Radio Frequency Identification and Time-Driven Activity Based Costing: RFID-TDABC

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THESIS SUMMARY

Aston University

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This thesis extends the use of Radio Frequency Identification (RFID) data for accounting of warehouse costs and services. Time Driven Activity Based Costing (TDABC) methodology is enhanced with the real-time collected RFID data about duration of warehouse activities. This allows warehouse managers to have an accurate and instant calculations of costs. The RFID enhanced TDABC (RFID-TDABC) is proposed as a novel application of the RFID technology.

Application of RFID-TDABC in a warehouse is implemented on warehouse processes of a case study company. Implementation covers receiving, put-away, order picking, and despatching.

RFID technology is commonly used for the identification and tracking items. The use of the RFID generated information with the TDABC can be successfully extended to the area of costing. This RFID-TDABC costing model will benefit warehouse managers with accurate and instant calculations of costs.

Although the study is limited in the scope to applying presented RFID-TDABC model only to warehouse operations of a SME company, RFID-TDABC concept will be of value to both academics and practitioners by showing how warehouse costs can be accurately measured by using this approach. Providing better understanding of incurred costs may result in a further optimisation of warehousing operations, lowering costs of activities, and thus provide competitive pricing to customers.

Keywords: RFID, warehouse, case study, time-driven activity based costing

DEDICATION

I dedicate this thesis to:

- My Lord and Saviour Jesus Christ.
- My wife Paulina, who since I met her is the constant source of joy in my life. I love you.
- My parents Ewa and Andrzej. I love you.
- All my family members who keep on asking “How is the PhD going?”.

The fire rises.

ACKNOWLEDGEMENTS

I would like to acknowledge and thank following persons who are important in my academic path:

- Prof. Ming K. Lim with whom I started my academic journey and who was my PhD supervisor until 2012.
- Mr. Brian Price who is my current PhD supervisor. Thank you for all the encouragement and help!
- Dr. Louise Knight for the “water-cooler”conversations which were always encouraging me in the academic work.
- Prof. Ed Sweeney with whom I hope to complete numerous research projects in Supply Chain Management.

PUBLICATIONS

Following publications were the basis for the chapters of this thesis:

- Ming K. Lim, **Witold Bahr**, Stephen C.H. Leung, *RFID in the warehouse: A literature analysis (1995-2010) of its applications, benefits, challenges and future trends*, International Journal of Production Economics, Volume 145, Issue 1, September 2013, Pages 409-430, ISSN 0925-5273.

- **Bahr, Witold** and Lim, Ming K. (2010). *Maximising the RFID benefits at the tyre distibution centre.* IN: 12th International MITIP Conference. Aalborg University, Aalborg (DK), 29-31 August 2010.

- **Bahr, Witold** and Lim, Ming K. (2009). *Implementation challenges of application of radio frequency identification (RFID) in warehouse.* IN: 11th international Conference on the Modern Information Technology in the Innovation Processes of the Industrial Enterprises. Universit degli Studi di Bergamo, Bergamo (IT), 15-16 October 2009.

- **Bahr, Witold** and Lim, Ming K. (2009). *RFID Adoption Issues in the warehouse.* IN: 19th International Conference on Material Handling, Constructions and Logistics. Belgrade (RS), 15-16 October 2009.

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1. INTRODUCTION

1.1 Introduction

The first chapter of the thesis gives a brief overview of the research problem in a Section 1.2. Then research questions, aims and objectives are presented in a Section 1.3. Next research contribution is discussed in a Section 1.4. Thesis structure is presented in a Section 1.5. Lastly, Section 1.6 offers some concluding remarks.

1.2 Research problem

Radio Frequency Identification (RFID) was said to be a revolutionary technology that captivated academics and practitioners alike because of its potential for efficiencies and operational improvements (Ngai et al., 2008). Since the RFID mandates issued to suppliers by retailer Walmart, interest in the RFID technology increasingly grew (Lim et al., 2013; Ngai et al., 2008). However, as a literature review conducted by Lim et al. (2013) noted, the growth in interest in applications of RFID to warehousing was relatively stagnant as compared with other topic subsets related to logistics. An apparent lack of interest in RFID within warehousing has been attributed to a singular focus on its benefits, namely the identification of items.

The research problem addressed by this thesis is a question of what other benefits of RFID can be provided, and what new applications of RFID can be introduced in warehousing.

It is the purpose of this thesis to extend the use of RFID data for accounting of warehouse costs and services. Time Driven Activity Based Costing (TDABC) methodology is enhanced with real-time collection of RFID data about the duration of warehouse activities. This allows warehouse managers to have accurate and instant calculations of costs. An RFID enhanced TDABC proposed as "RFID-TDABC" is a novel application of RFID technology, which brings the benefits of RFID to the area of cost calculation and accounting. Idea of the RFID-TDABC was firstly introduced by Bahr and Lim (2010), who is the author of this thesis, and evaluated by Siguenza-Guzman et al. (2013) to be "useful in a logistics environment where there are mostly repetitive processes."

1.3 Research questions, aims and objectives

This thesis research questions (RQ) are directly drawn from calls in the literature to investigate the impact of RFID on costing methods. The research questions this thesis aims to answer are as follows:

1. RQ1: Can RFID provide "automatic accounting of the future"? (Varila et al., 2007)
2. RQ2: Can RFID be used in conjunction with a TDABC costing model? How can RFID benefit a TDABC costing model? (Everaert et al., 2008)
3. RQ3: What is the impact of measuring time with RFID on a TDABC cost model? (Somapa et al., 2012)

This thesis aims to provide a positive answer to the proposed research questions in a warehousing research context. In broad terms it is envisaged that RFID technology can provide automation to accounting methods when used with the TDABC costing model, when it is used to collect time data about activities. Another aim is to find out the impact of using RFID with the TDABC cost model. Potential benefits of increased time measurement accuracy and operational improvements are also envisaged.

In order to achieve the aims and answer the research questions the specific objectives are set out: conduct a case study at a representative warehouse, compare implementation of TDABC and RFID-TDABC, and lastly provide some insights and comparisons based on achieved ressults.

1.4 Research contribution

This thesis explores the use of RFID in the warehousing, and proposes using it in conjunction with a TDABC costing methodology - referred to here as RFID-TDABC model - in order to provide additional benefits beyond typical item identification. The RFID-TDABC concept is the original contributions of this thesis.

RFID-TDABC is implemented in a case study warehouse. Successful implementation suggests that RFID-TDABC can be applied in warehouses to provide tracking of activity costs, thus leading to further optimisation of warehousing activities, increased understanding of operational costs, and expanded benefits offered by the RFID beyond product identification.

1.5 Thesis structure

Chapter 1 provides the introduction to the research problem. It summarises the main points of contribution to the body of knowledge. Lastly, it is presenting the thesis structure.

Chapter 2 discusses the research methodology used in this thesis. Firstly the research philosophy is stated. Then process of developing the research questions is presented. Research methodology theory is introduced and research methodologies relevant to supply chain and logistics research are evaluated. Next, the overall research design is presented. Lastly, comments on research rigour, validity and reliability are given.

Chapter 3 presents the overview of the RFID technology. Elements of an RFID system such as RFID tags and RFID readers are presented. A brief history of RFID is given and a comparison is drawn between RFID and a legacy Auto-ID system (barcode). Then numerous RFID applications are presented and the benefits of RFID are evaluated.

Chapter 4 presents a warehouse and its operations: receiving, put-away, storage, order picking, and despatching. Operational problems in a warehouse are discussed and use of RFID technology is given as a way to alleviate them. Examples of RFID implementation at a warehouse are presented. Then benefits of using RFID at a warehouse are evaluated and obstacles to using RFID in a warehouse are addressed.

Chapter 5 evaluates several approaches to costing in warehouses. Firstly warehouse costs frameworks are discussed and their evaluation leads to proposing the combined perspective on warehouse costs. Next, the traditional costing method and the alternatives (such as EVA, SCOR, balanced scorecard, ABC, TDABC) are discussed. A detailed presentation and evaluation of activity-based costing (ABC) is conducted alongside contrasting the benefits and advantages of an ABC model with a focus on the logistics industry. Time-driven activity-based costing (TDABC) is presented as a further development of an ABC model and the benefits and advantages of TDABC are evaluated and compared with an ABC model. Evaluation of the TDABC leads to enumerating several weaknesses of the TDABC model.

Chapter 6 introduces an RFID-TDABC model as a new way to calculate warehouse costs. A short overview of the RFID-TDABC model is followed by the theoretical background of the RFID-TDABC model. Next, the research value of RFID and integration with TDABC is considered, which highlights alleviating weaknesses of the TDABC model. Then the RFID-TDABC model at work is explained. The numerous benefits of using the RFID-TDABC model are presented.

Chapter 7 introduces the company Exquisite Bathrooms which is used as a case study for showcasing the implementation of RFID-TDABC at the warehouse. Firstly data regarding the company and its activities is collected and analysed. Then, TDABC is introduced and time equations and calculations are provided for activities of receiving, put-away, order picking, and despatching. Next, RFID-TDABC is implemented for these four activities and an overview of results is provided. The meaning and significance of the results of a case study are provided in the next chapter.

Chapter 8 discusses the results of a case study at the Exquisite Bathrooms warehouse. The meaning and significance of these results is presented. Then comparison is made between costing methods: traditional costing, TDABC, and RFID-TDABC. Case study results are further scrutinized and benchmarked against the literature. A business case for RFID-TDABC is outlined alongside return on investment (ROI) calculations. Although in a small enterprise ROI may not be favourable for implementation or RFID, there are numerous other advantages of RFID-TDABC that may justify its practical use.

