that identifies the maximum number of tags that a reader can read in one second. Back in 2007, this tag density was between 50-100 tags for passive tag systems and 50 to 900 tags for active tag systems in one second (Bank 2007). In applications where this metric is too low, a solution could be the deployment of more readers with smaller coverage areas.

Handheld or stationary

Handheld RFID readers are more flexible and come in two main forms: a fully integrated device or a PCMCIA and a SDIO or Compact Flash Card. The fully integrated device is comparable with a Personal Digital Assistant (PDA). Some have the ability to also scan barcodes. The second handheld RFID readers, the interface cards, can plug into PC's or laptops to form a local RFID reader station. Stationary readers are fixed readers and are mostly seen at door and gate entrances and at fixed locations.

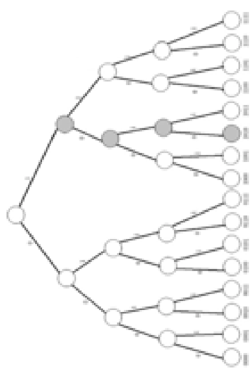
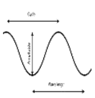


Figure 21 Binary Tree Anti-collision Protocol, Source Bank 2007

Radio Wave Bleeding



In a system where multiple readers are placed on fixed location, the possibility of 'bleeding' arises. Assume a RFID system in a high-rise building. Due to the geographical location of the building, it is possible that a RFID Reader reads a RFID tag from another floor thereby, it is possible that the tag is read by a reader which is in three-dimensional space the closest to the RFID tag. This is not in every situation wanted. It is almost impossible to assign a certain reader to a certain tag, in this case, both on the same floor desired. This 'bleeding of radio waves' can be solved by fixed readers which are searching for specific fixed tags only. A method like 'singulation' can be performed. In this case, the reader is searching for specific tags by its Unique Tag ID by following a tree method. First, the reader is looking for Unique Tag ID's which starts with a 1, following asking for Unique Tag ID's starting with 10, then 101 and following 1010. In this way, a coupling will be established with only the tag wanted.

Like in case of RFID tags, there is no right RFID readers for all environments and therefore, it is advisable to determine the targeted environment and based on the circumstances, select the appropriate RFID reader. Antenna type, communication sequence, the data transmission procedure from the tag to the reader (inductive, backscatter, capacitive) and the frequency are all factors which influences the performance of the RFID reader in an environment and thereby, the performance of the RFID system.

e) Middleware

The data coming from the RFID readers becomes valuable information when this data is used in a broader context: at a business level. The middleware is the component of a RFID system which filters, structures and transmit the raw data to the enterprise systems, like a Warehouse Management System (WMS), an Enterprise Resource Planning (ERP) or a Systeme, Anwendungen und Produkte (SAP) system. The three main tasks of the middleware component are 1) filter all usable data and block excess or duplicated data, 2) transform the RFID data to the right format for further use by other systems and 3) organizing the right information pass through the right application of the enterprise. According Sweeney 2005, a middleware must include a balanced combination of seven so-called core capabilities: Reader and Device Management, Data Management, Application Integration, Partner Integration, Process Management and Application development, Packaged RFID Content and Architecture Scalability and Administration. These seven core capabilities will be explained below.

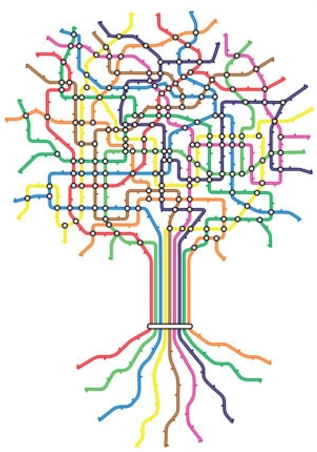


Figure 22 Function RFID Middleware

Reader and Device Management
The RFID middleware needs to allow interaction between users and readers by offering the possibility to configure, deploy and issue commands of readers through a common interface. This first core capability provides this possibility.

Data Management
This capability filter and route the data to the appropriate destination. Both low-level logic (like filtering out duplicated reads) and more complex algorithms (like content-based routing) could be organized by this capability.

Application Integration
This capability offers the possibility to messaging, routing and connecting features required to reliably integrate RFID data into existing enterprise systems, like ERP, WMS and SAP. Ideally, this is done on a Service-Oriented Architectural (SOA) basis which involves either simple data exchange or two more services coordinating some activity, such as inventory control or order placement.

Partner Integration
The RFID middleware should offer the possibility to share RFID data among partners to improve collaborative processes between each other. This Business-to-Business (B2B) integration feature provides, for example, partner profile management, support for B2B transport protocols and integrations of data by Electronic Data Interchange (EDI) or Web-based systems like AS2.

Process Management and Application Development
This capability generates the information needed by multiple applications and enterprises. This means that it 'collects' the right information from the right source to the right RFID data obtained by the reader. An example is inventory replenishment. If the middleware has an actual list of available amount of one product on stock, the inventory level becomes critical if this middleware gets no information from the point-of-sale data. This capability compares the list of inventory level and sales and thereby, holds the inventory at a stable safely level.

Packaged RFID Content
This possibility provides structured information sheets. These sheets can be transformed to product data schemas, routing of products and inventory levels. This information forms the start of optimizations in processes. Output in Excel formants is a common known example.

Architecture scalability and administration
The last capability provides flexibility in the RFID system. This feature dynamically balance processing loads of data across multiple (enterprise) servers and reroute data if such a server fails.

In the RFID system, the part from RFID tag until the RFID reader collects data like the identification of unique Tag ID's. It is from the middleware and on that this data become information for an enterprise system due to assigning a meaning to this data.

f) Enterprise
The last component of an RFID system are the systems on an Enterprise level. Well-known systems like a Warehouse Management System (WMS), an Enterprise Resource Planning (ERP) system and a SAP system are electronic systems each which his own purpose and used by almost every organisation. These system should be benefit from the real time data obtained by a RFID system by optimizing (daily) processes. For the purpose of the research, no more information is given on enterprise systems.

g) The RFID System
With the description of each component in a RFID system, it should be able to get a sense how the system will work in an organisation. An schematic overview of a RFID system is given in *Figure 23 Example of a RFID system Source Yan B. et al. (2012)*. The RFID tag (in this figure named 'Label') is used in order to identify unique products. In every step of the supply chain (from 'Cultivation base' to 'Store' in this figure), the RFID system gets information about the identification and location of individual products. This is communicated by the RFID Middleware to other Enterprise systems (here named: 'Node Enterprise'). With the use of such a system, the enterprise is able to know the location of every single product in their supply chain, offering a possibility to optimize processes.

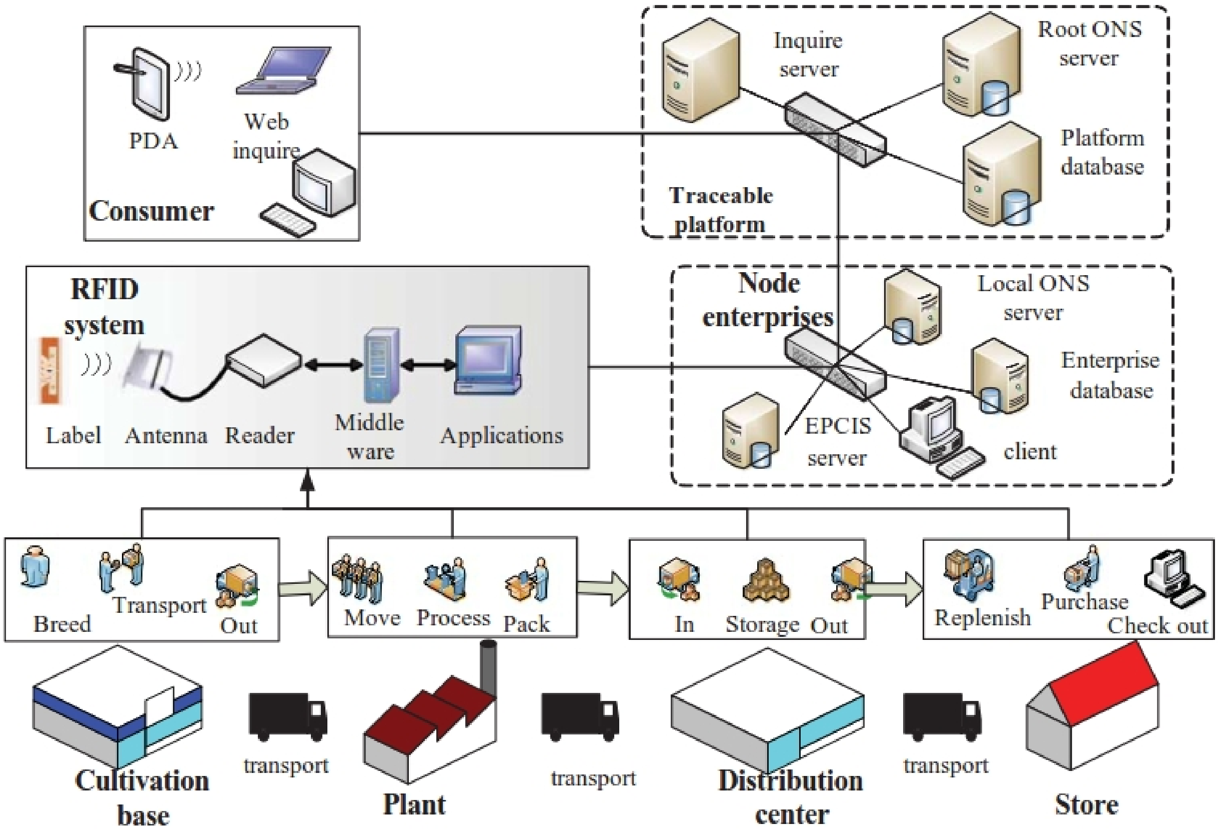


Figure 23 Example of a RFID system Source Yan B. et al. (2012)

References

Papers:

Landt J. (2001) Shrouds of Time - The History of RFID, The Association for Automatic Identification and Data Capture Technologies AIM, (Transcore)

Sun C., Jiang F., Jiang S. (2013) Research on RFID Applications in Construction sector, Journal of networks, vol. 8. no. 5, pp 1221-1228

Tajima M. (2007) Strategic value of RFID in supply chain management. Journal of Purchasing and Supply Management, 13(4), 13. doi: 10.1016/j.pursup.2007.11.001

Yan B., Hu D., & Shi P. (2012) A traceable platform of aquatic foods supply chain based on RFID and EPC Internet of Things. International Journal of RF Technologies, 4, 17.

Ebooks:

Bank J., Pachano M., Thompson L., Hanny D. (2007) RFID Applied, John Wiley & Sons Inc. Ebook

Finkenzeller K. (2010) RFID Handbook - Fundamentals and applications in Contactless Smart Cards, RFID and NFC, Third Edition, John Wiley & Sons Inc. Ebook

Malik A. (2009) RTLS for Dummies, John Wiley & Sons Inc. Ebook

Sweeney J.P. (2005) RFID for Dummies, John Wiley & Sons Inc. Ebook

Appendix C. RFID applications

In this Appendix, a description of applications of RFID systems in other industries is given first, followed by RFID applications in the construction sector in order to give a sense about the possible applications of RFID systems. Both sections ends with an summation of benefits achieved with RFID system applications.

a) RFID applications in other industries

Although RFID is rare in the construction sector, RFID is widely used in multiple other industries for multiple purposes. Erabuild 2006 identified the following industries and areas:

A. Retail Industry	B. Food Industry	C. the US Department of Defence (DOD)
D. Pharmaceutical industry	E. Healthcare Industry	F. Garments – Apparel Industry
G. Parcel and Post	H. Container Logistics	I. Airports
J. Aviation Industry	K. Automotive Industry	L. Libraries and Media
M. Animal detection	N. Asset Management	O. Other areas*

Table 44 RFID applications in other industries, source: Erabuild 2006

*O.: Sport event like 'Vasaloppet', a major ski contest held in Dalarna, Sweden (14.000 skiers participating the main event, 40.000 skiers including all side events). In order to keep track of all skiers and their results, a RFID system (supplied by Championship the Netherlands, in cooperation with IBM) is deployed. Each skier is equipped with a RFID tag, mounted on the leg. If a skier pass one of the nine 'choke points' during the 90 kilometres of track, the RFID tag communicates with the reader and sends its ID. This information is publicized on the internet, time records are set and afterwards, results are accessible via cell phones in form of text messages.

*O: Sport event 'Football World Cup 2006 Germany'. The 3.2 million tickets have contained a RFID tag. Philips was the manufacture of these tags. The FIFA wanted to guard their tickets against forgeries and the black market. Tickets weren't transferable, so the buyer have to attend the game. The RFID tag only contained access information, no personal data. The costs of the RFID tags were estimated at €0,10 each, a total investment of € 320.000,-.

Other applications of RFID in other industry than the construction sector are given below.

Landt 2001 noticed that one of the early, widely adapted RFID systems into public domain was electronic toll collection at highways, 1987 in Norway, and at the Dallas North Turnpike highway in 1989 United States of America. Other applications developed as well, like preventing theft of automobiles, managing traffic, gaining entrance to buildings, automating parking, controlling access of vehicles to gated communities, corporate campuses and airports, dispending goods, ski lift access, tracking library books, animal identification. In 1997, the credit card industry had developed RFID based cards as an alternative to the familiar magnetic strip[6] nowadays known as contactless payment.

A real-case application can also be found in the new T5 terminal of London Heathrow. The baggage handling occurs on a barcode-based system since the BAA (British Airport Authority) did not saw the added value of RFID at the time of design of the project. With its opening, many problems arose with baggage handling and it is questionable afterwards why RFID was not implemented by the BAA since RFID was a successful system in other airports worldwide that day. Ironically, AMEC, an international engineering and service company i.e. the construction contractor of the T5 project, used RFID to manage and track tools on the T5 project site[7] and gained many benefits with this system.

[6] RFID Journal: 'If at First You Don't Succeed', http://www.rfidjournal.com/articles/view?4227, (20-04-16)

[7] RFID Journal: The T5 Debacle, https://www.rfidjournal.com/articles/view?4150, *(20-04-16)*

Bank (2007) found some unique RFID application which will briefly discussed here.

<u>Baja Beach Club Barcelona – injected at the door</u>

A RFID tag implant in the human body (anywhere clubbers want as long as it is able to be read from one meter when passing through the portal or by another RFID reader) give clubbers a new elite status. Clubbers can gain access with the implants to exclusive areas and they can purchase food or beverage by simply waving their hand (the tag) near the proper RFID reader. The purchased amount is simply added to the Customer's tab and is treated like a club card. The system was selected due to its originality, which differentiated Baja from their competitors. It offers more Customer service, better club experience and insights could be obtained in clubbers' behaviour.


Chippen in de Baja Beach Club

Een onderhuids dranktegoed

Figure 24 Newspaper articles Baja Beach Club

<u>Salmon population Colombia River Basin</u>

The population of salmon is of great importance of fisherman, the local industry and ecologists in the region of the Colombia River Basin. Each year, around 2 million salmon receive a RFID tag which holds 64 bits of data. The tags, with a size of approximately 12mm in length, are read by giant antenna (5x5m), attached to RFID readers, located at through-water passage chutes next to powerful turbines. This antenna is able to read hundreds of tags simultaneously, passing by with speeds nearly 100km per hour, at one meter distance. Low-frequency (134 kHz) tags are used in order to be able to read the tags in the water. The investment of US$600 million annually helps the BPA (Bonneville Power Administration) to learn more about the behavioural patterns and migration paths of salmon. As a result, death in the salmon has been reduced by 15 to 20%.

<u>Casino betting chips</u>

In order to learn tendencies of gambles, RFID tags are incorporated in casino betting chips. Data is transferred to a database, evaluated with a table management system which profiles an individual's gambling tendencies and its habits. With this, a casino can know how often someone win and lose, how much money he spend and how often he is playing. The Flamingo Hotel, the Wynn Hotel & Resort and the Hard Rock Hotel & Casino are just a few examples which apply such a system. Besides gamblers' behaviour, the system also evaluate dealer's performance and eliminate counterfeit chips, which is a regular problem in casinos. The RFID chips are providing a strong value proposition to the gaming industry in a variety of ways.