Chapter 9 summarises the thesis. Firstly the contribution to the body of knowledge is outlined. Then research implications are set out for academics and practitioners. Lastly, limitations of the work are presented, leading to suggestions of further work that could be done in the future.

1.6 Summary

The introductory chapter of the thesis gave a brief overview of the research problem. Then research questions, aims and objectives were presented.Research contribution was discussed and thesis structure was presented. Next chapter provides overview of the research methodology.

2. METHODOLOGY

2.1 Introduction

This chapter discusses the research methodology used in this thesis. Firstly the research philosophy is stated in Section 2.2. Then the process of developing the research questions is presented in a Section 2.3. Research methodology theory is introduced in Section 2.4 and research methodologies relevant to supply chain and logistics research are evaluated in Section 2.5. Then the overall research design is presented in Section 2.6. Comments on research rigour, validity and reliability, are given in Section 2.7. Lastly, Section 2.8 provides a summary of this chapter.

2.2 Research philosophy

The research philosophy of this thesis follows the positivist paradigm by making use of a case study combined with mathematical modelling. According to Sachan and Datta (2005) it is the preferred approach (at 60%) by most researchers in the logistics and supply chain management area.

2.3 Development of research questions

Development of the thesis' research questions and the RFID-TDABC proposition started with a literature review in the area of RFID technology, warehousing, and costing models. Figure 2.1 presents the literature review frame-

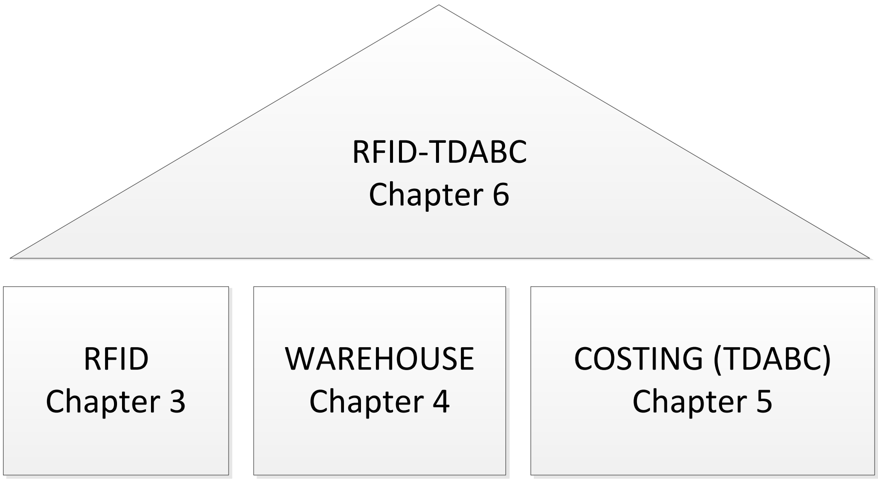

Fig. 2.1: Literarture review framework

work. Research questions that this thesis aims to answer are directly drawn from calls in the literature to investigate the impact of RFID on costing methods:

1. RQ1: Can RFID provide "automatic accounting of the future"? (Varila et al., 2007)

2. RQ2: Can RFID be used in conjunction with a TDABC costing model? How can RFID benefit a TDABC costing model? (Everaert et al., 2008)

3. RQ3: What is the impact of measuring time with RFID on a TDABC cost model? (Somapa et al., 2012)

2.4 Research methodology

Collis and Hussey (2009) define research methodology as "an approach to the process of the research encompassing a body of methods" (p. 337). The choice of a research methodology is guided by a number of factors (Saunders, 2011):

- The research question and objectives;
- The researcher's existing knowledge;
- The amount of time and resources available; and,
- The researcher's philosophical underpinnings.

There is a wide range of possible methodologies and choosing between them is a very important issue. These methodologies are not mutually exclusive and a mixed methods approach may be appropriate to answer the set of research questions being asked. In the process of a research design decisions are made regarding an appropriate: strategic methodological approach, data collection, and data analysis techniques.

2.5 Research methodologies in supply chain and logistics research

Preferred research methods in the supply chain and logistics research area are presented in Figure 2.2 from a study by Larson and Halldorsson (2004). Each of the methodological approaches is firstly defined and then evaluated to meet the research aims and objectives.

Surveys are difficult to define due to their ubiquity and many different studies have been labelled as surveys. Surveys have the following central features (Robinson, 2002):

- the use of a fixed, quantitative design;
- the collection of a small amount of data in standardized form from a relatively large number of individuals;

Method	Mean	Std. Deviation	*JBL* 1978-1993
Survey	3.78	1.13	54.3%
Interview	3.78	1.11	13.8%
Case Study	3.76	1.24	3.2%
Archival/Secondary Data	3.33	1.20	9.6%
Simulation/Modeling	3.08	1.63	19.2%
Focus Groups	2.29	1.48	n/a
Experiment	2.07	1.57	n/a

Fig. 2.2: Preferred research methods in supply chain

- the selection of representative samples of individuals from known populations.

Use of survey is not a suitable methodology for the purposes of this research. The approach taken is to gather expert views to develop and evaluate a new cost model.

Interviews as a research method involves the researcher asking questions and receiving answers from people and is widely used in social research (Robinson, 2002). Although interviews are a flexible and adaptable way of finding things, they are considered to be unsuitable as a main research method to meet these research aims and objectives. RFID-TDABC is currently being developed as a costing model and only a very limited number of experts knows about this model. However, elements of interview methodology are used as a part of the data collection.

Archival/secondary data collection is a part of a wider methodology called content analysis (Robinson, 2002). This method is unsuitable as the main research methodology to give insights about RFID-TDABC since there are only a few documents about the RFID-TDABC. Idea of the RFID-TDABC was introduced by Bahr and Lim (2010) and evaluated by Siguenza-Guzman et al. (2013) to be "useful in a logistics environment where there are mostly repetitive processes.” However, elements of archival/secondary data method are used as a part of the data collection.

A focus group is a group interview on a specific topic and is characterised as an open-ended group discussion guided by the researcher (Robinson, 2002). Focus groups as a research methodology is unsuitable for meeting the research aims and objectives for the similar reasons interviews are rejected.

The use of experiment is characterised by the researcher actively manipulating or changing aspects of what is being studied (Robinson, 2002). Experiment is not a suitable methodology for meeting the aims and objectives as the RFID-TDABC model has not been implemented in a real warehouse. More importantly the ”what is studied” element is the RFID-TDABC model/concept itself and as such it can’t be changed or manipulated.

Case study is defined as ”a strategy for doing research which involves an empirical investigation of a particular contemporary phenomenon within its real life context using multiple sources of evidence” (Robinson, 2002). A case study gives the opportunity to present the application of qualitative methodology in research (Hartley, 2004), hence the process of implementing an RFID-TDABC model is explained using a case company. Case study is found to be a suitable method for meeting the research aims and objectives because evaluating the RFID-TDABC model requires an application to the real life context of a warehouse.

The case study method is augmented by the simulation, since some elements of the proposed solution do not yet exist. Giordano et al. (2013) suggests that simulation is suitable for “the system for which alternative procedures need to be tested *may not even exist yet*”(p. 185). Simula-

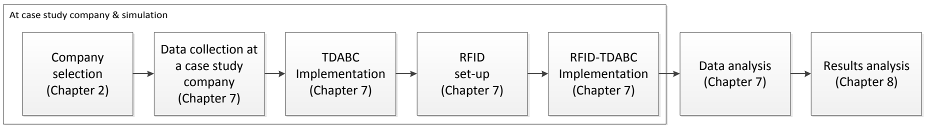

Fig. 2.3: Overall research design

tion/modelling is defined as an attempt to carry over the essential structural elements of a real world phenomenon into a relative well controlled environment (Robinson, 2002).

2.6 Overall research design

Once research questions, aims, and objectives are stated and a research methodology is selected the overall research design can be presented. Figure 2.3 shows the research design used in this research.

Research design starts with the company selection, which is discussed in the next section. Then data collection is conducted at the case study company based on the guidelines discussed in a following section. After this TDABC can be implemented as a first step to building an RFID-TDABC model. It is followed by setting up an RFID system at a case study warehouse. Then the RFID-TDABC model can be implemented. Lastly analysis of obtained results is conducted. Analysis of the results includes discussion about their meaning and significance.

2.6.1 Company selection

The company selected for this case study research is a small-medium enterprise (SME) called Exquisite Bathrooms (disguised name by owner's request). Exquisite Bathrooms is a distributor of bathroom products operating from a warehouse in Birmingham, UK. A detailed description of the company is provided in a Section 7.2.

The selection of the case study company was based on several factors. The majority of companies in the UK are SMEs and majority of logistics related businesses are located in the West Midlands (as shown on a Figure 2.4 obtained from ProLogis). The decision to select an SME was also directed by the findings from a literature review, which showed that all studies on TDABC and logistics were based on SMEs (Bruggeman et al., 2005; Diaconeasa et al., 2010; Everaert et al., 2008; Somapa et al., 2012). Furthermore, encouraging use of information-computer technologies (ICT) in SMEs logistic companies is a key to building better supply chains of the future (Evangelista et al., 2013). Lastly, using SMEs in research helps in achieving a better research impact.

2.6.2 Data collection

In order to build the TDABC model and further extend it to a RFID-TDABC model, a range of data was required. A TDABC models requires two parameters: the cost per unit for the consumption of resources in the resource pool and time consumed or spent by the activities in the process. Before starting data collection for this study, analysis of how this was done in other TDABC case studies was conducted. This is presented in Figure 2.5.

Data was collected by a number of methods in order to obtain sufficient details to build accurate models. Data collection included gathering information from financial statements, bill of ladings, customer's orders, interviews with management and warehouse staff, and lastly making warehouse activity observations. Time estimates were obtained of warehouse activities observed during visits to the site by measuring activities with a watch Casio G-Shock GW-9200-1ER. In a few cases, durations of the activities could not

Fig. 2.4: Location of the logistics hubs in the UK

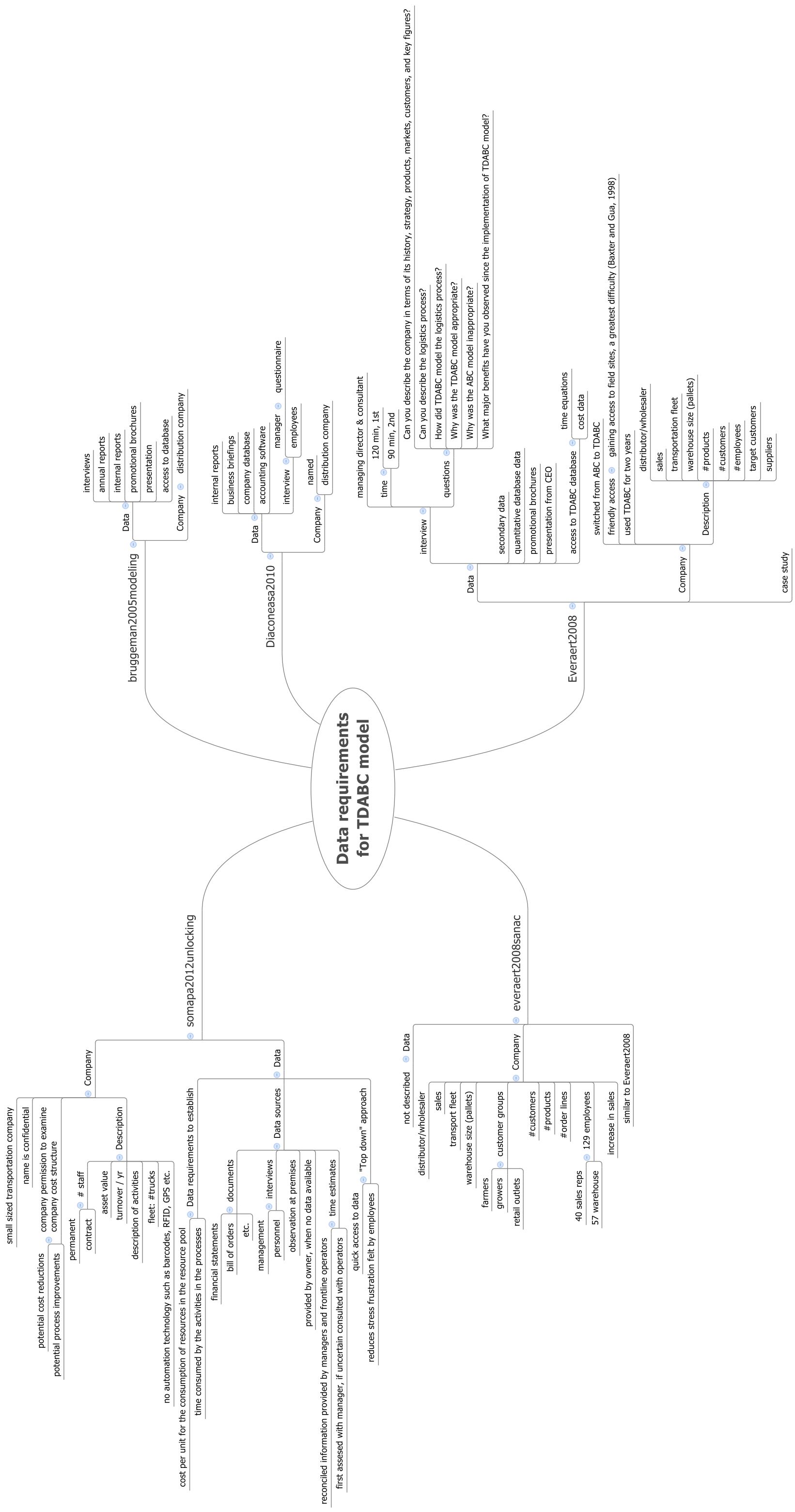

Fig. 2.5: Data requirements for building TDABC models.

be measured as events did not occurred during the visits. As an alternative estimations were provided by the warehouse manager. In order to reduce measurement errors, obtained time estimates were also reconciled with the management and relevant warehouse staff. Using a mixture of a 'top-down' approach with direct measurements by the observer provided quick access to data and reduced discomfort felt by employees when asked to provide their assessment of the exact activity times. Confidence in time measurements was increased by taking ten measurements for each activity and using triangulation to validate results.

2.6.3 Data analysis

Data analysis from a case study was conducted using elements of simulation/modelling in a spreadsheet (i.e. Microsoft Excel or Open Office). During the data analysis an TDABC costing model and a RFID-TDABC costing model were created and compared.

2.6.4 Results analysis and interpretation

Results from the case study were analysed and interpreted in order to make them meaningful and to be able to draw conclusions regarding the research questions, aims, and objectives. A comparison between various costing methods was provided. In order to validate the results they were benchmarked against the results obtained in warehouses by other researchers. Additionally, the business case for the RFID-TDABC was provided and the ROI explained. Interpretation of the results concludes with outlining the advantages and practical applications of this RFID-TDABC model.

2.7 Research rigour: validity and reliability

In reflecting on the validity and reliability of this research, the four qualitative criteria recommended by (Lincoln and Guba, 1985) have been adopted:

- credibility,
- transferability,
- dependability,
- confirmability.

The credibility criterion involves establishing that the results of research are credible from the perspective of the participants in the research. Whilst there is always room for improvement in this area, this issue was addressed to some extent by inviting warehouse management to comment on summaries of the research findings. Obtaining results from only one case study is not intended to be definitive and transferability is difficult. However, the process of continuously relating the empirical findings back to the literature helped in this regard. Dependability emphasizes the need for the researcher to account for the changing context within which research occurs. In this regard, the author fully documented the whole process of implementing RFID-TDABC, from design through to analysis and results discussion. Confirmability refers to the degree to which the results could be confirmed by others. Future work should build on the findings of this research using the proposed methodology and making use of methodological triangulation.

2.8 Summary

This chapter discussed the research methodology used in this thesis. Firstly the research philosophy was stated. Then process of developing the research questions was presented. Research methodology theory was introduced and research methodologies relevant to supply chain and logistics research were evaluated. Next, the overall research design was presented. Lastly, comments on research rigour, validity and reliability, were given. Next chapter presents overview of the RFID technology.

3. RADIO FREQUENCY IDENTIFICATION (RFID)

3.1 Introduction

This chapter presents an overview of RFID in Section 3.2. The RFID tags are discussed in Section 3.3. RFID readers are presented in Section 3.4. A brief history of RFID is given in Section 3.5. A comparison between Auto-ID systems is made in Section 3.6. Then numerous RFID applications are presented in Section 3.7. The benefits of RFID are presented in Section 3.8. Lastly, Section 3.9 provides a summary for this chapter.

3.2 Overview of RFID

RFID is an abbreviation for Radio Frequency Identification and as the name implies it is a technology that transmits information through radio waves. Information is transmitted between RFID tags (also called transponders) and readers (or interrogators) (Hunt et al., 2007). The information flow in a basic RFID system is presented in Figure 3.1 (based on Dua and Meyers (2007)). The tag receives a radio signal from the reader. The tag is activated and sends back the data to the reader. The collected information is passed on to the RFID middleware for processing, for use in business applications. Each tag consists of unique identification information about the item to which it is attached, e.g. item ID, date of production, shipping detail, expiry date, etc. depending on the intended uses (Dua and Meyers, 2007).

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Fig. 3.1: Basic components of RFID system and information flow

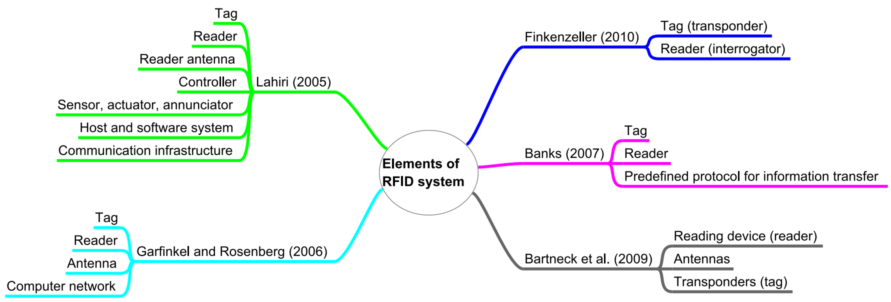

Fig. 3.2: Five views on elements of RFID system

An RFID system is defined as an "integrated collection of components that implement an RFID solution" (Lahiri, 2005, p. 7) and is also referenced as an RFID infrastructure (Banks, 2007). There is a difference of opinion among authors regarding what constitutes an RFID system. Five different propositions of what constitutes an RFID system are presented in Figure 3.2. It can be deducted from Figure 3.2 that an RFID system in its most basic form consists of a tag (transponder) and a reader (interrogator), which is the view put forward by Finkenzeller (2010).

3.3 RFID tags

3.3.1 Elements of an RFID tag

An RFID tag is defined by Lahiri (2005) as “device that can store and transmit data to a reader in a contactless manner using radio waves”[p. 9]. Although RFID tags come in different shapes and sizes, as illustrated by Figure 3.5, they all have in common three essential components (Banks, 2007; Finkenzeller, 2010): antenna (coupling element), integrated circuit (chip), printed circuit board/substrate (housing). Figure 3.4 illustrates the three core elements of an RFID tag. Additionally, some tags may have their own power source (i.e. battery) and/or sensory elements.