<u>Wild Rivers Waterpark in Southern California</u>

With 40 different attractions, the area of this family water park is huge, easily for children to get distracted and lost from their parents. Each visitor can get an RFID enabled waterproof tag that fits around the wrist by entering the park. At strategic location, readers are used to identify the tags. Touch screens around the park can get access to the last known location of a RFID tag, localizing a missing child near a reader. In 12 months, 27% of the families lost at least one child for a period of time. For this company, it is very important to attain the highest level of Customer service since it is only open 120 days a year. This RFID applications helps to achieve this level of desired Customer service.

An indication about benefits achieved in practice is given below. After this section, an indication of possible RFID applications in the construction sector are given.

Walmart: Reduced inventory levels by 70%, improved service levels from 96% to 99%, reduced administration costs by re-engineering their supply chains (Sarcac 2010). Walmart has reduced 6-7% of supply chain costs, equating to around US$1.4 billion (AMR in Michael 2005) and reduced stock-outs by 16% (Bottani and Rizzi, 2008, by analysis of University of Arkansas in Sarac 2010).

Tesco: Increased sales, a higher customer satisfaction and an education of DVD stock-outs (IDtechEx).

Mark and Spencer: 83% reduction in reading time for each tagged dolly, 15% reduction in shrinkage, a reduction in lead time and also an improvement of inventory management (Wilding and Delgado 2004 in Sarac 2010).

Air Liquide (Gas cylinders company in France): operating and service costs reduction: 500.000 tags payback in ± 1 year (IDtechEx).

China International Marine Containers Group Ltd: eliminated search for wrong positioned containers 4 time per month, eliminated loss of about 8 containers in transit per year, reduced the yard forklift leasing during peak volume by 50%, improved shipping accuracy close to 100%, eliminated 1 hour yard checks per day, eliminated manual record and paper work, ROI within 1 year (IDtechEx)

Norfolk Ocean Terminal: 3% improvement in accuracy (i.e. 3% fewer misrouted shipments) and 39% Time saving (Watson 2007)

Boeing (AeroScout): centralized security and management and improved Quality of Service and reliability of data (IDtechEx)

Department of Defense USA (DOD): in 2007: $115million spend on RFID 2010: $230 million spend suspected 2010: $560 million spend by total Federal USA suspected (Watson 2007), reduce inventory value in Iraq: from $127 million to $70 million, reduce wait time for items: 28 days to 16 days, increase fill rate: 77% to 89%, educe retail backlog: 92.000 to 11.000 orders (Watson 2007) in total, 97% of all pallets are shipped with RFID tags (Tajima 2007).

Port of Rotterdam, the world's largest active RFID installation is implemented in the Port of Rotterdam (Bank 2007 P.349).

To make clear which applications RFID can offer to the construction sector, a description of these applications has been given in the following paragraph.

b) RFID applications in the construction sector

From the paragraph, it became clear that RFID can be used for many different applications in multiple sectors. Jaselskis (1995), Sun (2013) and Valero (2015) investigated possible applications of RFID in the construction sector. They found that RFID can be used for Construction Time & Schedule Management, Construction Quality Management, Building Maintenance, Construction Safety Management, Construction Document Management, Construction Material Management and Construction Waste Management. A brief explanation of each application is described below.

Construction Time & Schedule Management

A RFID system can provide information about the shipment of products, enabling for more accurate logistics and progress during the realization phase. The current time a certain process takes can be used as a benchmark value for optimization processes. Besides, knowing the time spent on locating and tracking tools and equipment can suggest for a different site lay-out. RFID can also be used in case of monitoring of the construction progress.

Construction Quality Management

RFID, with additional sensors, can monitor e.g. temperature fluctuations within concrete pouring and asphalt pavement during its realization and during the maintenance phase. Having real-time information regarding the strength and maturity of these materials can provide optimization of the processes (such as curing rate / optimum concrete strength) and providing information for quality documents. Jaselskis (1995) for example, investigated such a system which can create insights in later discovered quality problems of the in-situ concrete and asphalt. The environmental impact of shipments can be investigated as well. Knowing the exact path a shipment has made offers the potential to optimize the delivery process of multiple suppliers to a project site by increasing the vehicle loading rate or combining shipments, lowering CO_2-emissions and disturbance for the surrounding environment.

Building Maintenance Management

RFID, with additional sensors, can provide information about physical values of the building, e.g. the current climate in-door, the amount of people which are inside a building and the use of sanitary facilities. With this information, rooms and areas can be optimize for the purpose they need. When no one is present in a room, heating, lighting and ventilation is not necessary, nor is cleaning. RFID with additional sensors can also be used to read meters such as industrial liquids, water, gas and electric from a (safe) distance.

Construction Safety Management

For safety purposes, RFID can give usable warnings to workers. For example, RFID can warn workers about a certain harmful material (e.g. asbestos), preventing them for accidental contact. Also, an alert system can give warnings when a worker is too close to a nearby edge. A RFID system can also provide warnings to workers when they are too close to an operating heavy equipment at project sites. In case of a fire in a building, RFID can guide people to the right side of a building, optimizing the escape plan of a facility. In case of underground activities (e.g. tunnelling), RFID can give an overview of the exact position of individual workers and equipment. Thereby, emergency services can see the exact location where someone and something is, in case of calamities. RFID can either be used for door access to give people access to certain restricted areas in a building. RFID can be used to monitor the workers' behaviour as well. In a future application, RFID can store workers' related information such as medical information about a specific person, giving emergency services valuable information about the person' health. Currently, due to privacy reasons this is not applicable.

<u>Construction Documentation Management</u>
RFID can be used to document the products which are used inside a building. Law enforced parties in the food sector to know exactly the point of origin of consumer food. With the increasing concern about the point of origin of products regarding a sustainable environment, it will be a matter of time when governments enforces property owners to know the exact product life cycle of the products used inside a building. RFID can save this type of information locally on a tag. RFID can supports as-built documentation as well, due to the exact known position of materials. At last, RFID tags can contain drawings and related information about a building, informing people during the utilization phase.

<u>Construction Material Management</u>
For construction material management, RFID can identify materials and equipment, reducing the confusion regarding arrivals of ordered supplies and their whereabouts at a project site. Jaselskis (1995) proposed such a RFID system to control the delivery process on site. Automatically identifying products at the entrance gate gives a real-time overview of which products are on site, also giving the possibility for an automatic billing system. RFID can also indicate fraud and theft on-site. The controlling of inventory can be done automatically by use of a RFID system. Buried and hidden materials can be located with a RFID system. Also, the work history of tools and equipment can be saved at attached RFID tags, giving information on-the-spot about inspection, rental dates, owner and responsible person of a specific tool or equipment. RFID offers the possibility to apply Automatic-Guided-Vehicles (AGV) at project sites. These AGV's can be used at (large) storage facilities or as a delivery vehicle to the point-of-use. In this case, RFID tags are used for path 'correctors' for the AGV's, offering also information about the exact location of products throughout the project site.

<u>Construction Waste Management</u>
Tagging materials which will be used for reuse or recycling purposes can minimize illegal dumping materials in nature. Knowing the (last) location of different types of material waste can prevent recycling companies for illegal dumping. Contractors can also update information about waste which is present in a certain building, offering recycling companies the possibility to bid on the waste and later, localize the different type of material waste inside a building.

In summary, RFID can be used for the following purposes in the construction sector:

Application	Purpose
Construction Time and Schedule Management	* Shipment information * Searching information * Information regarding construction progress monitoring
Construction Quality Management	* Physical information of products and elements (temperature, vibration, moisture etc.) * Information regarding shipment' environmental impact
Building Maintenance Management	* Building' physical information (temperature, vibration, moisture) * Information regarding (liquid) meters
Construction Safety Management	* Warning systems: * harmful materials * fall prevention * collision heavy equipment * Information supply in case of a fire * Workers' location * Door access * Information regarding workers' behaviour * Information regarding workers' health on-the-spot
Construction Documentation Management	* Information regarding product life cycle * Information regarding as-built situation * Drawings and documentation regarding a building on-the-spot
Construction Material Management	* Identify & localize unique materials (equipment and persons) * Real-time inventory information * Information regarding buried/hidden materials * Information regarding work history of tools & equipment * Path correctors for Automatic-Guided-Vehicles
Construction Waste Management	* Information regarding the localization of material waste on-site and en-route

Table 45 Applications of RFID in the construction sector

Although there are limited real case scenarios of RFID applications in the construction sector, RFID is subject to some researcher who try to investigated the possible benefits of RFID systems for construction practitioners. Therefore, a summation about multiple researches and outcomes is given below.

Grau et al. (in Li 2016), a Real Time Location System, Material Tracking in construction sector: From 36.8min to 4.56min search time (-88%) Saving: $121,507
Jang and Skibniewski (In Li 2016), a Real Time Location System, Material Tracking in construction industry: Save 64% Labour cost (24 month during construction project)
Song and Eldin (in Li 2016), Real Time Data Management for the estimation of process and to reduce cycle time in construction sector: indicated a delay of 16.3 min in truck cycles, reduced cycle time prediction error with -6%
Shin T et al (2011), RFID, improvement Time Efficiency in construction sector, 32% more efficient operations in Construction Supply Chain Management
Moon and Yang 2010 (in Nasr 2013), RFID for Construction monitoring, concrete pouring activities (data regarding concrete pour amounts, delivery time and time spent by mixer trucks on the road were generated and made available on a Web application)
Chin et al. 2008 (In Nasr 2013), RFID + 4D CAD, monitoring in construction sector, used for erection of structural steel members (This combined approach delivered better logistics and progress management results: 17% more time efficiency)
Hamalainen H. 2008 (In Sun 2013) RFID + Sensors in construction sector, Construction quality monitoring, monitor temperature fluctuations within an identifiable location of placed concrete or asphalt pavement to provide real-time information regarding strength and maturity
Fontelera J. 2005 (In Sun 2013), RFID for Building Maintenance in construction sector, effectively improve maintenance efficiency
Demiralp G. 2012, RFID for material tracking in manufacture / construction sector, significantly improve production efficiency and the largest benefits are from the elimination of missing panels and incorrect shipments

In the retail sector, the following figures should give an indication what impact RFID can have.
Sarac 2010, RFID for inventory management in retail, RFID implementation can reduce the distribution centres inventory level by 23% and completely eliminate backorders, a reduction in order quantity that can reduce the distribution centre inventory level by up to 47%
Keith et al (in Michael 2005), RFID for material handling in retail, check-in time in distribution centres could be reduced by 60-93% yield labour savings of up to 36% in order picking 90% reduction in verification costs for shipping processes

These figures offers no guarantee for similar results in every company. It should also be mentioned that most of the researches are limited by one product in a two-way supply chain environment and thereby, are not investigated with multiple products. Also, some studies are based on analytical models, leaving the dynamics of the construction sector behind. Nevertheless, these figures should give an indication of the potential RFID can offer to the construction sector.

References
Bank J., Pachano M., Thompson L., Hanny D. (2007) RFID Applied, John Wiley & Sons Inc P528 Ebook
Demiralp G., Guven G., Ergen E. (2012) Analysing the benefits of RFID Technology for cost sharing in construction supply chain A case study on prefabricated precast components, Automation in Construction 24
EraBuild (2006) Review of the current state of RFID technology, its use and potential future use in Construction, Report, a Co-operation between 'National Agency for Enterprise and Construction, Tekes, Formas and DTI, pp 100
IDTechEx. (2015). *RFID Knowledge base Sample Case Studies*. Cambridge United Kingdom.
Jaselskis E.J., Anderson M.R., Jahren C.T., Rodriguez Y., Njos S.(1995) 'RFID applications in construction sector', Journal of Construction Engineering Management, Vol. 121 (2)
Landt J. (2001) Shrounds of Time - The History of RFID, The Association for Automatic Identification and Data Capture Technologies (Transcore)
Li H., Chan G., Wong J., Skitmore M.(2016) Real-Time Locating Systems applications in Construction, Automation in Construction 63 (37-47)
Michael K., McCathic L, (2005) The pros and cons in supply chain management, Proceeding of the international Conference on Mobile Business, Copyright IEEE, pp 623-629.
Nasr E., Shehab T., Vlad A. (2013) Tracking Systems in Construction Applications and Comparison, 49th ASC Annual International Conference Proceeding, Associated Schools of Construction
Sarac A., Absi N., Dauzère-Pérès S. (2010) A literature review on the impact of RFID Technologies on Supply Chain Management, International Journal Production Economics 128 (77-95)
Shin T-W., Chin S., Yoon S-W., & Kwon S-W. (2011) A service-oriented integrated information framework for RFID/WSN-based intelligent construction supply chain management. *Automation in Construction, 20*(6), 10. doi: 10.1016/j.autcon.2010.12.002
Sun C., Jiang F., Jiang S. (2013) Research on RFID Applications in Construction sector, Journal of networks, vol. 8. no. 5
Tajima M. (2007) Strategic value of RFID in supply chain management. *Journal of Purchasing and Supply Management, 13*(4), 13. doi: 10.1016/j.pursup.2007.11.001
Valero E., Adan A., Cerrada C.(2015) Evolution of RFID Applications in Construction - A literature review, Sensors 15 (15988-16008
Watson L.S., Miller D.L., Walton C.M., Skinner R.E. (2007) Research Opportunities In Radio Frequency Identification Transportation Application, Transportation Research Board, E-C114

Appendix D. Case Studies (confidential)

In this appendix, the five case studies used in this research will be described. These case studies are selected by the following five criteria from the project portfolio of Heijmans non-residential, see *Paragraph 3.1 The selection of the case studies* on page 17 of the main report.

- **Non-residential construction at Heijmans NV.**
- **A maximum variation sampling**
- **Execution completion after January 2012, no more than 5 projects**
- **Risk factor '3'**
- **Key indicators: - Complex planning in regarding with multiple disciplines, or**
  - Large project site

These case studies will be investigated in order to get knowledge about the daily practice of non-residential construction projects. This knowledge is needed in order to understand if, and why, an added value of a RFID system is favourable in this specific project. Therefore, a description of each project is given in this chapter. First, the project 'Schiphol Lounge 2 Amsterdam' will be described. Hereafter the 'Telecity AMS1 Amsterdam', 'Eurojust The Hague', 'Hart van Zuid Rotterdam' and the 'National Military Museum Soesterberg' case study will be described.

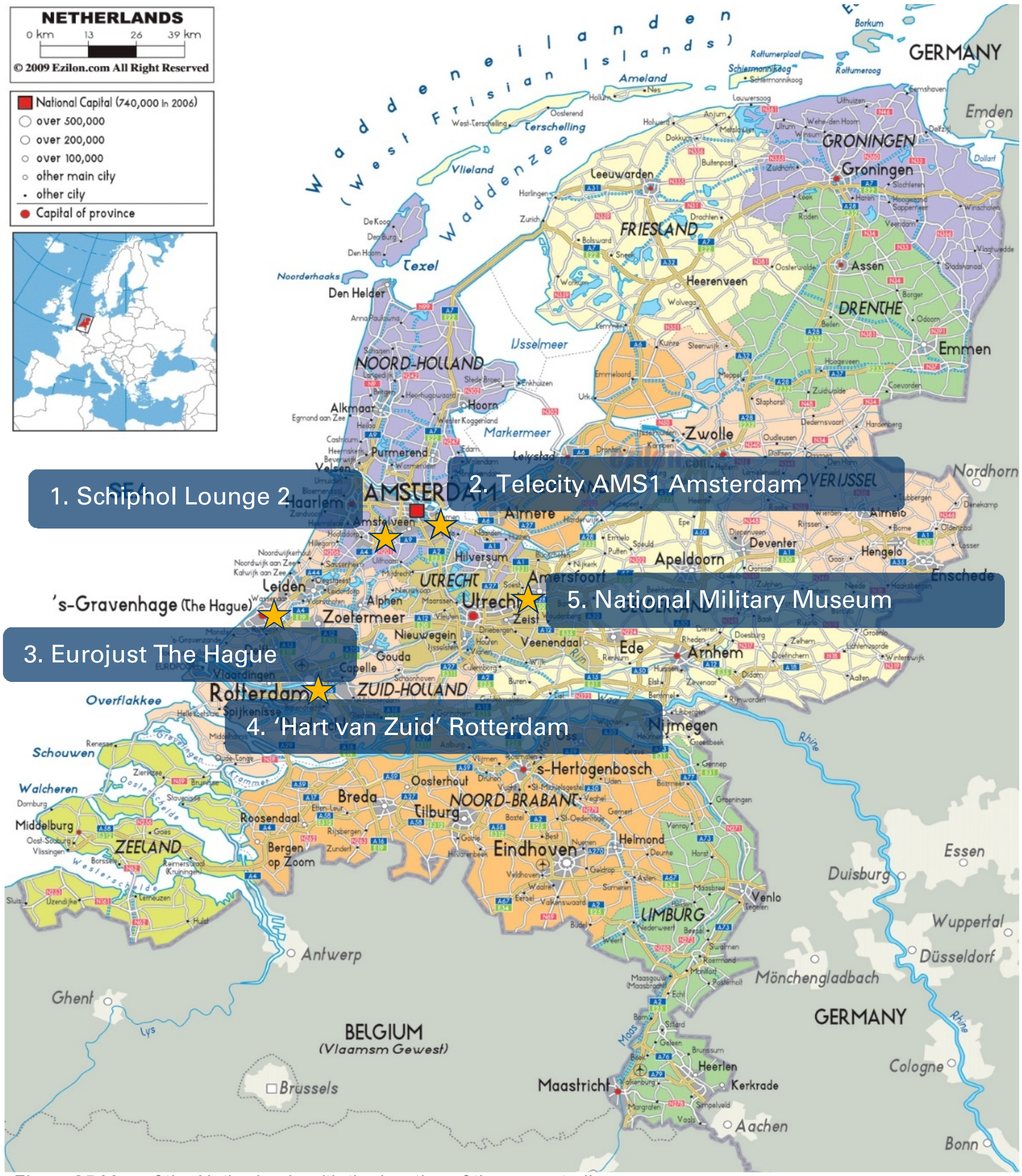


Figure 25 Map of the Netherlands with the location of the case studies

a) Schiphol Lounge 2 Amsterdam, the Netherlands

confidential

confidential

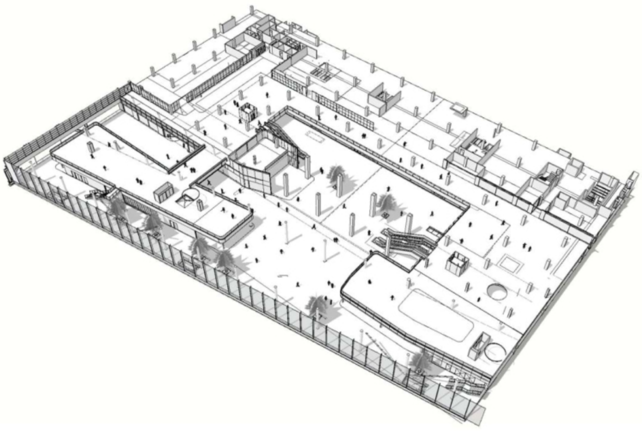


Figure 29 BIM Model Schiphol Lounge 2

Figure 30 Schiphol Lounge 2 Interior 1

Figure 31 Schiphol Lounge 2 Interior 2

Figure 32 Schiphol Lounge 2 Interior 3

b) Telecity AMS 1 Amsterdam, the Netherlands

confidential

confidential

Figure 35 Design Telecity AMS1

c) Eurojust The Hague, the Netherlands

confidential

Figure 37 Direct surrounding Eurojust

confidential

d) Hart van Zuid Rotterdam, the Netherlands

confidential

confidential

Figure 41 Projects for the program 'Hart van Zuid', marked yellow

e) National Military Museum Soesterberg, the Netherlands

confidential

Picture 6 National Military Museum 1

Picture 7 National Military Museum 2

Picture 8 National Military Museum birth eye' viewpoint

Picture 9 National Military Museum 3

confidential

Appendix E. Interview Protocol

In this appendix, the interview protocol which has been used in the expert interviews for research question 2 has been given. The original is Dutch written, so are the comments of the experts. This appendix is a translated version. The main and important thoughts of the experts are used in order to get information from practice (see *paragraph 4.1 Within-case analysis* on page 22 of the main report). This protocol has not be send to the interviewee before the interview took place. It has been handed over at the beginning of each interview. After each interview, answers on the questions below are formulated and this protocol has been send to the interviewee in order to validate the results.

Introduction
Managers of Heijmans Non-Residential believes that current construction logistics is inefficient, resulting in a low labour productivity and waste at project sites. Radio Frequency IDentification (RFID) is pointed out by researchers to lower waste and improve labour productivity during the realization phase of construction projects since it offers jobsite workers the real-time information about the location of construction products. Although RFID is used for many years in multiple sectors (including retail, automotive, aviation, transport) with proven benefits, it has not been used yet in the construction sector. A lack of knowledge and proven benefits has limited the implementation of a new technology where the payback time is unknown for construction contractors. It is too risky to invest without knowing the benefits of it. Since the literature describes only a RFID system for the whole sector, this research is meant to bridge the gap between literature and practice. Since every non-residential construction project differs greatly, different RFID systems are needed in different situation in order to function properly and to provide an added value to the project. The research question is:

'Which RFID system should be applied under which project circumstances in order to obtain the most added value for non-residential construction projects?'

Purpose:
The purpose of this interview is to get insights which of the identified fourteen added values of a RFID system is the most desired one in this non-residential construction project, and why this added value is the most desired one.

Interview Approach:
This expert interview will be a 'semi-structured interview'. This means that only a few predefined questions are noted. This offers the possibility to go deeper or broader on certain aspects / discussions of this interview. Sixty minutes are scheduled for this interview. Afterwards, I will process the results of this conversation and I will send it back to you in order to validate my findings.

Originality / added value of this research
The literature considers only on a RFID system, not considering the composition of a RFID system. It is this composition of components which makes a RFID system applicable in a certain context. Two experts, one of Heijmans and one of a subcontractor of this case study, will be interviewed in order to get to know what the needs from practice are. Based on these needs, RFID systems will be designed. In this way, the promotor of this research (Heijmans non-residential) will get to know under which circumstances which composition of components (the RFID system) should be applied to create a certain added value for non-residential construction projects.

a) Interview protocol – <*Project Name*>

Company:	………………………………	Name:………………………………………
Role in project:	……………………………..	Function:……………………………………
Subject:	Project <*Project Name*>	Function in project:……………..............
Time:	……………………………..	Working experience:……………………
Place:	……………………………..	Education:…………………………………
Date:	……………………………..	
By:	Rens van den Hurk –	Graduate intern construction logistics, University of Twente
Duration:	60 min.	Contract value:……………………….. (*in case of a subcontractor*)

- Short explanation about the purpose of this interview
- Emphasize the time available for the interview (ca. 1hour)

5min introduction of the person

1. From which moment are you involved in this project and has your function been changed?
2. What is your background history (Education, motivations, drivers for work)?
3. How do you explain the role of your company in this project?
   (*in case of a subcontractor)*

Introduction Rens van den Hurk (background, education)
Introduction Master's thesis

Failure costs ± 11%, reduction of labour productivity on site
Characteristics construction sector (1. No serially, 2 unique circumstances, 3. fragmentation)
Additional characteristics: very labour intensive, many laws and regulation, high competitive market, short term vision.
Failure costs: waste at a project site --> lack of proper information and communication between participants

---

10min: The project <*Project Name*> Current situation

4. What makes this project different from other projects?
5. Can you tell me what for consequences this has for the realization or utilization phase?
6. What do you mean with construction logistics?
7. How has the construction logistics been shaped in this project?
8. Has the construction logistics been changed in this project and, if so, why?
9. Who coordinates this construction logistics in practice?

10min: Waste during the execution of projects

10. Do you think that waste take place on this project site, if so, what kind of?
11. Can you give an estimate why these wastes take place?
12. Do you know products or processes to counteract this waste?
13. Do you think that construction logistics can affect this waste?
14. Does everyone have the right information at the right time (related to construction logistics)?

10min: The RFID system

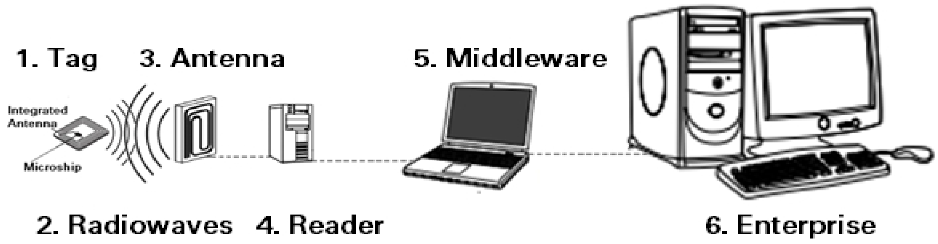


Figure 45 Components of a RFID system

15. Have you ever heard of RFID, if so, can you explain me what it is?
16. What is your opinion about new technologies at a construction project?
17. What do you think the opinion of your colleagues is about new technologies at construction projects?

15min: The added value of RFID

- (Explanation of the 14 added values (Scheme 16 next page)

18. With the circumstances of this project in mind, which added value should be desired in this project and why is this desired?
19. Which added value of the RFID system is the most desired (Scheme 16 next page)?
20. Why is this added value the most desired one?
21. Do you see advantages and disadvantages in such a RFID system?

5-15min: Closure

22. Summary unique project circumstances of this project
23. Summary bottlenecks in the construction logistic in this project
24. Summary added value RFID desired
25. Do you like to be kept informed about the results of this research?
26. Which subcontractor can I approach to hold a similar interview
(the purpose is to achieve a great impact with this RFID system)
(>*in case of employee of Heijmans*<)

---

27. **Checklist:**
O Prioritising Added value p.7, O Subcontractor, O Key Figures (p. 4)

b) Key figures project <*Project Name*>

28. Contract value:

29. Type of contract (mark which applies)*

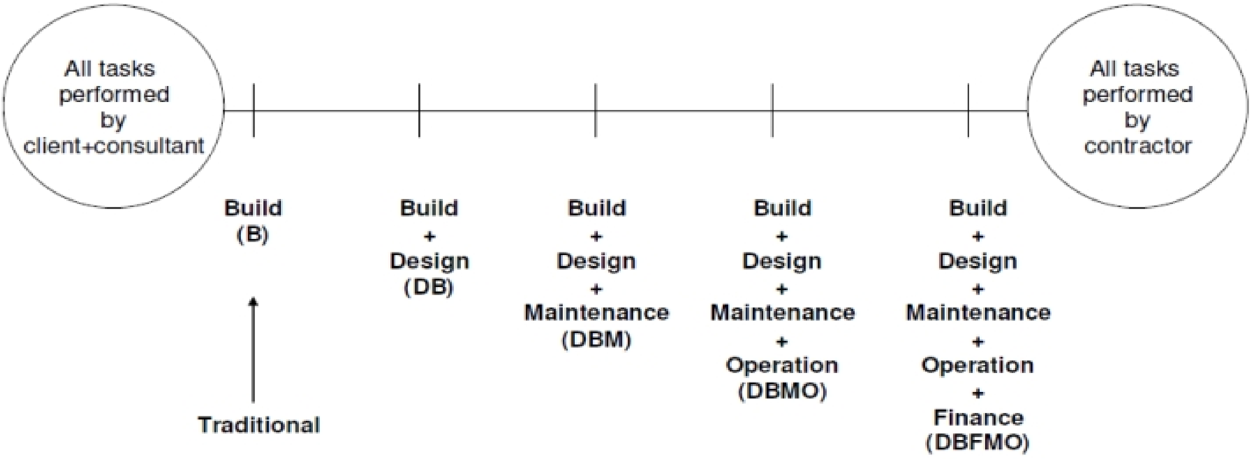


Figure 46 Spectrum of integrated contracts (de ridder 2006)*

* Or else (+ explanation):

30. Construction time:
31. Current phase (according to NEN-2574:1993):

Programme:	1. Initiative 2. Feasibility study 3. Project definition	Design:	4. First sketches 5. Preliminary design 6. Definitive design
Work out:	7. Specification of requirements 8. Pricing	Realization:	9 Preparation 10 Execution 11 Completion

12 Maintain / Operate
13 Demolition

- More specific:……………………………………………………………………………………..

32. Gross Floor area:………………………………
33. Number of levels:………………………………
34. Organogram project:………………………….

Client:……………………………………………

Developer:……………………………………

Architect:………………………………………..

Structural Engineer:…………………………..

MEP Engineer:…………………………………

End user:………………………………………..

Main contractor:………………………………

Additional companies (such as advisor, investor):
…………………………………………

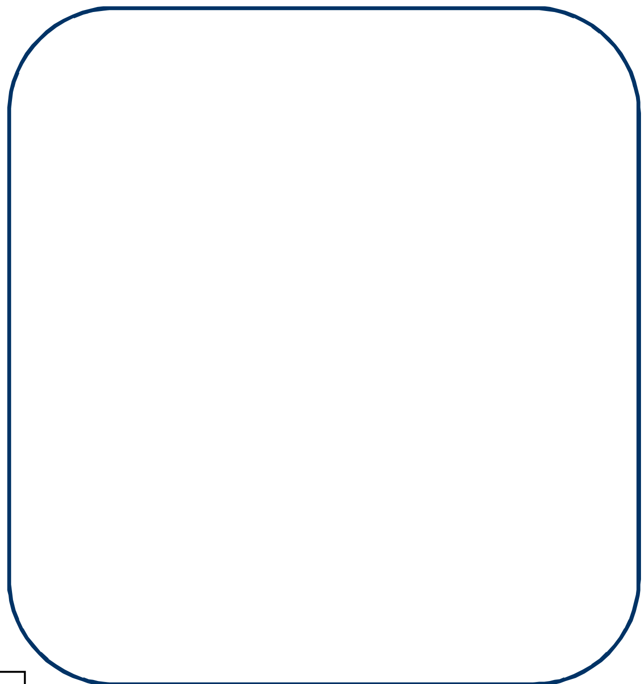


Figure 47 Organogram Project

* Ridder de H. (2006) 'Collaboration and procurement procedures in the civil engineering industry' Delft: Faculteit civiele techniek en geowetenschappen.