The antenna in the RFID tag transmits and receives radio waves and facilitates communication with the reader, and when it is used as a coupling element, it draws energy from the reader and energises tag for communication (Lahiri, 2005). Antenna determines the size of the RFID tag (Banks, 2007).

Integrated circuit or chip is another essential component of the RFID tag and can be described as the tag’s “brain” (Banks, 2007). Chip consists of several elements: modulator, power control, clock extractor, logic, and memory (Lahiri, 2005). Logic and memory elements constitute the ’brain’ part of the chip, as they provide implementation of communication protocol and storage for data, respectively (Lahiri, 2005). Depending on the complexity of the tag integrated circuit can only send its unique identifier or more data, for example collected from peripheral components (Banks, 2007).

Printed circuit board, substrate or housing is the material that holds components of the RFID tag together (Banks, 2007). Its function is to provide the protection to the chip and antenna and allow for optimal performance (Finkenzeller, 2010). Materials used in providing substrate/housing for RFID tags come in a wide range of options, from adhesive labels, flexible inlays to hard plastic enclosures etc. Figures 3.5 and 3.6 provide examples of such different types of such materials.

3.3.2 Types of the RFID tags

RFID tags can be classified in two different ways. Firstly, by the type of power supply that is used to activate the chip: active, passive, and semi-passive; and secondly by the type of frequency used: LF (low frequency), HF (high frequency) and UHF (ultra-high frequency). Figure 3.6 shows this classification and provides examples of tags from different producers in each category.

Active tags have an onboard power supply (i.e. battery) and may also include elements for performing specialised tasks (i.e. sensory elements) (Lahiri, 2005). Active tags use their own power supply to support communication with the reader. Use of own power results in achieving longer reading range and increased readability in harsh environments (Banks, 2007). Additionally, if tag has sensory elements to measure environmental factors like: temperature, humidity or positioning system, they are also supported from the onboard power supply (Lahiri, 2005). Power supply of the active tag is limited by battery, hence in order to extend operational life of the tag it works in so called beacon mode (Banks, 2007). Tag operating in beacon mode sends signal at regular intervals, this means that the more frequent interval the faster battery depletion. Due to use of battery, active tags are the most expensive type of tag and come in bulky form as shown in Figure 3.6. Active tags are commonly used in real-time location systems (Ni et al., 2004) or harsh environments (Banks, 2007) like construction site or container port.

Passive tags don't have onboard power source and are powered by the means of reflected energy from the reader(Dua and Meyers, 2007; Hunt et al., 2007). As a result passive tags have a simple construction and their price is significantly cheaper than active tags (Lahiri, 2005). Additionally, passive tags may take a very thin forms like inlay (see Figure 3.6 or adhesive label. However their form makes them more susceptible to changes in magnetic field around them which negatively affects their readability (Banks, 2007). Passive tags are deployed for tracking in RFID implementations where high volume of tags are required, for example: libraries, supply chain etc. (Hunt et al., 2007).

Semi-passive tags, also called battery-assisted tags, use the onboard power supply, but do not use it to assist in communication with the reader (Hunt et al., 2007). Onboard battery is used to supply power to tag's sensory elements and other specialised tasks (Lahiri, 2005). Semi-passive tags are a fusion between passive and active tags, which results in increased read ranges (Banks, 2007). Due to onboard battery and other sensory elements semi-passive tags are larger than passive tags (see Figure 3.6). Active tags are used where implementation requires recording environmental characteristics and use of high volume of tags, for example in tracking perishable food transportation (Jedermann et al., 2009).

RFID tags can also be categorised according to the used frequency (see Figure 3.6. Most commonly RFID tags utilise following frequencies: LF (low frequency), HF (high frequency) and UHF (ultra-high frequency), and rarely a microwave frequency (Banks, 2007). Each of the frequencies has different characteristics. Figure 3.3 presents effect of different materials on radio frequency waves and tag's performance (Dua and Meyers, 2007; Singh

Material	Effect on RF	LF	HF	UHF	Microwave
Cardboard	absorption, detuning	x	x	x	x
Liquid	absorption	x	x		
Plastic	detuning	x	x	x	x
Metal	reflection	x	x		
Human/animal body	absorption, detuning, reflection	x	x		

(x) – tags are easily read

Fig. 3.3: Effect of material on radio frequency waves.

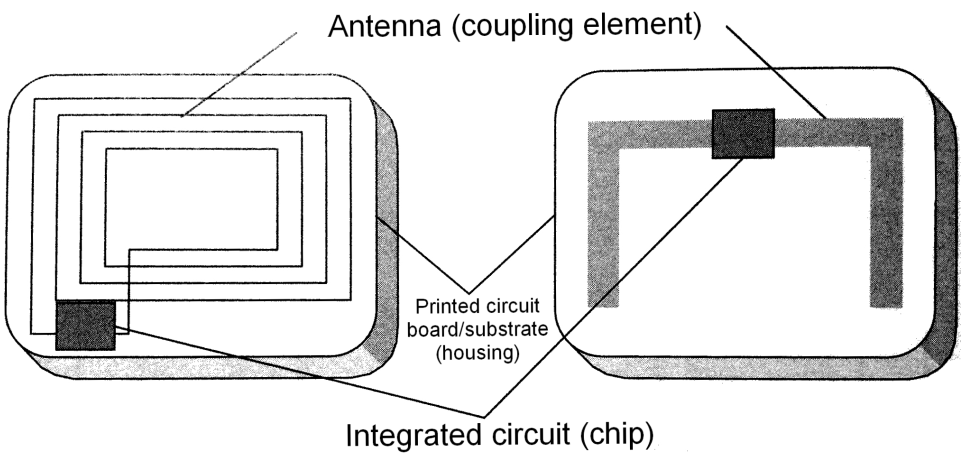

Fig. 3.4: RFID tag elements (based on Finkenzeller (2010))

et al., 2009). Environmental impact on performance of RFID tag plays a crucial role in choosing the type of tags in RFID implementation (Garfinkel and Rosenberg, 2006).

3.4 The RFID readers

Second element of the RFID system is the RFID reader, also called interrogator. RFID reader is defined as "device that can read from and write data to compatible RFID tags" (Lahiri, 2005, p. 22). Role of the reader is to communicate with tags within its read range and present gathered tags' data to business application that can make sense of this information (Banks, 2007).

Fig. 3.5: RFID tags come in different shapes and sizes. Source: Arnall (2007)

A typical reader contains following elements: radio frequency module (transmitter and receiver), control unit, coupling element and communication interface (Finkenzeller, 2010). Radio frequency module transmits power by reader's antennas throughout its reading zone and receives the response signal back if any tag is within the reach (Lahiri, 2005). Control unit with microprocessor and memory provides logic element to the reader, whereas communication interface is used for exchanging data with an enterprise application (Banks, 2007).

Similarly to tags, readers also have different shapes and sizes as presented in Figure 3.7. Depending on the application RFID readers may be a stationary unit in plastic enclosure, a sturdy stationary module for use in enterprises or a portable hand-held device that includes a mini-computer and display for use by shop-floor workers. In recent years RFID readers have been miniaturised and embedded in mobile phones (Garfinkel and Rosen-

Fig. 3.6: Types of RFID tags classified by power supply and frequency.

Fig. 3.7: Example of RFID readers from Alien Technology

berg, 2006).

3.5 Brief history of the RFID

Foundations of the RFID technology were laid by the Scottish physicist James Clerk Maxwell (1831-1879) who is a key figure in describing the entity, spread and transmission of electromagnetic waves (Bartneck et al., 2009). His work was further developed by German physicist Heinrich Rudolf Hertz (1875-1894) and Guglielmo Marconi (1874-1937) whose innovations challenged engineers in the twentieth century and beyond (Banks, 2007).

Radio communication especially advanced during the Second World War solving the problem of identifying returning aircraft. British air force used transponders attached to planes that sent a signal to interrogating base stations identifying if the plane is a friend or a foe (Domdouzis et al., 2007). After the war this technology was further developed and publication in October 1948 by Harry Stockman titled “Communications by Means of Reflected Power” is considered foundational to development of RFID technology as it is known today (Hunt et al., 2007).

Between 1950s and 1960s the technologies related to RFID were developed culminating in taking the technology to a wider market with setting up three companies Sensormatic, Checkpoint and Kogo which provided equipment for electronic surveillance of merchandise (Domdouzis et al., 2007). As well as introduction of RFID to tag and monitor nuclear materials by the U.S. Government (Garfinkel and Rosenberg, 2006).

Period of 1970s is described as time of “RFID Explosion and Early-Adopter Applications” (Hunt et al., 2007) with development in 1972 the RFID based access control by Schlage Electronics company and releasing the RFID research to the public by Los Alamos Scientific Laboratory in 1977 (Garfinkel and Rosenberg, 2006).

Increased availability of RFID research led exploration of new uses of RFID in the 1980s, like animal tagging, garage door openers and toll collection on the motorways (Garfinkel and Rosenberg, 2006; Hunt et al., 2007). At this point all new emerging applications of RFID were proprietary systems without any cooperation between the vendors (Hunt et al., 2007).

During the 1990s the RFID technology entered the mainstream with many companies like Philips, Mikron, Alcatel, and Bosch becoming involved in developing RFID technology (Garfinkel and Rosenberg, 2006; Hunt et al., 2007). During 1990s steps were taken to standardise the RFID technology as lack of standards was considered to be a significant hindrance to further development (Hunt et al., 2007). In 1999 the Uniform Code Council, EAN International, Procter & Gamble and Gillette established the Auto-ID Centre at the Massachusetts Institute of Technology (Violino, 2005). According to Bartneck et al. (2009) opening of Auto-ID Centre became a new chapter in the history of RFID, which led to expansion of RFID technology in the new XXI century.