35. Global sketch of the project (including gross dimensions L x W x H):

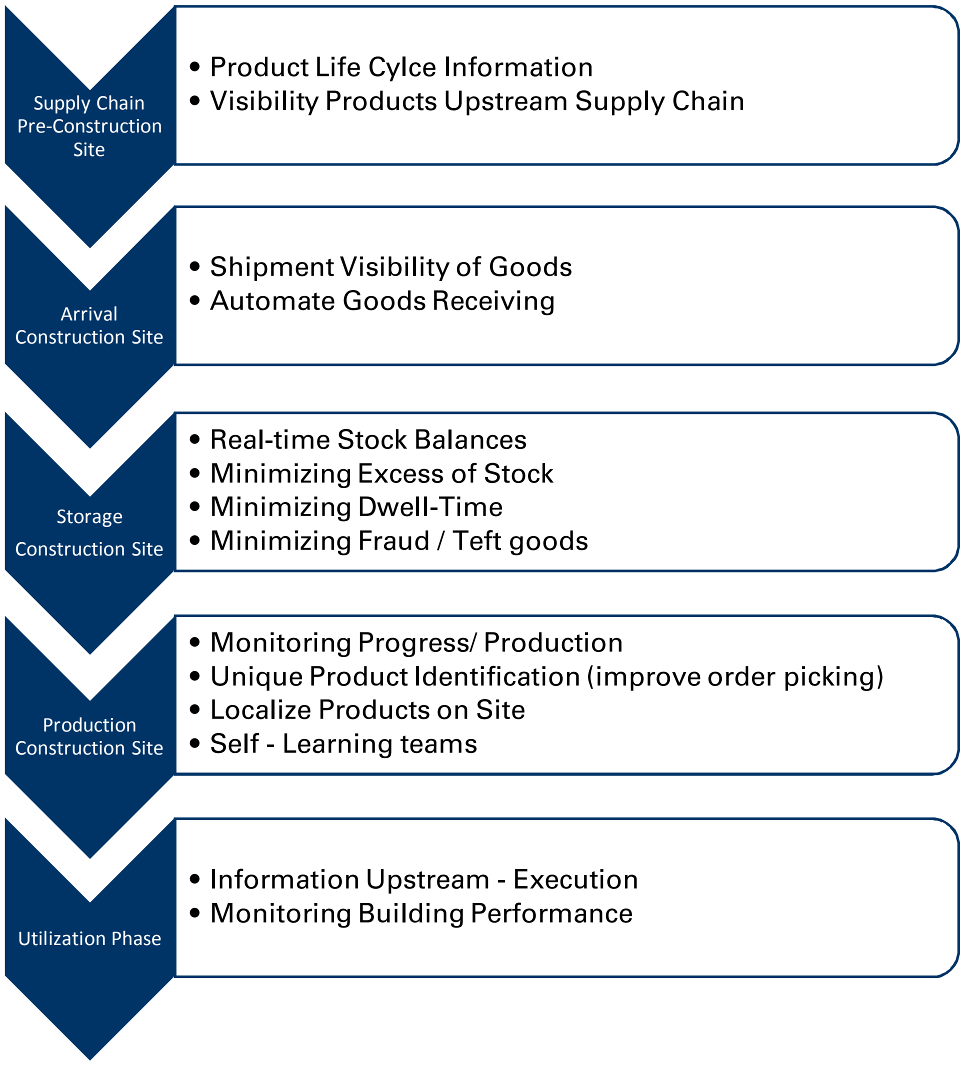
c) Advantages, Disadvantages, Drivers and Barriers RFID System

Advantages	Disadvantages
• Detailed descriptions of all products in construction Supply Chain • Possibility to optimize processes • Flexibility in organization/ solutions • Information available (often at execution / supplier level) • Improvement information sharing • Product Life Cycle information (from upstream to execution) • Supplier's delivery control • Automatic inventory control • Production monitoring + continuity • Minimizing uncertainty regarding current situation in decision making • Improvement in material handling	• Many different sizes, compositions and shapes of frequently changing products and materials • Lack of organized value chain operations • Lack of communication / mutual understanding among different actors in the processes • Immature / limitations of the technology • Extra processes to manage (tagging, ID database, organize information maintenance system) • Saturated (finite) radio spectrum • Fully trusting the technology • More expensive than current systems • Implementation, operating and maintenance costs
Drivers	**Barriers**
• Customer demands for traceability in the future • Lean Construction tools • Safety / security awareness • Demand for more productivity and profitability of construction processes • Just-In-Time deliveries • Extended use of data (decentralized information) • Improve market position / corporate image • Speed/visibility through the supply chain • Demand for quality control • 'Intelligent products / processes' – Internet of Things • Improved worksite security/reduction of shrinkage/theft • decrease manual and routine tasks at project sites • New business opportunities for maintenance services	• Missing coherence between digital systems (industry wide / inter-industry) • Missing standardized processes / data handling • Implementation + maintenance costs • Sluggishness and attitude form involved parties (human factor) • Insufficient implementation efforts • International competition • Development of new advanced technologies (such as LoRa[8]) • Resistance of employees / supply chain partners against new technologies • The absence of real case scenarios / figures • Unclear added value of a RFID system • No dominant actor (a "Walmart" for the construction sector) which stimulates the rest of the sector • Fragmentation in the sector • Privacy / safety concerns • Lack of awareness of the RFID system

Table 47 Advantages, Disadvantages, Drivers and Barriers of a RFID System in the construction sector

[8] LoRa stands for Long Range, it is a wireless telecommunication network for machine-to-machine communication. Due to its long range, low power and thereby long life expectancy, the network is considered to use for Internet-of-Things purposes.

d) Added value of RFID system



Scheme 16 Added Value RFID system at Different Construction Phases
<Project Name>, <Interviewee>, <Role Interviewee in the project>, <Date>

Appendix F. Results interviews (confidential)

In this appendix, a summary of the ten expert interviews of the five case studies will be given. Hereby, one can clearly see the needs from each expert' point of view about the added value of a RFID system for their construction project. In each of the following paragraphs, first the results of the expert of Heijmans will be given (Heijmans is the main contractor in each case studies) followed by a description of his motivation why he assigns a priority to an added value. Hereafter, a summary of the interview with the subcontractor (which is responsible for a smaller part of the project) will be given, also followed by a description of his motivation to assign a priority to an added value. After analysing the outcome of the first interviews and the literature from research question one, extra added values were identified. These are submitted to the same experts and confirmed by them or not (indicated by '*2nd feedback'* in this appendix and in the main report). A detailed description of the line-of-reasoning for each motivation for an added value has been given in *Appendix G Line of Reasoning*. The interviews will be discussed in the following order: Schiphol Lounge 2 Amsterdam, Telecity AMS1 Amsterdam, Eurojust The Hague, 'Hart van Zuid' Rotterdam and at last National Military Museum Soesterberg.

a) Schiphol Lounge 2, Amsterdam, the Netherlands

confidential

confidential

confidential

b) Telecity AMS 1 Amsterdam, the Netherlands

confidential

confidential

confidential

c) Eurojust The Hague, the Netherlands

confidential

confidential

confidential

d) Hart van Zuid Rotterdam, the Netherlands

confidential

confidential

e) National Military Museum Soesterberg, the Netherlands

confidential

confidential

confidential

f) Summary results interview

This table summarizes the motivation of each expert why he assigns a priority to an added value of the RFID system in their project.

Project	Expert	Role in project	Priority Added Value	Motivation
Schiphol Lounge 2	Expert Heijmans	Project leader	1. Localize Products on Site 2. Unique Product Identification *(2nd feedback)* 3. Automate Goods Receiving	1. Small products get lost on this project site 2. A lot of handling with reusable products 3. No control over goods receiving due to security checks of the Customs
	Expert Subcontractor	Project leader Finisher (interior)	1. Localize Products on Site (*2nd feedback*) 2. Unique Product Identification (*2nd feedback*)	1. Many products were delivered on site, Products get lost 2. Difficult to identify products which were delivered
Telecity AMS1	Expert Heijmans	Main site manager	1. Automate Goods Receiving (*2nd feedback*) 2. Localize Products on Site (*2nd feedback*)	1. The receiving person was not always known 2. Products get lost on the project site
	Expert Subcontractor	Project manager – Energy Management Provider	1. Localize Products on Site 2. Automate Goods Receiving (*2nd feedback*)	1. A lot of re-handling of products on storey levels whereby products get lost 2. Multiple different products are delivered in a box or on a pallet, taking time to identify all products
Eurojust The Hague	Expert Heijmans	Project leader & main site manager	1. Information Upstream – Execution 2. Monitoring Building Performance 3. Visibility Products Upstream Supply Chain 4. Shipment Visibility of Goods (*2nd feedback*)	1. Information availability during maintenance phase (fast & easy identification of products) 2. Insights in the performance of a building by sensors during maintenance 3. More control over shipments for a continuous productivity on site 4. Kilometre record for BREEAM
	Expert Subcontractor	Main site manager – Façade	1. Information Upstream – Execution	1. Information availability during maintenance (liability reasons)
Hart van Zuid	Expert Heijmans 1	Integral design manager	1. Shipment Visibility of Goods (Arrival) 2. Information Upstream – Execution (*2nd feedback*) 3. Monitor Building Performances(*2nd feedback*)	1 More control over shipments for a continuous productivity on site 2 Fast & easy identification of products 3 Better match between the use of a room and the installations
	Expert Heijmans 2	Project leader Ahoy & ICC	1. Information Upstream – Execution	1. Information availability during maintenance (fast & easy identification of products)
National Military Museum	Expert Heijmans	Project director	1. Information Upstream – Execution 2. Automate Goods Receiving 3. Storage (in general)	1. Information availability during maintenance (fast & easy identification of products) 2. No control over good receiving due to a lot of storage possibility 3. No control over stock and products on site due to the large storage possibility
	Expert Subcontractor	Project coordinator - Finisher (walls & ceilings)	1. Minimizing Dwell-Time 2. Localize Products on Site 3. Real-time Stock Balances 4. Monitoring Progress / Production 5. Unique Product Identification	1. Products are stored for a long time on site due to the large storage possibility (e.g. prone to damage) 2. Products get lost on the large storage possibility 3. No control over stock and products on site due to the large storage possibility 4. No solid information about jobsite workers' productivity 5. Easy (unique) product identification

Table 48 Overview motivation expert for added value RFID

In the following Appendix (Appendix G), the motivations for the added values (line-of-reasoning) will be further investigated in order to understand why an expert assigns a priority to an added value under specific project circumstances.

Appendix G. Line of Reasoning (confidential)

In this appendix, the line of reasoning for the motivation of the added values will be further investigated. This is an extended explanation of the findings given in *Paragraph 4.2 Cross-case analysis* on page 28 of the main report and of *Appendix F.* The project circumstances of a specific case study results in the motivation of the expert to assign a priority to a certain added value of the RFID system or not. Therefore, in order to determine under which project circumstances which added value is wanted, the motivation for the added values should be understand, see the following line of reasoning from the main report:

Project circumstances --> Motivation --> Added value RFID

One can see from *Table 15 Most important added value of a RFID system* on page 27 of the main report, the eight most important added values are related to four different construction stages:

Construction Phase	Added Value RFID	Relative Score
Utilization Phase	Information Upstream – Execution Monitoring Building Performance	69 points 25 points
Production Phase	Localize Products on Site Unique Product Identification	68 points 36 points
Arrival Phase	Automate Goods Receiving Shipment Visibility of Goods	52 points 25 points
Storage Phase	Minimizing Dwell-time Real-time Stock balances	25 points 24 points

Table 49 Most important added values RFID system related to the construction phases

In this appendix, the line of reasoning why experts assigns a priority to one of these added values will be set out. The focus of this analysis will be on the most important added values and project circumstances related to the added values of Table 49 given above. It have to be clear that this are not all determining project circumstances and desired added values but these are the most relevant project circumstances and added values, assigned by the experts. Throughout this appendix, certain abbreviations will be used in order to refer to a specific added value for a certain expert. The following abbreviation technique will be used:

1.1.2
Project 1
Expert 1
Added value 2

Information Upstream - Execution

confidential

confidential

Monitoring Building Performances

confidential

Localize Products on Site

confidential

confidential

'Unique Product Identification'

confidential

Automate Goods Receiving

confidential

Shipment Visibility of Goods

confidential

Minimizing Dwell-Time

confidential

Real-time Stock Balances

confidential

Appendix H. Interview building management systems

In addition to the applicability of a RFID system in combination with environmental sensors, extra interviews has been scheduled with experts in mechanical installations of Heijmans non-residential construction, HVAC Experst (2016). In current non-residential construction project, the client has most often the requirement to control the installations inside the building or from a distance (often via internet). The Building Management Systems used in buildings can be break-down in the following elements:

Sensors	-	These components measure environmental values on-the-spot
Ad-Hoc control box	-	These boxes collects information from sensors in a certain building section, often one per room
Control Unit	-	These units collects information from the ad-hoc control boxes often placed one per floor level
Administration pc	-	This pc runs the Building Management System and can show every value of each Ad-Hoc control box in a building.

The ad-hoc control boxes can stand-alone, meaning it can be self-regulated. If the ad-hoc control box measures an environmental value, measured by an sensor on-the-spot, outside a pre-defined level (it is too hot, too much CO_2 in the air or too much moister for example), the ad-hoc control box will turn on the installations for that building section in order to bring the values back to its pre-defined level.

The current Building Management Systems can control already a lot of environmental values inside a building, adjustable per room. The added value of a RFID system, in combination with environmental sensors, thereby, looks irrelevant. However, some specific added values of a RFID system has been identified during this interview:

Sensors	-	In the current situation, every single sensor on-the-spot is connected by a wire to the ad-hoc control box, which is wired to the control unit. The added value RFID can have is find in its feature to be wireless. More sensors can be placed more flexible inside the rooms. Since they do not need a connected wire, the presence of a cable tray is no longer needed. Also, the sensors can be replaced and evenly attached on furniture. Therefore, the environment can be measured more accurate and locally (compared to a sensor for a whole room), increasing the quality of the environment and its users. Besides, the wires for each individual, sensor are of great expense for the contractor.

So, the added value of a RFID system in current Building Management Systems can be found in its core feature of to be wireless. The sensors can be placed more flexible, they can be placed more locally and they will drop the cost of wires used in the building. By this, environmental data obtained by the sensors can be transmitted via a RFID system to the ad-hoc control boxes.

Appendix I. The RFID Systems in detail

In this appendix, the four RFID systems (eight subsystems) will be described in detail. The four RFID systems which are described in *Chapter 5 RFID systems for non-residential construction projects* of the main report are:

* Re-use products * Reduce kilometres	Sustainability	* Arrival * Storage	Control
* Off-site * On-site	Productivity	* Information * Sensors	Building Management

SfB classification system

Throughout this appendix, SfB reference codes will be used. The SfB classification system is an international acknowledged classification system for the construction sector and will be used to refer to certain categories of products. A SfB – code is made up by several numbers or letters from multiple tables. A list of referred codes in this appendix is given in the table below. An example is given in *Table 50 Example NL/SfB Code*. NL/SfB code 411-(21)-Fg2-(B3t) means vertical transport of bricks for the outside wall of a university hospital.

NL/SfB			
411	(21)	Fg2	(B3t)
University Hospitals	outside wall	Bricks (F = non-fried artificial stones, g2 = baked clay	Vertical transport by a tower crane

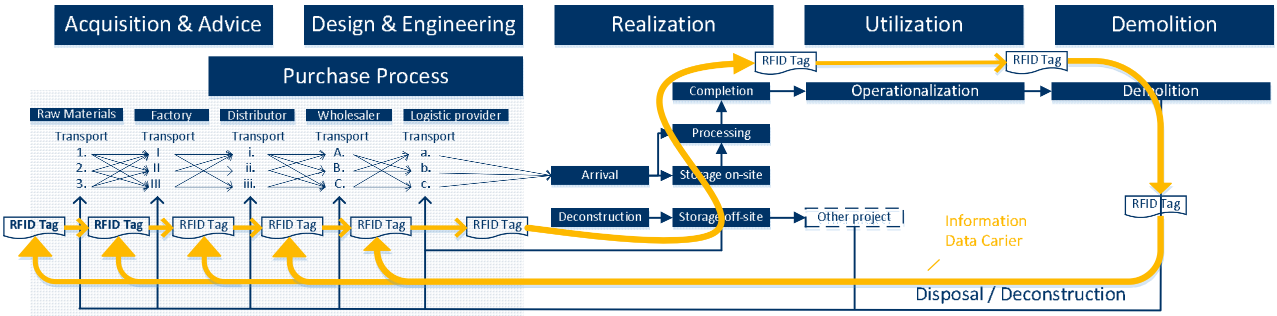
Table 50 Example NL/SfB Code

Table	Number / letter	
Table: 0 The environment of the building	3. Administrative, commercial and protected properties 4. Health and social properties	5. Recreation properties 7. Educational, science and information properties
Table: 1 The functional components of the building	1. Foundations 2. Structural work 3. Outfitting elements 4. Finishing elements 5. Mechanical installations	6. Electrical installations 7. Fixed assets 8. Movable assets 9. Terrain
Table: 2 The constructional components of the building	B. Strut and demolition C. Earthwork D. Piling E. Concrete (in-situ) F. Brickwork G. (huge) Prefabricated elements for substructure and superstructure H. Structures for beams and profiles I. Ductwork J. Meshwork K. Insulation (Heat + Sound) L. Lane shaped roofing M. Sheet (Metal)	N. Overlapping structures (corrugated, roof tiles, slates) O. Reserved P. Stucco Q. Reserved R. Stiff structures (without overlapping) S. Tiles T. Lane shaped structures (other than L.) U. Reserved V. Paint & Protection work W. Landscaping X. Structures for prefabricated elements (other than G. and H.)
Table: 3 The construction materials to be used	**Composite raw materials** a. Unmixed composite materials b. Reserved c. Reserved d. Reserved **Solid form raw materials** e. Natural stone f. Non-fried artificial stone g. Clay h. Metal i. Wood j. Organic materials k. Reserved l. Reserved m. Inorganic materials n. Plastics, Rubbers	o. Glass **Formless commodities** p. Fillers q. Lime and cement, binders, mortars r. Clay, plaster, magnesium and synthetic binder s. Bitumen **Raw materials to function** t Fasteners, add fillings u Protection and property-affecting materials v Paintings w Excipients x Reserved y Composites z Substances
Table: 4 The organisation of the construction project	A6r receiving orders, order procedures, processing of procedures for orders A6s Inventory Management A6t Distribution A6u Delivery / receiving B3. Transportation equipment (Project site)	B4k Equipment for storage and transport of bulk B4m Equipment for storage / transport not B4k D3. Transportation (Construction activity) T5. Adaptability in terms of usage (Fitness for use) T6. Consumption, waste, storage (Fitness for use)

Table 51 SfB (2005) codes of products code used in this chapter

a) RFID System 'Sustainability'

In case of the RFID system sustainability, there is an increasing need to have information about the origin and composition of products and to get insights in the amount of kilometres spent by the suppliers. The underlying reasons for this is to encourage the re-usability of products in new projects in order to minimize the use of new raw materials and to reduce the nuisance of trucks to its environment. This nuisance is created by noise and emission pollution, traffic jams and unsafe situations on the streets, all created by trucks. In order to obtain such kind of information, two type of RFID systems are proposed for 1) *Re-use of products* and 2) *Reduce the amount of kilometres* by suppliers' trucks. The following scheme shows the implementation of this RFID system in practice schematically.