Up to now RFID technology has been successfully applied and delivered business benefits in many areas, including: manufacturing, distribution and logistics, warehousing, cattle ranching, marine terminal operations, military, retail, document tracking, security access, and healthcare (Banks, 2007; Garfinkel and Rosenberg, 2006). With number of academic publications related to RFID on the increase (Lim et al., 2013; Ngai et al., 2008) and growing interest in the idea of "Internet of Things" (Atzori et al., 2010) more applications of RFID into the new areas may be expected in the future, like this thesis, which links the RFID technology with Time-Driven Activity Based Costing.

3.6 Auto-ID systems, the RFID vs a barcode

As it was mentioned in the introduction to this Chapter the RFID is one of the Automatic Identification and Data Capture (AIDC) technologies (Wamba and Boeck, 2008). Currently most important AIDC technologies include: barcode system, biometric, optical character recognition (OCR), smart cards and lastly RFID. These AIDC technologies are presented in Figure 3.8, which also indicates (arrow) relationship between smart cards and RFID as they both have some similar characteristics (Finkenzeller, 2010). This subsection briefly presents AIDC technologies and contrasts characteristics of RFID and barcode.

In the context of AIDC technologies biometrics encompasses all procedures that unmistakeably identify living beings (most commonly humans) by their individual physical characteristics (Finkenzeller, 2010). Common characteristics that identify humans in unmistakeable manner include scanning fingerprints, hand-prints, voice identification and retina scans. Biometrics is characterised by high cost of implementation and very low reading speeds, but gives the benefit of impossible unauthorised modifications (Finkenzeller, 2010). Biometrics is typically used in law enforcement applications, like: criminology and border control (Finkenzeller, 2010).

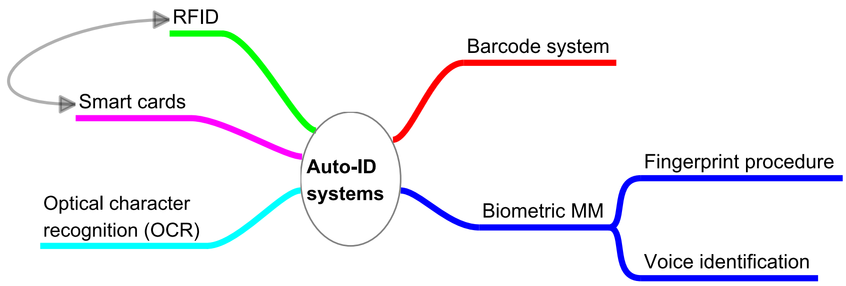

Fig. 3.8: AIDC technologies, based on Finkenzeller (2010)

Next AIDC technology is OCR at which core lies a principle of making human readable text readable automatically by the machine (Finkenzeller, 2010). Common applications of OCR include administrative fields, banking (i.e. cheques processing), postal systems (i.e scanning the destination address) and traffic enforcement (i.e. reading car number plates). OCR is characterised by low data density and since it is text, it is easy to read data for humans (Finkenzeller, 2010).

Smart cards are defined as "electronic data storage systems with additional computing capacity" (Finkenzeller, 2010, p. 4). Typical uses for smart cards include: financial transactions (i.e. debit/credit cards), telephone cards, and smart cards for mobile phones (Finkenzeller, 2010). Smart cards share some characteristics with the RFID tags (Finkenzeller, 2010), as both have very high data capacity and density. Data stored on both smart card and RFID tag is inaccessible to humans making them nearly impossible for unauthorised modifications. Lastly both of them are not easily influenced by harsh environments (Finkenzeller, 2010).

Barcode is the most successful and recognisable AIDC technology (Finkenzeller, 2010). Barcodes are defined as "a scheme in which printed symbols

ISBN 978-1-62808-050-6

9 781628 080506 >

Barcode with book ISBN code.

QR code that contains phrase:
RFID is an abbreviation for Radio Frequency Identification and as the name implies it is a technology that transmits information through radio waves.

Fig. 3.9: Example of typical barcode and QR code.

represent textual information" (Lahiri, 2005, p. 114) and operate in binary code made of parallel bars and gaps (Finkenzeller, 2010). Barcodes are typically printed on paper, packaging, or adhesive label (Lahiri, 2005). Example of a barcode is presented in Figure 3.9 (on the left), which shows encoding of a book ISBN code. Barcodes are scanned with laser scanners (Finkenzeller, 2010), but in recent years seen emergence of using cameras in mobile phones to read barcodes (Ohbuchi et al., 2004). Barcodes give the benefit of fast and accurate data collection that leads to increased operational efficiency and reduces operational cost (Lahiri, 2005). Barcodes are typically used in fields with safety requirements like medical or clinical applications, logistics for cargo/product identification, retail, libraries and many more (Finkenzeller, 2010).

Despite their popularity, barcodes have several drawbacks (Ahlund, 2005; Bartneck et al., 2009; Dua and Meyers, 2007; Hunt et al., 2007; Lahiri, 2005). Firstly, barcodes can be easily soiled, tarnished, torn, fade out or affected by moisture. Secondly, barcodes need to be in the line of sight of the scanner and be correctly positioned. Thirdly, environment conditions affect the reading accuracy, for example dampness. Lastly, barcodes can be read only within certain parameters of speed and only one barcode can be scanned at a time.

In order to alleviate some of these drawbacks and increase data density of barcodes new types of barcodes were developed, such as: Code 128, PDF417, Aztec Code, DataMatrix, MaxiCode and in recent years the QR Code (Lahiri, 2005; Soon, 2008). QR Code is a matrix symbol, which was developed in 1994 by Denso, one of major Toyota group companies, and combines high capacity of PDF417, high density of DataMatrix and fast reading of MaxiCode (Soon, 2008). Example of QR code is shown on the right side of Figure 3.9, where it contains a long phrase. QR Codes are applied in areas like: retail, logistics, public transport (i.e. tickets), hospitality management, patient identification, and marketing (i.e. website encoded as QR Code) (Soon, 2008).

Emergence of RFID as part of AIDC technologies drew a lot of attention to compare RFID with barcodes (Ahlund, 2005; Bartneck et al., 2009; Dua and Meyers, 2007; Hunt et al., 2007; Lahiri, 2005). RFID was promoted as barcode replacement (Wu et al., 2006), as it has several advantages over barcode. Summary of RFID and barcode characteristics is presented in the Table 3.1, which is based on following works: Ahlund (2005); Dua and Meyers (2007); Hunt et al. (2007); Lahiri (2005).

One of the explanation of key difference between barcode scanning and RFID scanning is proposed on website www.RFIDarena.com (see Figure 3.10). Author draws similarities between scanning and fishing, with fishermen using fishing rod, which represents barcode scanning, fishing net representing the RFID scanning, and fish representing objects. Barcode scanning iden-

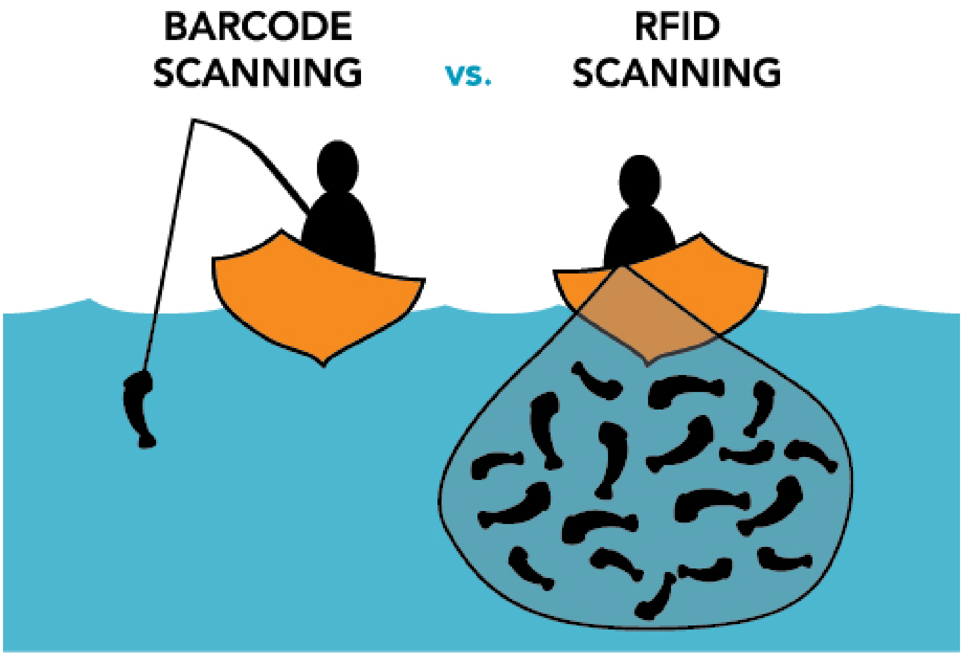

Fig. 3.10: Barcode scanning vs RFID scanning, Source: Säilä (2013)

tifies only a single object at a time, whereas RFID allows for simultaneous scans and identification of many objects at the same time.

Another important advantage of RFID over barcode is that no line of sight is required between reader and RFID tag. Moreover, the position of the scanned item and orientation of tag on the item is not important, whereas barcode requires proper orientation. Furthermore, RFID technology allows for unique identification of items, as opposed to category identification offered by barcode. RFID tags are also dynamic, which means their content can be securely changed in the tag writing process, while barcodes are static and have lower data storage capacity than RFID tags. Environmental susceptibility of RFID tags is higher and can be used in harsh environments, as opposed to barcodes which are difficult to scan when soiled. Lastly, RFID technology offers higher security than barcodes and longer reading range.

Due to its characteristics and advantages over other AIDC technologies

Characteristic	RFID	Barcode
Position reader	No line of sight required	Line of sight required
Identification depth	Uniquely identified items	Identifies only item category
Position of scanned item	Item orientation to reader not important	Requires proper orientation
Simultaneous scans	Simultaneous identification of many items	Scans only single item at a time
Data updates	Dynamic read/write capability	No write capability, static information
Environmental susceptibility	Can be used in harsh environments	Soiled labels difficult to read
Memory/data size	More data storage capacity	Limited data storage capacity
Standardisation	Worldwide standards still in process	Worldwide standards in place
Price	More expensive: $0.10-plus cost to attach	Cheaper to produce: $0.001
Attaching process	Currently requires two steps: tag creation and tag attachment	Single step: can be easily printed on boxes during manufacturing
Data transmission	Electromagnetic	Optical
Access security	High	Low
Read range	Centimetres to meters, depending on system	Up to several meters, within line of sight

Tab. 3.1: RFID vs. barcode

RFID becomes increasingly applied in many different areas, which is discussed in the next subsection.

3.7 The RFID applications

Since 1995, and especially after RFID mandates from American Ministry of Defence and largest American retailer WalMart, the number of applications of RFID technology in wide range of sectors systematically increased (Lim et al., 2013; Ngai et al., 2008).

Chao et al. (2007) states that main focus of RFID applications is identification of objects or persons. There are however different ways of realising identification in industrial or service sector settings.

Industrial applications of RFID include: retail, logistics, construction, manufacturing, health care, pharmaceutical industry and animal detection (Banks, 2007; Domdouzis et al., 2007; Lim and Winsper, 2012).

RFID technology is applied in retail industry in several ways. Firstly, in apparel industry RFID tags are typically attached to individual pieces of garment and in early stages of RFID adoption were used only for theft prevention (Banks, 2007). Recently, applications of RFID in apparel industry provide also supply chain visibility, inventory management and on shelf availability (Lim and Winsper, 2012). Secondly, in food retail RFID is used to achieve food safety standards, track shelf life, provide traceability and manage inventory (Lim and Winsper, 2012). Lastly, RFID technology provides beverage industry with possibility of making operational improvements, stock visibility, shrinkage prevention and alcohol pouring control (Lim and Winsper, 2012). Examples of RFID applications in retail include: apparel tracking at men's department at Galeria Kaufhof (Thiesse et al., 2009), traceability system used by producers of Parmigiano Reggiano (the famous Italian cheese) (Regattieri et al., 2007) and proposition of glass refill system based on RFID (Bhattacharyya et al., 2010).

Developments in RFID technology were enthusiastically received by logistics practitioners (Jones and Chung, 2010) and applied in various areas of logistics including: supply chain visibility (Delen et al., 2007), inventory control and management (Domdouzis et al., 2007; Finkenzeller, 2010), pallet tracking (Chow et al., 2006), container management (Ngai et al., 2007), and tracking returnable transit items (Hellström, 2009). In depth discussion of application of RFID in warehousing is presented in section Section 4.4.

Construction industry is a challenging and harsh environment which demands AIDC technologies to withstand these conditions. Studies found

RFID to be especially suited for construction industry due to its long reading range and durability (Ergen and Akinci, 2007). Examples of RFID applications in construction include: concrete processing and handling, cost coding for labour and equipment, and materials control (Jaselskis et al., 1995). Furthermore, tracking pipe spools, identification of pipe-work joints, tracking structural steel parts, valuable asset tracking (theft prevention) and location of burried assets may be also achieved with RFID (Domdouzis et al., 2007).

Manufacturing is another area with increased interest in RFID applications (Lim and Winsper, 2012). In manufacturing RFID is used for real-time parts and tools localisation (Domdouzis et al., 2007; Huang et al., 2008), material visibility (Lu et al., 2006), inventory control (Banks, 2007) and tracking items through production process (Brewer et al., 1999).

Health care and pharmaceutical industries also benefit from use of RFID technology (Banks, 2007; Li et al., 2006; Lim and Winsper, 2012). Examples of applications of RFID in health care include tracking assets in hospital (Hakim et al., 2006), tracking patients and visitors (Wang et al., 2006), tracking environmental factors of transported blood bags (Domdouzis et al., 2007; Kim et al., 2007). Pharmaceutical industry typically uses RFID for tracking high value drugs (Lim and Winsper, 2012) and attempts were made to automate and track drug dispensing to patients (Lahtela et al., 2008; Shieh et al., 2008).

RFID applications in animal detection are fairly mature (Banks, 2007; Li et al., 2006) and examples include cattle ranching (Swedberg, 2008; Voulodimos et al., 2010) and RFID tagging of domestic animals for purpose of tracking and veterinary management (Garfinkel et al., 2005).

RFID technology is also increasingly applied in both service and public sectors (Lim and Winsper, 2012). Service sector, especially leisure and tourism industry uses RFID for access control, payments collection and prevention of counterfeit tickets (Finkenzeller, 2010; Lim and Winsper, 2012; Öztayşi et al., 2009). Additionally RFID is increasingly used for tracking children at amusement parks thus preventing them from being lost (Li et al., 2006; Lin et al., 2010). Public sector applications of RFID include tracking library collections (Boss, 2003), providing customised museum tours and information guides Hsi and Fait (2005); Huang et al. (2011), and collecting public transport payments (Banks, 2007; Lim and Winsper, 2012).

RFID technology provides numerous benefits for each of particular applications. They are discussed in the next section.

3.8 The RFID benefits

Widespread deployment of RFID technology depends on benefits that are perceived and achieved with it Whitaker et al. (2007). Lahiri (2005) defines RFID benefits as their advantages that come from characteristics of product as they exist today. According to this definition RFID advantages over other AIDC technologies include: contactless, writeable data, readings without line of sight, short and long read ranges, multi-tag reading, ruggedness and durability of tags, and ability to measure environmental conditions (Lahiri, 2005).

Other authors perceive RFID benefits in terms of its technological value in particular application. For instance Dutta et al. (2007) asserts that value of RFID is derived from applications that provide company with labour cost savings, reduced shrinkage and increased product visibility. Similarly, Tajima (2007) discusses general RFID benefits in the supply chain and particular benefits applicable to each tier. General benefits include: reduced material handling, increased data accuracy, faster exception management, improved information sharing and aforementioned reduced shrinkage (Tajima, 2007). Particular benefits include for manufacturing tier: production tracking, quality control and supply, and production continuity; for logistic provider: material handling, improved space utilisation, asset management; and lastly for retailers: reduced stockouts, lower inventory, and better customer and aftersales services (Tajima, 2007).

Aforementioned benefits and value derived from RFID technology are also realised in many other applications as discussed earlier. Particular RFID benefits achieved in warehousing are discussed in Section 4.6, but firstly discussion on warehouse and its operations is provided in the next chapter.

3.9 Summary

This chapter presented the overview of the RFID technology. Elements of the RFID system such as the RFID tags and the RFID readers were presented. A brief history of the RFID was given and a comparison was drawn between RFID and a legacy Auto-ID system (barcode). Then numerous RFID applications were presented and the benefits of the RFID were evaluated. Next chapter discusses warehouses and application of the RFID in warehousing.

4. WAREHOUSE

4.1 Introduction

This chapter presents a warehouse and its operations in a Section 4.2. Operational problems in a warehouse are discussed in a Section 4.3 with the use of the RFID technology as a way to alleviate them is covered in a Section 4.4. Examples of the RFID implementation at a warehouse are given in a Section 4.5. Benefits of using the RFID at a warehouse are evaluated in a Section 4.6 and obstacles to using the RFID in a warehouse are addressed in a Section 4.7. Lastly, Section 4.8 provides a summary for this chapter.

4.2 Warehouse operations

Core warehouse operations focus around the flow of materials in the facility, which are receiving, put-away, storage, order picking and despatching (Berg and Zijm, 1999; Gu et al., 2007). Figure 4.1 presents more detailed view of general warehouse activities, denoting also: cross-docking, value added activities, sorting and packing.

Receiving operation starts warehousing process, in which the arriving items are unloaded from the transport carriers. Arriving items may be delivered to a warehouse by different modes of transport, most commonly by road or train transport. At receiving the identity, quantity and condition of unloaded items is checked, and items may be repacked to different stock keeping units, i.e. put into cages, palletised or de-palletised, after which they await for the next process called put-away. During put-away products are physically moved from the staging area to the locations in the warehouse, where they will be stored. Alternatively, in process of cross-docking, items are moved to shipping without being put to storage. Storage is the placement of goods in the facility for the purpose of safe keeping, protection and retrieval as required by customers' orders. On some occasions, value added activities like labelling, configuration, assembling or kitting are performed on the stored inventory. Several processes are typically performed on the inventory: replenishment, cycle counting, stock taking and general housekeeping. Replenishment ensures that single SKU stocks are made full, cycle counting and stock taking are procedures to calculate inventory on hand, whereas housekeeping encompasses activities regarding cleaning of work areas from dust, packaging waste etc.

Order picking or order fulfilment refers to the removal of items from the storage locations for the purpose of fulfilling customer orders. Picking activities can be either manual, use various MHE or be entirely automated. Picking activity ends with completing the order. Completed orders are checked to ensure picking accuracy and may be sorted or consolidated before despatching. In consolidation multiple orders are grouped for the same destination. Despatching, also called shipping, is the last warehousing activity, in which goods are released finally from warehouse inventory, loaded onto a transport carrier and leave the facility.