Scheme 17 Flow chart 'Sustainability'

Requirements RFID system 'Sustainability'

The general and technical requirements of this RFID system are given in de table below. The technical requirements are determined by use of the literature analysis and interviews with Flederus M. 2016 and Geertsema 2016.

System	Added value (Expert based)	General requirement RFID system	Technical Requirement RFID system	Current wastes
Re-use products	Unique Product Identification Overall priority experts: 36	Products must be made identifiable on the project site and between project sites for re-use purposes	Information (on-tag): EPC, product name, project name, origin, date, composition, manufacturer, static and product Life Cycle information Security on-tag: encrypt Read distance: 3m handheld reader, Read Amount: single piece (handheld reader) Products: NL-SfB 2005: Table 0: 3, 4, 5, 7 Table 1: 2, 3, 4(not 41 & 42), 5, 6, 7, 8, 9 Table 2: C, D, E, F, G, H, I, J, K, L, M, N, O, Q, R, S, T, U, X Table 3: a, b, c, d, e, f, g, h, i, j, k, l, m, o, p, q, r, s, t7 Table 4: B3, D3, T5, T6	The handling of recyclable products is currently only agreed in the agreements between companies. However, many of these intended recyclable products inside buildings are difficult to identify for these handling purposes (demolition, transportation, storage, transportation and processing of the products) since these product often do not have an identification number to refer to once they are processed. Therefore, it is hard to obtain unique product' information once a products has been processed into a building
Reduce kilometres	Shipment Visibility of Goods Overall priority experts: 25	Give insight in the route a certain products has made, starting with the last-mile transportation to the project site. Give insights in which products were delivered in which shipments since multiple products can be delivered in a single shipment.	Time: read at construction arrival Information: (on-tag): EPC (on-network): the route of the last-mile from loading at supplier until unloading at the project site, product name + shipment nr. Read Amount: bulk reading Read distance: 6meter fixed readers Products: NL-SfB 2005: Table 0: 3, 4, 5, 7 Table 1: 1, 2, 3, 4, 5, 6, 7, 8, 9 Table 2: B, C, D, E, F, G, H, I, J, K, L, M, N, O, P, Q, R, S, T, U, V, W, X, Y, Z Table 3: a, b, c, d, e, f, g, h, i, j, k, l, m, o, p, q, r, s, t, u, v, w, x, y, Table 4: B3, D3, T5, T6	Since the main contractor outsource many of its activities, and every subcontractor outsource parts of his activities, the execution process is very fragmented. With the focus on the outcome, the main contractor does have limited control over the movements of products by the subcontractors. In order to minimize the amount of kilometres driven for a project, thereby, starts with insights in the amount of kilometres at this moment. However, it is currently hard to obtain reliable information.

Table 52 Requirements of the RFID system 'Sustainability'

RFID system 'Sustainability'

The two different systems will need different components. Especially the readers will differ from each other, indicated in the table below.

Re-use products	Reduce kilometres
RFID Tag	
Passive / semi-passive / active: Passive RFID tag, no energy supply plan needed Memory: User Memory (bank 11). EPC (bank 01 'Protocol') needed for reference between multiple companies / sectors worldwide Type of memory: Read-Write Class: 2 GS1 (Passive read-write tags) Security: By password (4digits) Frequency: UHF (longest read range, fast data rate, small) Antenna type: Linear-type (electric component of the electromagnetic field: radiative) Substances: RFID label Tag level: Solid products: product level, non-solid products: truck level Tag place: Solid products: edge of plate, surface of pipes, near original barcode, Cable tie Bulk material: truck level Non-solid products: truck level Attention: presence of steel (Meshes, installation components) Example: Alien 9640 Squiggle	Passive / semi-passive / active: Passive tag no energy supply plan needed Memory: EPC (bank 01 'Protocol') needed for reference between multiple companies / sectors worldwide Type of memory: Read-Only Class: 0 GS1 (Passive read-only tags) Security: Not needed (only EPC code) Frequency: UHF (longest read range, fast data rate, small) Antenna type: Linear-type (electric component of the electromagnetic field: radiative) Substances: RFID Label Tag level: Solid products: Product level Non-solid products: truck level Tag place: Solid products: near barcode / information sticker Non-solid products: truck level Risk: presence of steel (Meshes, installation components, metal sheets) Example: Alien 9740 Squiggle
Frequency	
Frequency: 860-960 MHz. Coupling method: Backscatter Regulation: Global	Frequency: 865.6 – 867.6 MHz Coupling method: Backscatter Regulation: EU
Reader + antenna	
Handheld / mobile / fixed-location: Handheld Type or Reader: read-write Handheld Power: 2Watt (European regulation) Antenna type: Circular Scanner: RFID tag + Barcode (1D) for visible reference Connection: WLAN / WWAN Security: encryption Example: uGrokit Smartphone reader,	Handheld / mobile / fixed-location: Fixed-location + Fixed antennas + additional Handheld reader, Type or Reader: Read Only reader (project site) Read-Only readers (loading docks supplier) Power: 2Watt (European regulation) Antenna type: Linearly Polarised Scanner: RFID tag + Barcode Connection: WLAN / WWAN Security: encryption Example: Laird S9025PL Antenna, Speedway R420 Fixed Reader, uGrokit Smartphone reader,

Table 53 Components of the RFID system 'Sustainability'

Re-use of products

This RFID system is focussed on the re-use of products on site or the re-use of products between sites. Therefore, the information exchange becomes of primary importance. Product identification becomes problematic after the realization phase due to the missing reference code (e.g. barcode). One have to know the composition of products, the origin of its composed materials and fabrication date, in order to determine the re-usability of products inside buildings. Since products are made of raw materials all around the world, for example see *Figure 52 Global supply chain (Harrison A. 2008)*, the system must be an open-loop system, meaning, every actor around the world should be able to add and obtain information on and from the tag. This is supported by, Olsen 2000 (p. 118) who is proposing for a model about the information exchange between actors in the horizontal supply chain (called material supply chain i.e. the material life cycle) and the vertical supply chain (the construction value chain i.e. the project life cycle), given in *Figure 53 Information exchange between multiple chains, based on Olsen 2000*. All relevant information of products should be stored on the RFID tags in order to not loose information in (online)databases and between multiple chains. Hereby, the tag becomes a data carrier.

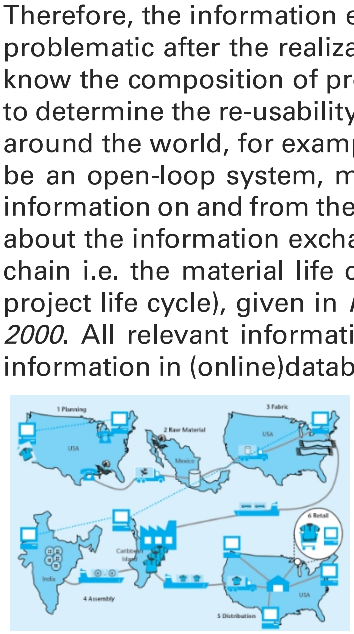


Figure 52 Global supply chain (Harrison A. 2008)

Ideally, this is done on a source-tagging basis: the manufacture of a product should attach a RFID tag to his product. This is also the actor in the supply chain who is owner of the current EAN numbers (barcodes) and can therefore easily obtain EPC numbers from GS1. In case of the re-use of already used products inside a building, RFID tags should be attached to products in order to provide the products with information.

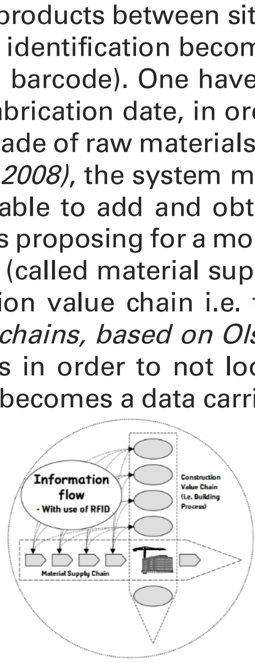


Figure 53 Information exchange between multiple chains, based on Olsen 2000

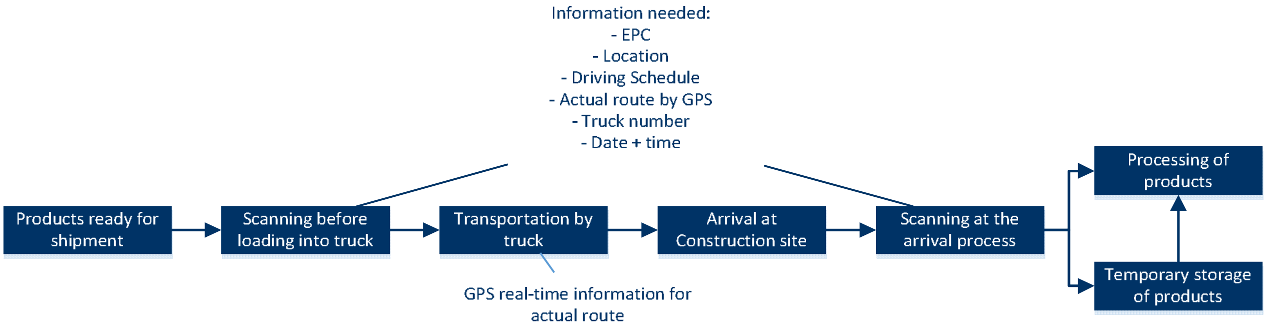
Harrison A., Hoek van R. (2008) 'Logistics Management and Strategy - Competing Through the Supply Chain', Third Edition, Prentice Hall - Financial Times

Olsson F. (2000) 'Supply Chain Management in the Construction sector - Opportunity or Utopia', Lund University Sweden Thesis

Reduce kilometres

In order to reduce the amount of kilometres spend in the construction supply chain, one have to know the actual amount of kilometres spent in the supply chain. Since all companies are operating each in a very specific domain of the construction supply chain, the sector is found to be very fragmented. Currently, it is hard to know for the main contractor where the resources of a manufacturer are coming from and in what route they have passed through the material supply chain. Therefore, information about these routes should function as a footprint for minimizing the amount of kilometres spend by trucks. The level of nuisance to the environment, starting with information about the 'last-mile' transport and elaborate upstream the supply chain over time can also be indicated. The RFID system proposed for is visualised by process steps in *Scheme 18 Process steps RFID subsystem 'reduce kilometres'*. Since the only information on the RFID tags should be the EPC code, a vast collaboration and information exchange between multiple companies in the supply chain is needed. Some examples of gate readers are given in *Figure 54 Examples of Fixed RFID readers at the gate entrance*.

Figure 54 Examples of Fixed RFID readers at the gate entrance



Scheme 18 Process steps RFID subsystem 'reduce kilometres'

Notes

Although these two systems will provide a wealth of information for sustainability purposes, the system will be confronted with some practical limitations in the sector. The first subsystem (re-use of products), information on the tag should be secured in order to prevent unauthorized persons / companies to add, change or delete information on the tags. Agreements have to be made in the total material supply chain. However, since this material supply chain is complex, fragmented and exist of multiple companies and sectors worldwide, it will be very complicated to implement such a system. Although such product life cycle information is very desirable for sustainability purposes, it will take a long time to adopt such a system. Also, the tag-level becomes of important since many products in the construction sector will be cut, sawn or chop into pieces, especially for outfitting and finishing products (table 1: category 3 and 4 of the SfB classification). In an ideal situation, every product in a building is provided with an RFID tag, in practice this will be impossible. One have to decide which specific products, and how many, he wants to identify since it is not worthwhile (or even possible) to provide all single products with an RFID tag because products will be edited in size and composition and many will be transported in bulk, making it hard to tag on a product-level basis. Finished products which will not have to be edited for further purposes are considered to be worthwhile to provide with a passive tag. However, making already processed products in buildings identifiable will have a great impact on the resources used in the sector since most of the construction projects are renovation or transformation projects instead of new construction. Unfortunately, obtaining information about the origin and composition of products can be an exhausting process since the source is not always known. The added value 'Unique Product Identification' is ranked as fourth most important added value by the experts. However, this is mainly ranked for material handling purposes, not for sustainability purposes (see *Paragraph b) RFID System 'Productivity'*). On the other side, this added value could have a great impact on sustainability programs for Heijmans in the future. An indication about the cost and benefit factors is given in the table next.

Costs	Benefits
Fixed: fixed RFID gate readers (with additional handheld readers) Fixed reader + antennas on site Computer / servers Wireless Access Points / repeaters Personnel costs (like training) Installation service costs (set-up) System integration (adjustment of current enterprise software system) Business process reengineering Software costs (like middleware, database and interface system, maintenance, licence costs and company data interchange systems) A standard information lay-out have to be developed / followed by every actor world wide Flexible: Number of passive tags Attachment of tags to products Manage the information on products	Information about a product' composition and its origin all-times available anytime Unique product related information instead of information on SKU-level New business opportunities (like selling the system as a product /service for interested parties) Future-proof-application for 'raw materials passport' (which can be forced by the government in the nearby future) and a 'circular economy'. Transparency in the total material supply chain Proof of sustainability use of products Great impact / support for sustainability programs in the future for Heijmans

Table 54 Cost & Benefits aspect RFID subsystem 're-use products'

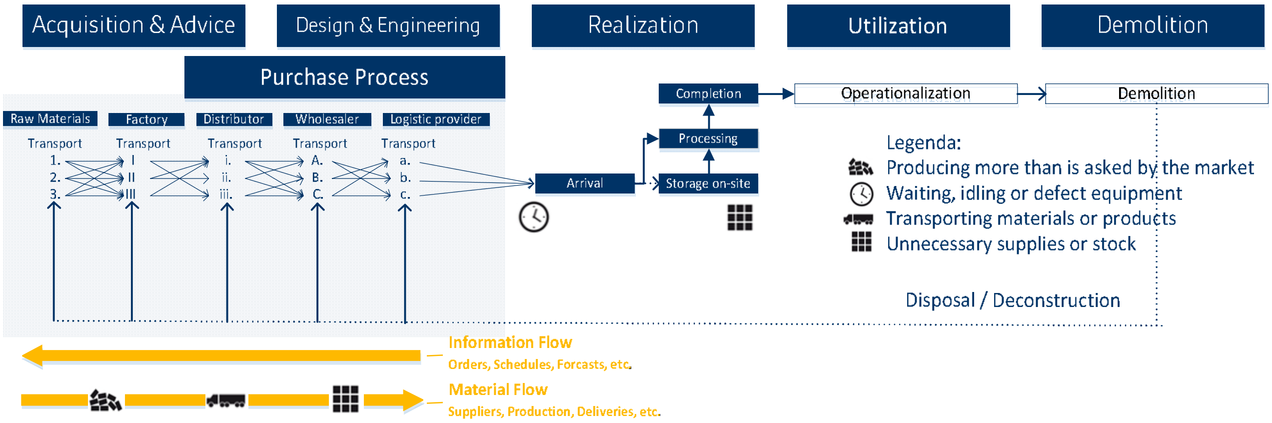
In case of obtaining information about the kilometres driven by suppliers, a collaborative partnership should be evolved with mutual interests: reducing the amount of kilometres. Currently, there will be made an estimation about the amount of shipments needed for a project. The actual driven kilometres is hard to prove since such information has not been record so far. RFID can be a tool to provide such information automatically, offering the possibility to extend the system for handling purposes (see *paragraph 5.3 RFID System 'Control'* of the main report). The supply chain becomes transparent, minimizing uncertainty in the delivery process and offering the opportunity to improve processes between companies. Evenly, one can obtain automatically a Proof-of-Delivery note. The last-mile transportation will be improved with such a system. This will in turn decrease the amount of wrong deliveries, which will also decrease the amount of kilometres spend by trucks. However, the presence of steel in trucks can limited the readability of the RFID tags by fixed RFID gate readers at the project site. Special attention is needed here, based on the design of the truck and its steel components. This added value is ranked as 7th most important by the experts from the case studies.

Costs	Benefits
Fixed: fixed RFID gate readers (with additional handheld readers) Computer / servers Wireless Access Points / repeaters Personnel costs (like training) Installation service costs (set-up) System integration (adjustment of current enterprise software system) Business process reengineering Software costs (like middleware, database and interface system, maintenance, licence costs and company data interchange systems) A standard information lay-out have to be developed / followed by every actor GPS sensor on trucks (+ data interchange with tag) Data interchange between companies Flexible: Number of passive tags Attachment of tags to products	Information about actual kilometres spend for a project / product Reduce amount of kilometres by trucks (lowering transportation costs, noise and emission pollution, traffic jams and unsafe situations on the streets. Future proof (offering benchmark values for reducing the the amount of kilometres, possibly asked in future sustainability programs Improvement in the delivery process Automatically generated Proof-of-Delivery note Decrease the (manual) control checks at the project site Better and more detailed insights (measured) on actual process performances Insights on a fact-based instead of assumptions.

Table 55 Cost & Benefits aspect RFID subsystem 'reduce kilometres'

b) RFID System 'Productivity'

In this paragraph, the RFID system '*Productivity'* will be explained. Experts do have a need for more control over the delivery process when the continuity of jobsite workers is jeopardized. In such a situation, every time delay will have a direct effect on following subcontractors and so, on the total project schedule. For this RFID system, two different subsystems are proposed for since there are two different kind of information needed. These two subsystems are explained below. The following scheme makes clear the focus of this RFID system by symbolizing the wastes with icons.



Scheme 19 Flow chart 'Productivity'

Requirements of a RFID system 'Productivity'

In the table below, the general and technical requirements of this RFID system are mentioned. The technical requirements are determined by use of the literature review and interviews with Flederus M. 2016 and Geertsema 2016.

System	Added value (Expert based)	General requirement RFID system	Technical Requirement RFID system	Current wastes
Off-site	Shipment Visibility of Goods Overall priority experts: 25 Visibility Products Upstream Supply Chain Overall priority experts: 12	Get insights in the logistic processes of needed products of subcontractors and logistic service providers. Get insights from the site office in the production processes of needed products from manufacturers and distributors.	Time: information per end manufacturing process. See information on a computer updated via an internet connection Read amount: bulk reading Range: 8m (fixed) 3m (handheld) Information: (on-tag) EPC (on-network) product name + current location + shipment number + suspected delivery date + current process completion day process Products: NL-SfB 2005: Table 0: 3, 4, 5, 7 Table 1: 3, 4, 5, 6, 7, 8, 9 Table 2: C, D, E, G, H, R, X Table 3: o, q Table 4: A6r, A6s, A6t, A6u, B3, B4k, B4m, D3	Since the supply of products is often outsourced to subcontractors or logistic service providers, there is a limited control in a timely arrival of products on site. This control is needed in the deliveries of the products which will be directly processed into the building and not temporary stored at the project site.
On-site	Real-Time Stock Balances Overall priority experts: 24 Monitoring Progress / Production Overall priority experts: 11	Give automatically a signal when certain products on stock falls below a pre-defined threshold Calculate the productivity of certain crews, based on the time difference between arrival of products and the processing of products.	Time: productivity calculation on a daily basis Time: Signal stock storage in real-time Information (on-tag): EPC product name (on-network) EPC + responsible company + responsible crew + delivery date Security: encrypt connection with the server Products: NL-SfB 2005: Table 0: 3, 4, 5, 7 Table 1: 3, 4, 5, 6, 7, 8, 9 Table 2: F, I, J, K, L, M, N, O, P, Q, R, S, T, U, V, W Table 3: o, q Table 4: A6r, A6s, A6t, A6u, B3, B4k, B4m, D3	It is hard to get insights in the productivity of jobsite workers in these kind of products due to the many movements of many different materials on site.

Table 56 Requirements of the RFID system 'Productivity'

RFID system 'Productivity'

The two different RFID systems results in different components, indicated in the table next.

Off-site	On-site
RFID Tag	
Passive / semi-passive / active: Passive RFID tag, no energy supply plan needed Memory: User Memory (bank 11), EPC (bank 01 'Protocol') Type of memory: Write Once Read Many (WORM) Class: 1 GS1 (passive WORM tags) Security: By password (4digits) Frequency: UHF (Fast data rate and read range) Antenna type: Linear-type (electric component of the electromagnetic field: radiative) Substances: Label or hard-case tag Tag level: Product level Tag place: next to barcode location or inside products Attention: presence of steel Example: SMARTRAC R6 DogBone	Passive / semi-passive / active: Passive RFID tag, No energy supply plan needed Memory: EPC (bank 01 'Protocol') Type of memory: Read-Only Class: 0 GS1 (Read-only passive RFID tag) Security: Not needed (only EPC code) Frequency: UHF (Cheapest, fast data rate and read range) Antenna type: Linear-type (electric component of the electromagnetic field: radiative) Substances: Hard-case tag Tag level: Product level Tag place: next to barcode location Attention: presence of steel Example: Alien 9740 Squiggle
Frequency	
Frequency: 865.6 – 867.6 MHz Coupling method: Backscatter Regulation: EU	Frequency: 865.6 – 867.6 MHz Coupling method: Backscatter Regulation: EU
Reader + antenna	
Handheld / mobile / fixed-location: Fixed readers + antennas at conveyer belts / dock doors / inside trucks Type or Reader: Read Write reader Power: 2Watt (European regulation) Antenna type: Linearly Polarised Scanner: RFID tag + Barcode (1D) for visible reference Connection: WLAN / WWAN Security: encryption Example: ThingMagic M6 Fixed reader, RFMAX DCE9028 Antenna	Handheld / mobile / fixed-location: Fixed-location + multiple antennas Type or Reader: Read Only reader Power: 2Watt (European regulation) Antenna type: Circular Scanner: RFID tag Connection: WLAN / WWAN Security: encryption Example: Invengo XC-RF807 Fixed Reader, Laird S9025PR Antenna

Table 57 Components of the RFID system 'Productivity'

<u>Off-site</u>

Once downstream (the project site) does have real-time information about the status of certain processes upstream (manufacturers, distribution, warehouses or logistic service providers), the execution team on-site can anticipate on time delays in the delivery process. The information about the location and thereby, a manufacturing process, can be shared via RFID and the internet automatically. The status of certain processes can be updated once a product passes a choke point (a physical location that will be passed through by all products) inside factories or at companies. The signal should be updated in the software system, synchronized between partners in the material supply chain. Hereby, it becomes visible downstream if a product is still in its manufacturing process, if it is stored at a distribution or warehouse centre, if the product (i.e. delivery) is ready for the 'last-mile' and even, where this 'last-mile' is located (e.g. in a traffic jam, waiting for an open bridge or around the corner of the project site). Since many logistic service providers do have an in-build localization system on their trucks (commonly via GPS), the location of specific products becomes known since the unique EPC can be linked the specific truck number when the products are loaded into the truck.

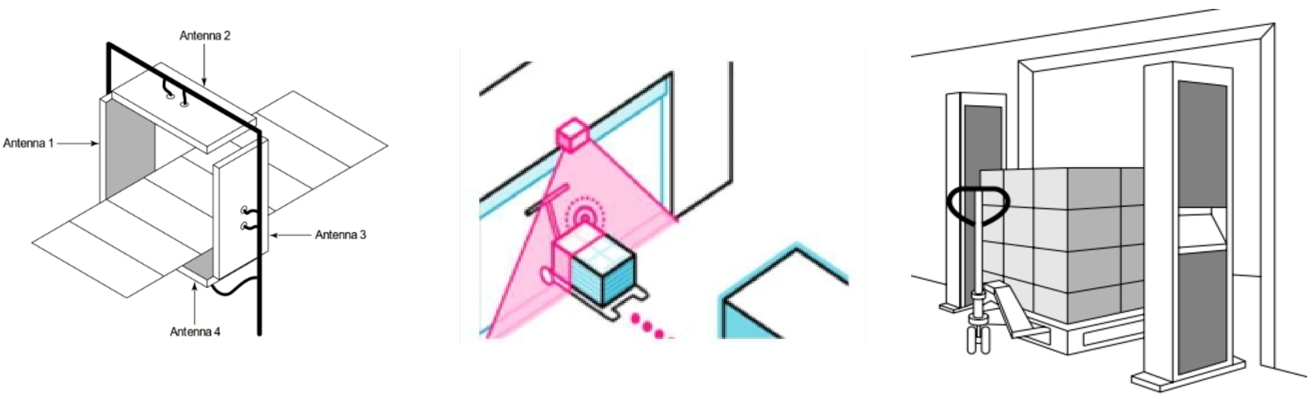


Figure 55 Examples of automatic registration points throughout the construction supply chain

On-site

Next to a timely arrival of products to the project site, one has to have information about the productivity of jobsite workers on site. Therefore, in order to tailoring the supplies with the productivity, information is needed about the productivity on-site. In a construction project which changes frequently, it is hard to get to know the actual productivity of certain crews due to the many changes on site on a daily basis. Therefore, this productivity can be calculated easily by knowing which products are processed on a daily basis (or weekly basis for example). Real-time information about stock on site is needed for this. This stock must be monitored in real-time (by fixed readers and choke points) due to the often short time interval. Due to economic reasons, the storage location should be as small as possible in order to minimizing the reading distance of RFID readers and tags. The time difference between arrival – storage and storage – processing of products can be indicated easily with this RFID system. With these two time data, one can make estimation about the productivity of a certain crew. Besides, this created time interval between two locations on site can perfectly serve as a basis for improvement in productivity, calculated by Lean Six Sigma principles for example. Some examples of this automatic registration system are visualized below.

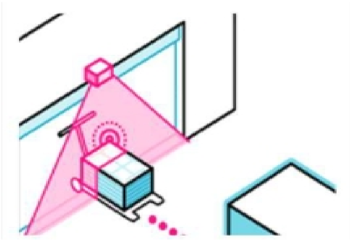


Figure 56 Door portal reader

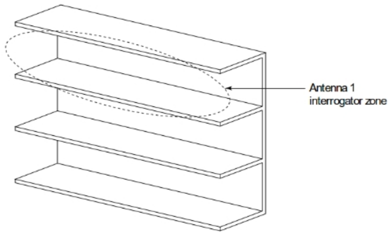


Figure 57 Real-Time Stock Balances Shelf

Figure 58 Controlled Storage Site

Notes

More information about the status of processes throughout the material supply chain should result in more control over the supply of products to the project site. Ideally, the status of every single product should become known. In practice this is not convenient. Only for some products, it can be worthwhile to see its exact location in the material supply chain like products which are critical to a certain installation process on site. However, manufacturers, distributors, warehouses and logistic service providers must give insights in their internal processes in order to get the needed information, such a system will give 100% transparency in the supply chain. Such information can be shared via the EPC code of the RFID tags. The kind of data which is visible for other companies in the supply chain must be managed and regulated by appointments between companies throughout the supply chain. Not only for the contractor could this be valuable information (status of certain products), the other parties in the supply chain can also take its benefits from this system. They can optimize their processes since the exact movements of every product through the chain becomes visible. By the experts of the case studies, 'Shipment Visibility of Goods' is ranked as 7th most important added value and 'Visibility Products Upstream Supply Chain' is ranked as 9th most important added value. In the table below, cost and benefits factors are given.

Costs	Benefits
Fixed: fixed RFID gate readers	More insights in the route products have passed throughout the supply chain
Computer / servers	More control in the delivery process (ensuring timely arrival to the project site)
Wireless Access Points	Increase transparency in the construction supply chain
Personnel costs (like training)	Automatic and 100% coupling between the physical process, location and status of products
Installation service costs (set-up)	Control differences between actual delivery and planned delivery
System integration (adjustment of current enterprise software system)	Management by facts instead of management by assumptions
Business process reengineering	Better and more detailed insights (measured) in actual performance
Software costs (like middleware, database and interface system, maintenance, licence costs)	
WLAN (Wi-Fi or by cable) connection to a pc.	
Data-interchange between multiple companies	
Flexible: Number of passive tags	
Attachment of tags to products	
Manage the information on products	

Table 58 Cost & Benefits aspect RFID subsystem 'Off-Site'

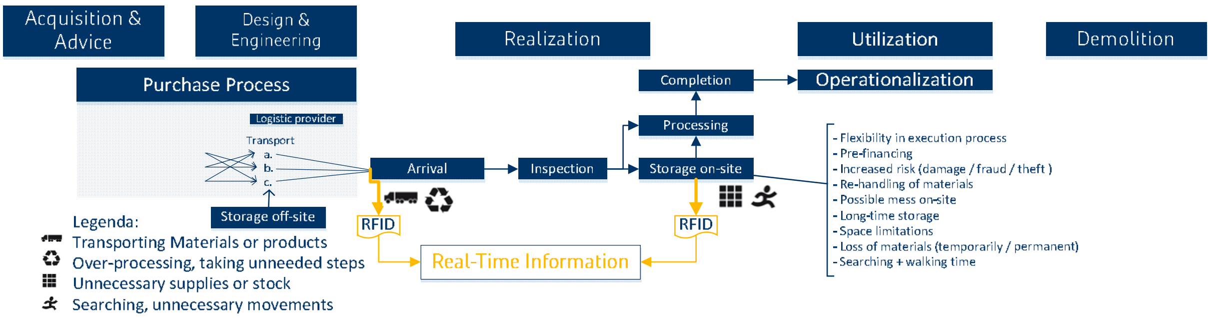
In case of monitoring the production of jobsite workers, the processing of products will be used to calculate this value. However, this is a very cumbersome way to calculate the labour' productivity. Although with more data better assumptions about the productivity can be made, the handling of products is often just a small part of the time needed for a full working activity. Evenly, this working activity can be different in other projects too. Therefore, for the sake of this system, estimating the labour productivity only by the processing of products is not beneficial. Once this system will be used for other purposes (like '*storage'* – see RFID system '*Control'* in the next paragraph), this system can be also be implement to estimate also the labour productivity in order obtain added value for the main or subcontractor. The added value '*Real-Time Stock Balances*' is ranked as 8th most important added value and '*Monitoring Progress / Production'* is ranked as 12th most important added value by the experts from the case studies. The table below shows the costs and benefit factors of this subsystem.

Costs	Benefits
Fixed: fixed RFID gate readers + fixed readers & antennas Computer / servers Wireless Access Points Personnel costs (like training) Installation service costs (set-up) System integration (adjustment of current enterprise software system) Business process reengineering Software costs (like middleware, database and interface system, maintenance, licence costs) WLAN (Wi-Fi or by cable) connection to a pc. Controlled storage area on site Flexible: Number of passive tags Attachment of tags to products Manage the information on products	Give more insights in the productivity of jobsite workers (not full insight) Give insights in the stock on site Give information about the time difference between storage and processing of products.

Table 59 Cost & Benefits aspect RFID subsystem 'On-Site'

c) RFID System 'Control'

The RFID system '*Control*' will be explained in this paragraph. In some cases, there was a limited control in the arrival of products and thereby often a limited control over the temporary storage of products on site. This is remarkable since (sub)contractors are of increasing risk when products are delivered too early to the project site. There is an increased risk for damaging products and fraud to products for instance. Besides, the project site will be transformed into an unorganized area wherein it is hard to find back products once the storage is not controlled. There will be an increasing safety danger for tripping due to the created mess on site. It will also increase the walking distances and searching time for products by jobsite workers. So, this RFID system is contemplated to increase the control over the supply and the storage of products on site by automatically identify which products are supplied to the project site and creating information about the location of products stored on the project site. This will result in the two different subsystems, namely 1) '*Arrival*' and 2) '*Storage*', explained below. The flow chart related to this RFID system and the interference of these two subsystems during the realization process is given below.