According to the study by Gu et al. (2007), out of the four core warehouse operations both storage and order picking are the most research covered activities, with 53 and 67 papers on each respectively. Receiving and shipping operations did not receive the same level of academic attention as only 4 papers focused on both. This discrepancy may be explained by the fact

Aston University

Illustration removed for copyright restrictions

Fig. 4.1: General warehouse activities, based on Chua et al. (2009)

that order picking consumes up to 60% of the total labour activities in the warehouse (Drury, 1988) and may account for 55% of all operating costs in a typical warehouse (Tompkins, 2010). Similarly, storage costs are also significant (Van Den Berg and Zijm, 1999). Nevertheless, next subsections present more detailed overview of each of the core warehouse operations.

4.2.1 Receiving

Receiving operation is defined by Frazelle (2002)(p. 74) as "the setup for all other warehousing activities" and starts goods flow through the warehouse (Van Den Berg, 2007). Importance of receiving is cannot be underestimated, as errors at receiving cause difficulties at subsequent activities: put-away, storage, picking and despatching. Acceptance of damaged or inaccurate deliveries is likely to result in inaccuracies during shipments, resulting in loss of money and time (Frazelle, 2002).

After goods arrive at the warehouse they are unloaded and receipt worker verifies if delivery is complete and undamaged and signs a transport document after which, for example truck which brought the goods departs (Van Den Berg, 2007). This initial check prevents from disputes and liabilities at later stage (Chua et al., 2009). When goods are brought into the unloading area, they are counted in detailed and verified in the WMS and outcome is registered. Some goods, like fresh produce, may require a quality inspection. If products are missing, damaged, or do not meet requirements in any other way operator registers the errors Van Den Berg (2011). As receipt process is a formal transfer of goods from supplier to the warehouse a care must be taken in verifying whether correct goods were delivered, as such there is a typically assigned period of time (i.e. week) in which claims about errors may be made (Van Den Berg, 2007).

There are several policies on goods inspection: visual, batch/sampling, 100% inspection and laboratory test inspection Chua et al. (2009). Each policy has a trade-off between accuracy and time consumption. Visual inspection is quick but may be inaccurate and leading to disputes, whereas 100% inspection is time consuming but accurate (Chua et al., 2009). Batch/sampling inspection is a trade-off between the two options and it is often used after supplier gains certain level of credibility (Chua et al., 2009). Laboratory testing is the most time consuming, but is necessary with certain goods like chemicals, raw materials etc.

Richards (2011b) reports that increasing number of retailers introduces process called good faith receiving, in which products are accepted to warehouse only with a random spot checks. However, any discrepancies found later are charged to the supplier. This method speeds up the receiving process and serves as motivation to supplier to increase accuracy of deliveries.

After checks, cargo is prepared for storage by palletisation if it is in loose form or it is depaletised (bulk-breaking) (Chua et al., 2009). During palletisation cargo is stretch-wrapped as protection from dust and way to stabilise the load (Chua et al., 2009). Additionally, pallets and SKUs are labelled with bar-codes or RFID tags may be attached. If cargo already arrived bar-code labelled or RFID tagged, the laborious receiving process is significantly speeded up (Bahr and Lim, 2010; Richards, 2011b).

4.2.2 Put-away

Put-away operation follows receiving and is defined as "order picking in reverse" (Frazelle, 2002, p. 80). This brief definition denotes that goal of put-away is to put or place items in their relevant storage locations. Typically there are two areas where goods may be placed: bulk area and pick area (Van Den Berg, 2007). Bulk area contains pallets or other type of SKU in full quantities and is used for replenishing the pick area, where items are stored in their individual quantities like cases or units (Van Den Berg, 2011). Alternatively, items may skip the storage stage in the process of cross-docking (Maknoon and Baptiste, 2009).

Putting away items should be done in the accordance with the designated storage policies (Richards, 2011b). However, according to Frazelle (2002) there is a natural tendency among put-away operators to choose locations that are most convenient to them, for example easy to locate, nearest to the floor, nearest to their friend, near toilets or break room. This tendency is recognised as a problem and in modern warehouses it is the WMS, which selects the most suitable location for storage and enforces it on the worker or in absence of WMS decision on where to store items belongs to the warehouse manager (Richards, 2011b; Van Den Berg, 2007)

Selection of suitable put-away location depends on number of factors that are programmed in the WMS logic. Factors that should be considered when deciding put-away location include (Richards, 2011b; tenHompel M. and Schmidt, 2007; Van Den Berg, 2007):

- size, weight and height of palletised goods
- maximum utilisation of storage capacity
- current order date
- family group products
- sales combinations
- separation of certain group of products
- weight and maximum capacity of shelves or racking
- balance of space utilisation
- close to pick location
- grouping products by lot number

Following the put-away at locations designated by WMS allows for maximising storage density and capacity and operational productivity (Frazelle, 2002). Use of bar-code and more recently the RFID technology further extends the supervision over the put-away process (Bahr and Lim, 2010) and ensures that items are stored in the right locations.

4.2.3 Storage

Storage is the major warehouse activity (Ackerman, 2004) and it involves storing goods in their relevant locations in the warehouse facility (Frazelle, 2002). Gu et al. (2007) identifies three key areas of storage function: level of inventory for SKU; frequency and time of replenishment of SKU; and location of SKU and its distribution between warehouse areas. In order to resolve with these issues several solutions were designed in areas of: inventory management, replenishment, and storage location assignment (Van

Den Berg, 2011). Both inventory management and replenishment are different from warehouse management. They "tend to be very distinct roles" (Richards, 2011b, p. 123) and belong to category of inventory control, and as such are beyond scope of warehouse management functions (Gu et al., 2007) and are not further discussed. Detailed reviews of inventory control problems may be found in Gallego et al. (1996) and Hariga and Jackson (1996). Further focus of this section is the problem of storage assignment for SKUs and existing strategies to solve it efficiently.

Fixed storage bin is the simple strategy for location assignment in which each article has assigned the fixed location in the warehouse storage (ten-Hompel M. and Schmidt, 2007). This strategy is also known as dedicated storage (De Koster et al., 2007). There are two advantages to this strategy. Firstly, order pickers become familiar with the outline of a warehouse and searching time for products is significantly reduced (De Koster et al., 2007; tenHompel M. and Schmidt, 2007). Secondly, assigning heavy items at the bottom of the shelves or racking and lighter items above helps maintaining a good stacking sequence (De Koster et al., 2007). Main disadvantage of fixing storage location is that if the product is not in stock, the designated areas remain empty negatively affecting the storage utilisation (Richards, 2011b). In order to minimise this issue De Koster et al. (2007) suggests using fixed locations for picking areas in conjunction with more efficient strategies (i.e. random storage) in bulk storage areas De Koster et al. (2007).

Maximum utilisation of storage capacity is achieved with random storage, a strategy where items are stored at randomly selected eligible location with equal probability (De Koster et al., 2007; tenHompel M. and Schmidt, 2007). Advantages of random storage include the simplicity of the method, lower space requirements and higher level of utilisation of storage locations

(Petersen and Aase, 2004). Sharp et al. (1991) point out disadvantage of random storage, in which high space utilisation is realised at the expense of longer traversing distances for order pickers. Lastly, random storage policy can only be realised within the context of computerised warehouse (De Koster et al., 2007) and with emergence of RFID it may be efficiently implemented in warehouses (Ho and Sarma, 2008).

Third storage policy is called full-turnover storage, in which products locations depend on their sales turnover (De Koster et al., 2007). Products with the highest turnover are located in easy accessible locations i.e. near the depo, whereas slow moving products are located at the back of the warehouse in less prominent locations (Gu et al., 2007). Similarly, products can be arranged based on their popularity defined as "number of storage/retrieval operations per unit of time period" with popular products allocated to accessible storage locations (Gu et al., 2007).

Class based storage is fairly similar to previous method, but here items are divided into classes according to Pareto's rule with typically fastest moving products constituting 15% of totally stored items, but contributing 85% of the turnover (De Koster et al., 2007). Although Pareto's rule states that 80% of effects come from 20% of causes, the percentages may be approximate (Richards, 2011b). A well established methodology for implementing this storage policy is called ABC classification (Frazelle, 2002). Letters A, B, C denote the fast moving, medium moving and slow moving products, respectively (Van Den Berg, 2007). Once classes are assigned to products, the warehouse is zoned and items are stored in their respective ABC areas, with A being most easily accessible. ABC classes are typically determined by picking frequency or sales reports (Van Den Berg, 2011). Advantages of using ABC method include: reduced travel and handling times, with the main disadvantage being reshuffle of stock in case of dramatic demand changes (De Koster et al., 2007). Ackerman (2004) suggests that although identification of ABC categories should be done on ongoing basis, moving items between physical storage locations should be done at times suitable to balance the work load as it will make lead to significant savings in material handling costs.

Another storage policy is family grouping and is characterised by taking to account possible relationships between products (De Koster et al., 2007). Family grouping, also known as clustering, may be realised by storing frequently consolidated items in adjacent locations (tenHompel M. and Schmidt, 2007). Family groups includes objects that are typically ordered together (Frazele and Sharp, 1989). Advantages of family grouping include increased performance in material handling and picking operation, and decreased traverse time for order pickers, with the disadvantage being increased space requirements of this policy (Roll and Rosenblatt, 1983).

Lastly, De Koster et al. (2007) suggests that if the warehouse workforce was deciding the locations where to store the products, the new strategy could be called "closest open location storage", as items would be stored in the first free location encountered by the employee putting away the product. Result of this storage policy is imbalanced use of the available storage space with higher storage density towards the depot (Frazelle, 2002).

Choice of storage policy is closely correlated with the effectiveness of the order picking activity and Chua et al. (2009) suggest several principles for facilitating the picking function:

- Fast moving products should be kept at easily accessible locations (ABC classification).
- Fast moving items should be placed on the shelves within so called

"golden zone" of picking, which is the height between human waist to head.