Scheme 20 Flow chart 'Control'

Requirements of the RFID system 'Control'

In the table below, the general and technical requirements of the two RFID systems are given. The technical requirements are determined by use of the literature review and interviews with Flederus M. 2016 and Geertsema 2016.

System	Added value (Expert based)	General requirement RFID system	Technical Requirement RFID system	Current wastes
Arrival	Automate Goods Receiving Overall priority experts: 52 Unique Product Identification Overall priority experts: 36	Check-in products automatically at arrival to the project site without human interaction. Fast & easy identification of products on-the-spot for jobsite workers	Fast: <1 sec. between reading and showing information Easy: automatically scanning at arrival possibility to scan on-the-spot products Information: (on-tag) EPC (on-network) product name, receiving person/company, delivering person/company, working activity, building section date + time Read amount: bulk reading Range: 6m (fixed) 3m (handheld) Products: NL-SfB 2005: Table 0: 3, 4, 5, 7 Table 1: 2,3,4,5,6,7,8 Table 2: F,G, H,I,J,K,L, M, N, O, P, Q, R,S,T,U,V,W Table 3: a, b, c, d, e, f, g, h, I, j, k, l, m, n, o, p, q, r, s, t, u, v, w, x, y, z Table 4: B3, B4k, b4m, D3	Due to a limited control over the supply of materials, the main (and subcontractor) did not had any idea what was delivered on site. Products are hard to identify since they were handled (last-mile transport / temporary storage of reusable products offsite) by an external company without coordination of the contractor, or they were hard to identify because they were Custom-made. When the delivers are controlled, this was an manual process, prone to error.
Storage	- Localize Products on Site Overall priority experts: 68 - Minimizing Dwell-Time Overall priority experts: 26 - Real-Time Stock Balances Overall priority experts: 24 - Minimizing Excess of Stock Overall priority experts: 12 - Minimizing Fraud / Theft Goods Overall priority experts: 12 - Monitoring Progress / Production Overall priority experts: 11	Give insights in which products, are stored where and for how long at the project site. Give a signal when products leaves the project site or when they are stored for a certain period on the project site. Give insights in the dwell-time of products and thereby, the productivity of jobsite workers.	Time: last known position for storage Information (on-tag) EPC + product name, arrival date, supplier, ordering company, receiving person (on-network) product name, receiving person/ company, delivering person/ company, working activity, building section date + time Range: whole project site Read amount: single-piece reading bulk reading Security: encrypt Products: NL-SfB 2005: Table 0: 3, 4, 5, 7 Table 1: 2,3,4,5,6,7,8 Table 2: F,G, H,I,J,K,L, M, N, O, P, Q, R,S,T,U,V,W Table 3: a, b, c, d, e, f, g, h, i, j, k, l, m, n, o, p, q, r, s, t, u, v, w, x, y, z Table 4: B3, B4k, b4m, D3	Due to the amount of storage space available, it was hard to know which products were on site, where products were stored on site and how long products were on site. Hereby, many products were ordered in advanced, increasing the risk of damage, fraud and theft, the time products were stored on site and it created an uncontrolled (sometimes unsafe) situation. The productivity of jobsite workers, based on goods delivered – goods processed, was unknown. Even, the amount of stored products on site created a mess on site and an unsafe situation.

Table 60 Requirements of the RFID system 'Control'

RFID system 'Control'

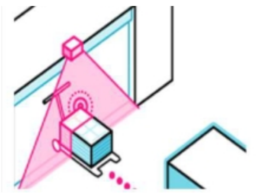
These two different systems will need different components, indicated in the table below.

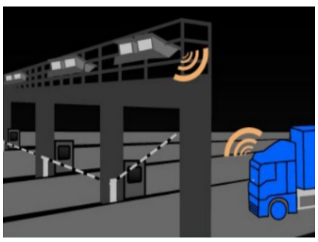
Arrival	Storage
RFID Tag	
Passive / semi-passive / active: Passive tag no energy supply plan needed Memory: EPC (bank 01 'Protocol') needed for reference between multiple companies Type of memory: Read-Write tags Class: 2 GS1 (Passive Read-Write tags) Security: Not needed (only EPC code) Frequency: UHF (Cheapest, fast data rate and read range) Antenna type: Linear-type (electric component of the electromagnetic field: radiative) Substances: Inlay Tag level: Product level / box level or truck level Tag place: next to barcode location Attention: presence of steel or liquids Example: Alien 9640 Squiggle	Passive / semi-passive / active: Passive RFID tag, no energy supply plan needed Memory: User Memory (bank 11), EPC (bank 01 'Protocol') Type of memory: Read-Write Class: 2 GS1 (Passive read-Write tags) Security: By password (4digits) Frequency: UHF Antenna type: Linear-type (electric component of the electromagnetic field: radiative) Substances: Inlay Tag level: Product level or Box level Tag place: Next to barcode location Attention: presence of steel or liquids Example: Tageos EOS-400 R6 tag Extra: Use of location tags on site
Frequency	
Frequency: 865.6 – 867.6 MHz Coupling method: Backscatter Regulation: EU	Frequency: 865.6 – 867.6 MHz Coupling method: Backscatter Regulation: EU
Reader + antenna	
Handheld / mobile / fixed-location: Fixed-location + multiple antennas at the gate and a handheld reader for on-the-spot reading Type or Reader: Read Write readers Power: 2Watt (European regulation) Antenna type: Linearly Polarised Scanner: RFID tag + Barcode (1D) for visible reference Connection: WLAN / WWAN Security: encryption Example: Times-7 A5530 fixed Antenna, Invengo XC-RF807 Reader, Alien ALH-9010 Handheld Reader	Handheld / mobile / fixed-location: Fixed-location + multiple antennas across the project site / location tags and readers on transporting equipment Type or Reader: Read Write reader Power: 2Watt (European regulation) Antenna type: Circular Scanner: RFID tag (+ Barcode (1D) for visible reference Connection: WLAN on site Security: encryption Example: Impinj Speedway Revolution R420 Reader, RFMAX DCE9028 / DCE8658 Antenna, Impinj Speedway Antenna Hub

Table 61 Components of the RFID system 'Control'

<u>Arrival</u>

Once a truck enters the project site, he will pass a gate. This gates functions perfectly as a choke point (every product which will be delivered to the project site passes this gate). This is the location where an automatic registration system should be placed. From the transport / retail sector and at toll gates, such gate readers are commonly used. Readers placed on the sides of this gate will create an reading zone in which the truck passes by. With this RFID system, it becomes easily to indicate which products are delivered on site and when, however, the reading becomes problematic in case of steel frame trailers, explained in the notes of this paragraph. This system can be extend in functionality in which it can create digital invoices, digital (proof of) delivery notes and an automatic billing system. Paper based invoices and delivery notes will be history, minimizing errors in the registration of receiving products due to the manual input of persons and maximizes the efficiency of this registration process. This system should be a closed-loop system in order to prevent unauthorized persons / companies to obtain the information from this RFID system.





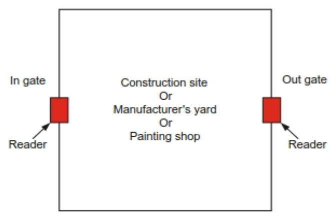


Figure 59 Examples of RFID Gate Readers

<u>Storage</u>

In case of a huge project site, the storage area can be huge, either, the storage area can be relative small area on a huge project site. In both situations, a RFID system can locate products on site. In a small (controlled) storage area like a storage depot, the location of RFID tags (i.e. products) can be done in real-time. Warehouses and distribution centres implement such RFID systems, visualized in *Figure 61 Project site / storage site lay-out Real - Time.* These depots are often not located directly next to the building under construction, so there is a need to see from a distance what is stored where in this facility. In case of a huge storage area, offering real-time visualisation of the location of tags is impractical. Either the range of the tags must be extend heavily, resulting in expensive active RFID tags, or there must be placed many fixed readers on site, increasing the costs of the hardware. On the other side, reading tags unnecessary (when they are not moved for a while) is not beneficial. Therefore, it is beneficial to provide transporting equipment (horizontal and vertical) with RFID readers in order to know the last-known location of the tags on site. Another option is the placement of so-called 'location tags' in the ground, in floors, walls and on (warehouse)doors can support transporting equipment with determining their location on the project site. Although this system is less accurate than a location system in real-time, it will be more cheaper and it will provide still usable information for jobsite workers. The information obtained by the readers should be send through a Wi-Fi network to a database since the range of Wi-Fi a much more than that of RFID tags. The system should be a closed-loop system, preventing unauthorized persons / companies to have access to information stored on the tags. The following figure shows some transport equipment and the placement of the readers / coordination equipment.

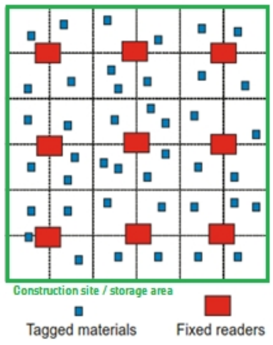


Figure 61 Project site / storage site lay-out Real - Time

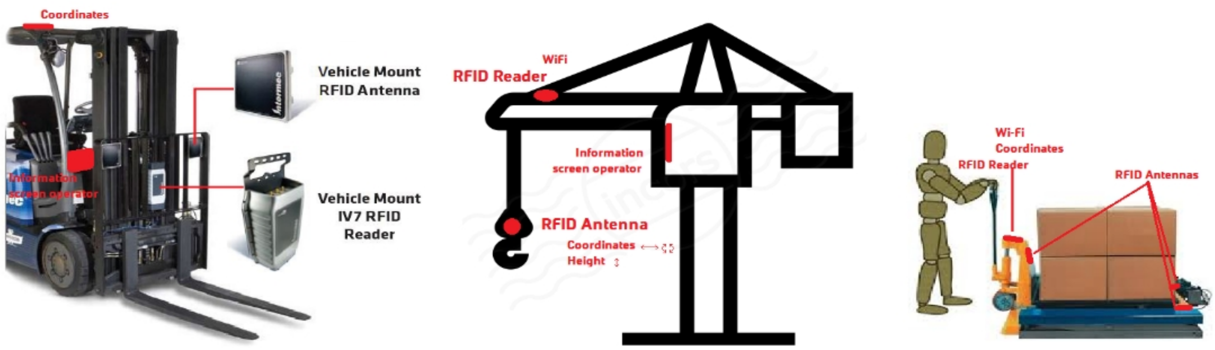


Figure 60 Project site / storage site lay-out Last-Known position

Notes

These two systems are proposed for by multiple researchers in the construction sector (e.g. Jaselskis 1995, Demiralp 2012, Sardroud 2012). Although they are implemented in a lot in other sectors, the application in the construction sector will be limited due to buildings are not produced in factories, projects are always unique due to its location, stakeholders and the design plans and the sector is characterized by its fragmented nature. These differences do have consequences for the applicability of such RFID systems in the construction sector. In case of the '*Arrival RFID system'*, steel in truck trailers will reflect the radio signals which limits the readability of the RFID tags. Therefore, special attention must be place to the design of the truck and the applicability of the subsystem '*arrival*'. A RFID tag outside a trailer which transfers the content of the trailer to the gate reader or a fixed unloading area on site with fixed RFID reader, eventual with the addition of a handheld-reader offers a solution in this case. Also, special attention must be placed to the design of the gate readers since they will be located at fixed places and the heavy transport equipment do have a limited manoeuvrability, offering a change of impact damage to the readers by the trucks. Since it is known by the supplier and the contractor (via data interchange between companies) what will be delivered at one moment, the control of the products will be based on 'management-by-exception-basis': the difference between expected deliveries and actual deliveries will be known immediately by this system). This decreases the manual registration errors drastically. Besides, in both cases (RFID gate readers and the use of handheld readers), the digitalization of invoices and delivery notes will result in a more efficient arrival process, resulting in more control over the deliveries by take out the manual input. The added value '*Automate Goods Receiving'* is ranked as 3rd most important by the experts and '*Unique Product Identification'* is ranked as 4th most important added value for them. Cost/benefits factors are mentioned next.

Costs	Benefits
Fixed: fixed RFID gate readers (with additional handheld readers) Computer / servers Wireless Access Points Personnel Costs (like training) Installation service costs (set-up) System integration (adjustment of current enterprise software system) Business process reengineering Software costs (like middleware, database and interface system, maintenance, licence costs) Data interchange between companies (delivery note) Flexible: Number of passive tags Attachment of tags to products Manage the information on products	Automatic registration systems of all products on site. Control between payments and actual deliveries (proof of delivery) Possibility for an automatic billing system, based on products delivered. System can serve as a service to subcontractor: what is delivered when on site? Elimination of paper invoices / delivery notes Minimizing the manual input which maximises efficiency Management-by-exception: difference between expected and actual deliveries becomes visible immediately Link / relation between digital and physical products (control mechanism) Increase transparency in the supply chain Better and more detailed insights (measured) on actual performance Decrease in human interaction

Table 62 Cost & Benefits aspect RFID subsystem 'Arrival'

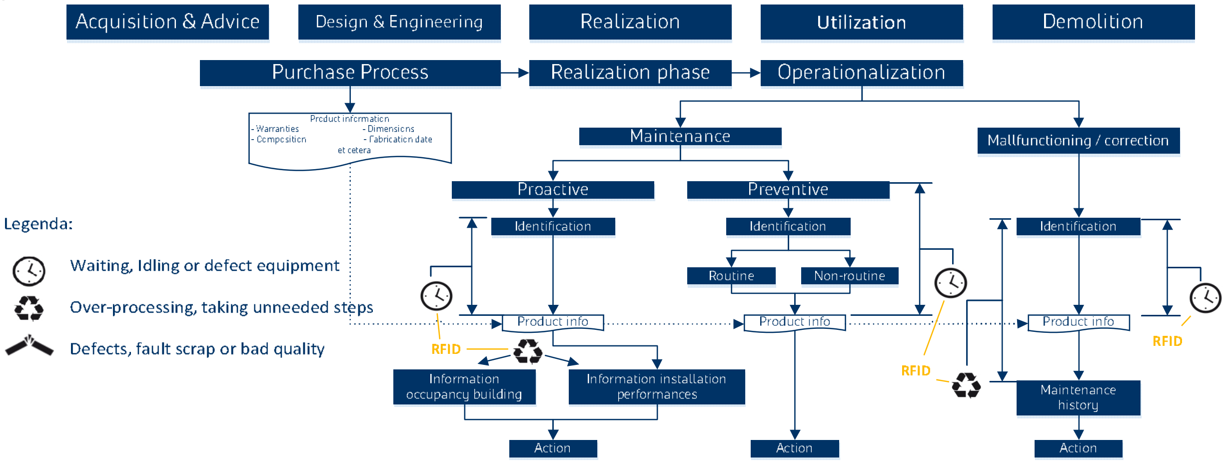
In case of the subsystem '*storage*', special attention must be placed to the site lay-out. Real-time information about the location offers a higher quality of information but is way more expensive in cases of a huge storage area. Although readers on transportation equipment and location tags on site offers a solution here, the exact location of products can still be different once someone manually moves products outside a reader' reading zone, minimizing the added value of this system. Next, fixed readers must be placed at choke points in order to indicate the difference between 'arrival', 'storage' and 'processed' of products. Only this difference will create information about the real-time stock balances on site. It is not worthwhile to continually read stored products which are not being moved. Although the whole infrastructure will cost a lot, it is possible to have a great control over the products stored on site and its location. These two systems (the '*Arrival*' and '*Storage*') are indicated to be complementary to each other. The added value for this system, 'Localize Products on Site', is ranked as 2nd most important added value by the experts. The other relevant added values are ranked: 5th ('Minimizing Dwell-time), 8th ('Real-Time Stock Balances'), 10th ('Minimizing the Excess of Stock'), 11th ('Minimizing Fraud/ Theft of Goods) and 12th ('Monitoring Progress / Production'). In the table next, the costs and benefit factors are mentioned about this subsystem 'Storage'.

Costs	Benefits
Fixed: reader + antennas on transportation equipment fixed (gate) reader at choke points Computer / servers Wireless Access Points + repeaters Personnel Costs (like training) Installation service costs (set-up) System integration (adjustment of current enterprise software system) Business process reengineering Software costs (like middleware, database and interface system, maintenance, licence costs) Wi-Fi network on site Wi-Fi connection of transport equipment Coordinating system on transport equipment or Localization tags on site Flexible: Number of passive tags Attachment of tags to products Manage the information on products	(real-time) Information about actual stock on site (real-time) Information about the location of stock on site Control over the storage of stock on site Less walking + searching time Minimizing dwell-time, lowering the stock on site, lowering pre-investment and minimizing risk of fraud/theft/damage to products since information of which products are stored when, where and for how long becomes known

Table 63 Cost & Benefits aspect RFID subsystem 'Storage'

d) RFID System ‘Building Management’

The last RFID system which will be elaborate is *‘Building Management’*. It has been recognized by the experts that it is hard and time consuming to identify products and obtain the product’ information during the maintenance phase. Besides, there is an increasing need for a pro-active maintenance phase instead of a preventive (or even corrective) maintenance phase. Therefore, real-time information about HVAC installation’ performances and the influential occupancy by building users should be obtained more frequently in order to optimize the technical life time HVAC installations and to increase the quality of the utilization phase. These two kind of information can be obtained by two different RFID systems: 1) ‘*information from products’* and 2) information from ‘*sensors*’. These two RFID systems will be explained here. A visualisation of the current maintenance phase with the identified wastes is given below.



Scheme 21 Flow chart RFID system ‘Building Management’

Requirements RFID System ‘Building Management’

In the table below, the general and technical requirements of the RFID systems are indicated. The technical requirements are determined by use of the literature review and interviews with Flederus M. 2016 and Geertsema 2016.

System	Added value (Expert based)	General requirement RFID system	Technical Requirement RFID system	Current wastes
Information	13. Information Upstream – Execution Overall priority experts: 69	Fast & easy identification of products for the maintenance engineer on-the-spot Fast & easy provision of product’ information for the maintenance engineer on-the-spot	Fast: <1 sec. between reading and showing information Data-rate network: 10 MB/sec. Easy: handheld reader Read range: 3m Read amount: single piece reading Information: (on-tag): EPC (on-network): EPC product name, manufacturer production date static information such as: - Technical - Functional warranties maintenance history Security: encrypt connection with the severer Products: NL-SfB 2005: Table 0: 3, 4, 5, 7 Table 1: 3, 4, 5, 6, 7 8 (optional) Table 2: G, H, X Table 3: a, b, c, d, e, f, g, h, i, j, k, l, m, o Table 4: B3, D3	It is hard to identify and obtain related information on-the-spot of: - Products in general - HVAC installation components - Custom-made products - Façade elements (maintenance history) By: - Huge asset list maps - Complex BIM models - Maintenance records In case of: - Preventive maintenance - Malfunctioning / corrective maintenance
Sensors	14. Monitoring Building Performance Overall priority experts: 25	Providing information about the actual occupation of a building and the performances of the installation systems in a building.	Information: occupancy, motion, temperature, CO_2 – level humidity, EPC + location Products: NL-SfB 2005: Table 0: 3, 4, 5, 7 Table 1: 5, 6 Table 2: n/a, Table 3: n/a Table 4: B3, D3 Visibility in Building Management Systems Wireless Read-range: 6m to ad-hoc control box Read amount: single piece reading Real-time information	Buildings and its installations are designed based on key figures from the past. In current Building Management Systems, it is hard to optimize the performance of installations to the actual use of the building. Real-time information about the occupation of the building and the performances of the installations will increase the predictability of the performances of installations in the future, increasing the quality of the maintenance phase.

Table 64 Requirements of the RFID system ‘Building Management’

RFID system 'Building Management'

These two RFID subsystems will need different kind of components. These components are listed down in the following table. The components are based on *Appendix B The RFID system*. An explanation about how these two system should work is given after the table.

Information	Sensors
RFID Tag	
RFID Tag: Passive RFID tag (no energy supply plan needed) Memory: EPC + TID (Bank 01 and bank 10) Type of memory: Read-Only Class: 1 GS1 Security: Not needed (only EPC code) Frequency: UHF (Cheapest, fast data rate, longest range) Antenna type: Linear-type (electric component of the electromagnetic field: radiative) Substances: inlay Tag level: Product level Tag place: next to barcode location or inside products Attention: presence of steel plates Example: Alien 9740 Squiggle	RFID Tag: Active RFID tag (Real-time information needed) Memory: EPC + TID (Bank 01 and bank 10) Type of memory: Read-Write Class: 4 GS1 (active tag) Security: By password (4digits) Frequency: UHF (fast data rate + longest range) Antenna type: Linear-type (electric component of the electromagnetic field: radiative) Substances: Hard-case tag Tag level: Product level Tag place: strategically chosen surface level in rooms Attention: presence of steel objects Example: RFMicron Magnus® S3 Single Chip Sensor IC Sensors: Occupancy, motion, temperature, Co$_2$-level, Humidity
Frequency	
Frequency: 865.6 – 867.6 MHz Coupling method: Backscatter Regulation: EU	Frequency: 865.6 – 867.6 MHz Coupling method: Active transmission Regulation: EU
Reader + antenna	
Handheld / mobile / fixed-location: Handheld Type of Reader: Read Only reader Power: 2Watt (European regulation) Antenna type: Circular Scanner: RFID tag + Barcode (1D) for visible reference Connection: WLAN / WWAN Security: encryption Example: Alien ALH-9010 Handheld RFID Reader	Handheld / mobile / fixed-location: Fixed-location + multiple antennas Type or Reader: Read Only reader Power: 2Watt (European regulation) Antenna type: Circular Scanner: RFID tag Connection: WLAN Security: encryption Example: ThingMagic M6 UHF RFID Reader (4 Port) Times-7 SlimLine A5010

Table 65 Components of the RFID system 'Building Management'

<u>Information</u>

In this system, the maintenance engineer or building operator will be able to scan with an handheld RFID reader the RFID tags. With this handheld reader, he or she can move around in a building. Since the exact position of some products and HVAC installation components is not always known (due to a lowered ceiling for example), the reader must have an circular type of antenna to read evenly in all directions of the reader (like an isotropic pattern, see *Appendix B The RFID system Figure 12 Isotropic Pattern*). In case of reading unwanted tags, one can lower the wattage of the RFID reader, lowering the read distance. The initial read distance should be approximately 3 meter in order to prevent reading multiple unwanted tags in the surrounding. Once the reader obtains the needed EPC, it should obtain product' information via an encrypted data connection (by WLAN inside a building or WWAN when there is no WLAN network in place). Thereby, minimum data is stored on the RFID tags itself. When someone knows the EPC on forehand and is searching for a product, he or she can use a '*search and find'* functionality on RFID readers. The unique code makes product information unique: one can store static information over the product life cycle (like SKU products contains) and it can contain dynamic information which changes overtime like who has transported the product, who has installed the product or maintenance history reports. Special attention to the RFID tags and its attachment to products and its orientation is needed in case of steel surface products. This system will be a used in a closed-loop environment, the information should be managed by the main contractor / building operator. The product' information should be added by organizations earlier in the supply chain, like the suppliers and manufactures. This are also the actors who should attached the RFID tags to the products. In *Figure 62 RFID tags in a room (Schematic),* one can see a building section with RFID tags placed on multiple products. In *Figure 63 Mechanical Engineer with a handheld RFID reader*, one can see a maintenance engineer who uses a handheld RFID Reader.

Figure 63 Mechanical Engineer with a handheld RFID reader

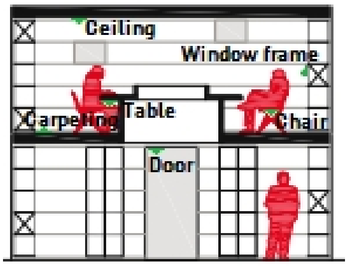


Figure 62 RFID tags in a room (Schematic)

Sensors

This subsystem should also be implemented in a close-loop environment. The information obtained by this RFID subsystem will not be shared with external companies which are not involved in the project. The environmental variables which are measured in current Building Management Systems are A) Temperature, B) Carbon Dioxide and C) Humidity, all possible to be measured with RFID sensors. For this subsystem, RFID tags with sensors are placed on fixed location, so can be the antennas for the RFID reader. Here, the multiple fixed antennas will be connected to a fixed RFID reader which is connected by a WLAN network (Wi-Fi or a Ethernet cable) in order to send the data from the sensors to the administration pc of the Building Management System. One can choose for a certain beacon rate of the RFID tags which will regulate the RFID tag to send data only at a pre-defined time interval. Another option is to obtain the data in real-time, however, lowering the life span of the batteries. Special attention to the RFID tags and its attachment to products and its orientation is needed in case of steel surface products or steel plates in the environment. With this system, it becomes possible to collect more sensory data on a more accurate level than currently can be measured. It must be clear that this subsystem is investigated in the context of this study, whereby the system is not compared to other existing wireless sensor systems.

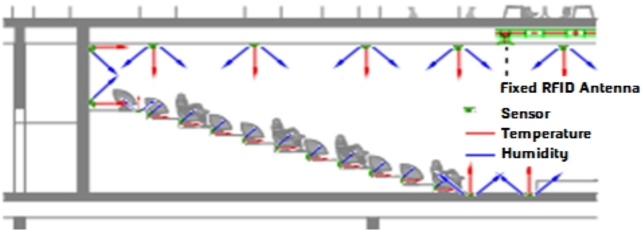


Figure 64 Multiple sensors in a single room

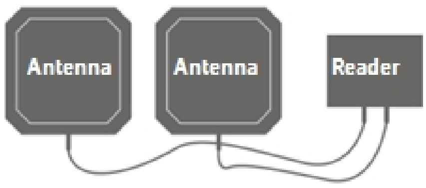


Figure 65 Lay-out 'monitoring building performances'

Notes

Although the two systems described above are mentioned to work in the ideal situation, practical limitations will occur. In case of the first subsystem (*'Information')*, a lot of steel is used in buildings, especially in HVAC installation components. Steel will reflect the radio signals, limiting the readability of the tags. However, the advantage RFID does have during the utilization phase over other identification technologies is to identify products uniquely instead of at a SKU-level. Therefore, the data will also be more accurate. It will be more easy than currently to obtain product' information such as maintenance history and product life cycle information, all linked to a tag' EPC. Next to the advantage to obtain unique product' related information, RFID has been found to provide new kind of information which can be of added value in the future:

1) As-built drawings and taken photos during the realization phase can be linked to a RFID tag in a room. Hereby, it becomes possible to localize exactly hidden tubes, pipes, installation ducts, timber frame (in case of plasterboard) and other concealed products. This will lower change of damage by drilling or screwing by building users.

2) In case of replacement of products due to damage for example (movable and fixed assets), all information about these assets (provided by digital files or BIM models) becomes accessible for building users by use of a RFID tag, strategically placed in a room (next to the light switch for example). All relevant information in a room can be linked to this RFID tag.

According to Flederus M. (2016), it is recommended to provide products with a selling price of €7, - and higher with an passive RFID tag. This cost/benefit decision could also be on a risk analysis basis. It could be worthwhile to provide a €1,- product once the impact of not having the right information quickly available is higher than €0,50 per tag. However, These consideration will be different in every case. An indication about the cost / benefit factors has been given in the table below. '*Information upstream – Execution'* is considered as the most important added value of the RFID system by the experts. In the table on the next page, some cost/benefits factors of this subsystem are mentioned.

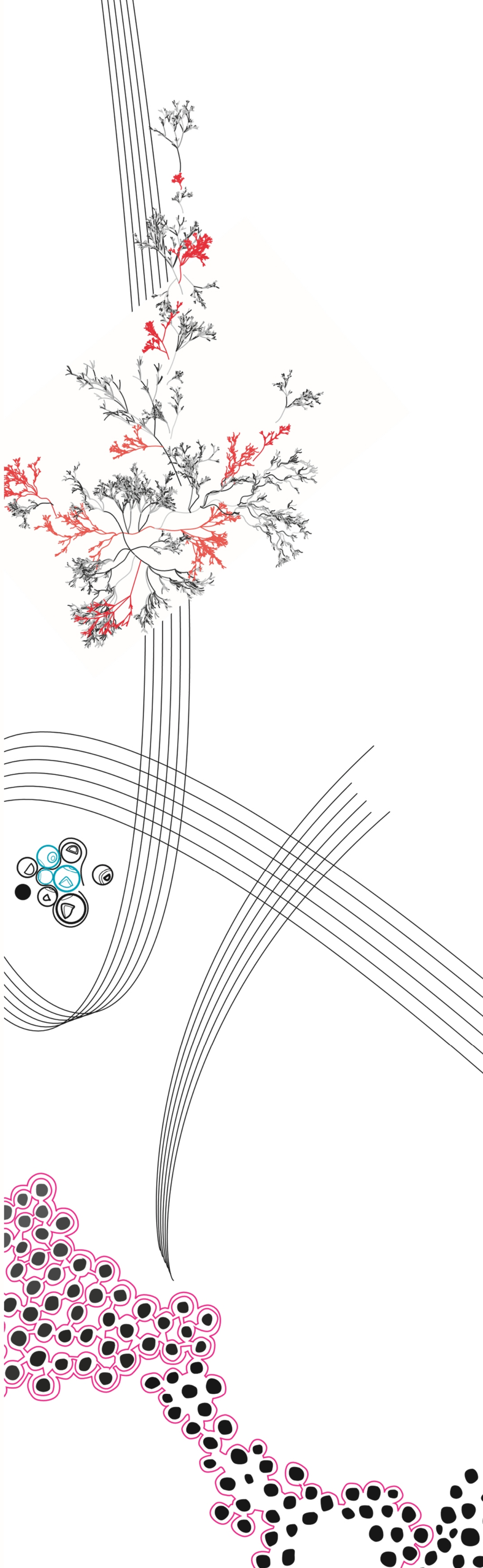
Costs	Benefits
Fixed: handheld reader (2x) Computers / servers, Wireless Assess Points Personnel Costs (like training), Set-up costs System integration (adjustment of current enterprise software system) Business process reengineering Software costs (like middleware, database and interface system, maintenance and licence costs) Coordination costs between companies throughout the construction supply chain Flexible: Number of passive tags	Information on-the-spot during maintenance Faster identification of products Improved data integrity Link between digital and physical products Decrease of manual interaction Reduce in operation costs by decrease in searching and identification time and increase in data availability Unique product related information instead of information on SKU-level New business opportunities (like selling the system as a product /service after a maintenance period

Table 66 Cost & Benefits aspect RFID subsystem 'Information'

In case of monitoring the building performances, current Building Management Systems can meet already the demands of the client. The added value RFID can provide in this case is to connect easily more sensors which obtain the data more locally and more accurate instead of at room-level. However, these sensors must be placed carefully since the readability can be blocked due to the presence of steel inside buildings. Also, these sensors must be placed in the building as late as possible during the realization phase since it is impractical to impose the attachment of a RFID tag with sensors during the manufacturing process, continued by handling, transporting and execution processes. The added value '*Monitoring Building Performances*' is ranked as 6th most important added value by the experts. An indication about the cost and benefit factors is given in the table below.

Costs	Benefits
Fixed: multiple fixed reader + multiple fixed antennas Computers / servers Wireless Access Points / repeaters Personnel Costs (like training) Installation service costs (set-up) System integration (adjustment of current enterprise software system) Business process reengineering Software costs (like middleware, Database and interface system + Maintenance and licence costs) Placement of RFID sensor tags Coordination of obtained information Flexible: Number of active tags + sensors Placing the active tags + sensors just before completion of the realization phase Replacing the battery / tags and synchronize with the systems.	New business opportunities (like selling the system as a product /service after maintenance period) Very accurate environmental measures (temperature / carbon dioxide, humidity and occupancy) Improved data integrity Higher control (and quality) in the indoor environment Better match between occupancy and indoor environment Dynamic building management and maintenance Decrease in energy costs Increase predictability of occupancy and technical life time of HVAC – installations Control on design plans (HVAC) and a pool of data which can be used as a learning curve (optimization in new projects)

Table 67 Cost & Benefits aspect RFID subsystem 'Sensors'



heijmans

UNIVERSITY OF TWENTE.