- Fast moving items should be distributed across several locations to minimise congestion in picking lanes.
- Items frequently picked together should be stored in adjacent locations.
- Slow moving stock should be allocated at high level locations at the back of the warehouse.
- Damaged cargo should be stored in designated and marked location, as to avoid being selected by the picker.

After products occupy their designated locations there are several activities that are performed on the stored items: stock taking, internal movements and housekeeping Chua et al. (2009); Van Den Berg (2007).

Stock taking is defined as an activity "to verify the actual physical quantity with the quantity maintained in the inventory system" (Chua et al., 2009, p. 96). It is an activity that all warehouses are obliged to undertake based on the country laws and accounting requirements (Richards, 2011b). Stock taking is necessary due to mistakes that happen during the inbound operation (receiving) and is a way of preventing inaccurate inventory records (Van Den Berg, 2011). Additionally, stock taking physically verifies value of stock in the balance sheet and helps to identify possible sources of inventory shrinkage, like fraud, theft or loss (Chua et al., 2009).

There are two methods of stock taking: periodic stock taking and cycle count stock taking (Chua et al., 2009). During periodic stock taking all inventory is physically verified at the same time at the end of a given period, typically at the end of financial year. The operation typically takes several days and inbound and outbound operations are suspended at this time (Richards, 2011b). Due to disadvantage caused by suspension of warehouse activities, in recent years cycle stock counting increasingly gained prominence (Richards, 2011b).

During cycle counting worker visits only several locations at a time and counts products stored in each location, as it is done according to a predetermined schedule each item is counted at least once during a course of a year (Chua et al., 2009; Van Den Berg, 2007). Cycle counting may be performed during other warehouse operations like put-away or picking, in which case worker is asked to count stock in adjacent locations Richards (2011b); Van Den Berg (2011). Cycle counting is best suited for warehouses which keep detailed inventory records (Chua et al., 2009).

Another activity taking place while goods are in storage are internal movements, which are defined as stock "movements not driven by orders" (Van Den Berg, 2007, p. 66). Typical reasons for internal movements include: replenishing stock in pick zones, stock is reclassified from slow to fast moving category (ABC classification), and improvements in space utilisation (Ackerman, 2004; Van Den Berg, 2011).

Lastly, purpose of housekeeping activity is to maintain cleanliness of cargo and maintenance of equipment (Chua et al., 2009). Additionally, it has important role in maintaining fire safety, protecting workers from slips and trips, and ensuring the proper waste disposal (Richards, 2011b). Chua et al. (2009) suggests taking following steps to maintain the clean condition of the stored products:

- Use stretch-wrap to protect cargo before storing it.
- Clean warehouse floor regularly.

- Use forklifts electric powered or LPG forklifts.
- Dust regularly.
- Close cartons after opening them.

4.2.4 Order picking

Rouwenhorst et al. (2000) provide a straightforward definition of order picking stating that it is a “retrieval of items from their storage locations”. However, the activity itself is considered to be the most complicated and laborious of all activities performed in the warehouse (Frazelle, 2002). There are several reasons for such evaluation of order picking.

Firstly, order picking is the most costly activity performed in the warehouse that consumes between 50-60% of all operating costs of a typical warehouse (Frazelle, 2002; Richards, 2011b; Van Den Berg and Zijm, 1999). It is staff, MHE and information system demanding activity. Whether order picking is manual or automated it puts an increased demand on the business, as manual operation is labour intensive and automated order picking systems are very costly (De Koster et al., 2007).

Secondly, increased market demands make order picking increasingly more difficult to manage (Frazelle, 2002) due to introduction of techniques like just-in-time (Goetschalckx and Ashayeri, 1989), emphasis on cycle time reduction and process agility (Lin and Shaw, 1998). Additionally, orders are accepted until late for next day deliveries due to increased customers’ demands and growing popularity of e-commerce (Ramanathan, 2010; Richards, 2011b).

Therefore order picking as the most laborious, the most costly and the most demanding warehouse activity has the highest potential for productivity improvements (Frazelle, 2002). Hence efforts have been made to improve order picking by introducing several picking strategies, various MHE equipment, improved facility layouts, evaluating efficiency of picking routes and implementing various information systems. Figure 4.2 presents order picking themes discussed in this section.

There are several strategies for performing order picking activity. Pick to order is a commonly used strategy, in which one warehouse worker (also referred to as order picker or pickers) picks entire order (Hackman et al., 2001). The advantage of pick-to-order strategy is its simplicity, however it does not provide required throughput in facilities with quick turnaround demands (Hackman et al., 2001). Conversely, in batch picking strategy a worker picks items for several orders on each tour, which at the end are sorted by different customer orders (Gue et al., 2006). Batch picking typically results in shorter operational time, but at a cost of loosing order integrity and increased chance of errors (Petersen II, 2000). Another strategy is pick-by-line, also known as pick-to-zero, in which "exact number of cases or items are presented for picking" (Rushton et al., 2014, p. 304). Pick-by-line is typically used in conjunction with cross-docking (Whiteoak, 1999). Next, zone picking strategy requires warehouse to be split into different zones with pickers assigned to each zone, orders are split and assigned to appropriate zones. (Gue et al., 2006; Petersen II, 2000). Zone picking is commonly used in facilities with different types of MHE for different types of products or where products need to be separated due to security, safety requirements (i.e. hazardous materials) or environment requirements (i.e. temperature or humidity) (Rushton et al., 2014). Lastly, in wave picking orders are released in waves as to control flow of goods throughout the warehouse activities (Rushton et al., 2014). For example, timing of picking wave may be depen-

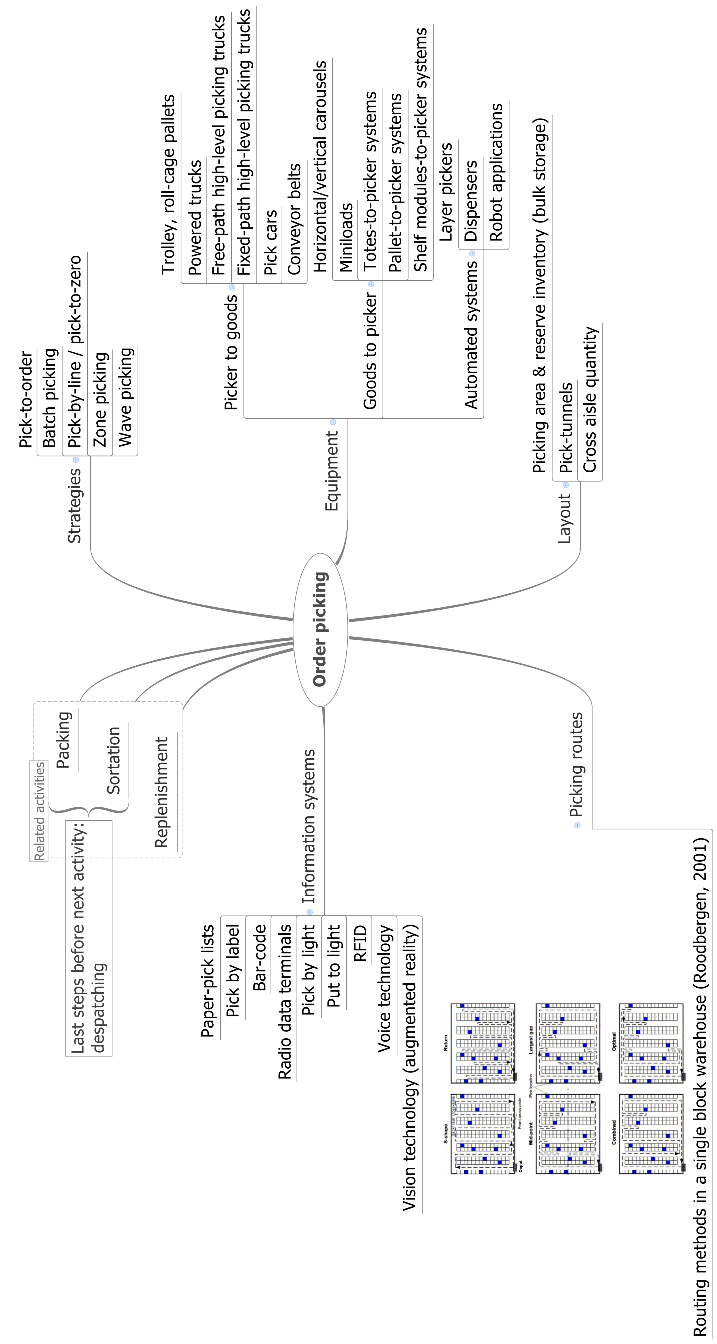

Fig. 4.2: Order picking: strategies, equipment, layout, routes, information system and related activities.

dent on despatching schedules and typical wave has duration between 30 minutes to 2 hours (Petersen II, 2000; Rushton et al., 2014). Application of wave picking results increased control over subsequent warehouse activities like sorting and despatching (Rushton et al., 2014), but requires more time and space for order consolidation (Petersen II, 2000).

There is a variety of equipment available to use in the warehouse to aid order picking activity that may be categorised by the way order is fulfilled: picker to goods, goods to picker, automated system (Berg and Zijm, 1999; Frazelle, 2002; Richards et al., 2013; Rushton et al., 2014). Picker to goods is a manual process in which worker travels to goods in order to pick them, typically using some sort of equipment as listed in Figure 4.2. Choice of the equipment should suit storage equipment used in the warehouse, type of picked goods, and picking strategy (Richards, 2011b; Rushton et al., 2014). Another category is goods to picker, in which "operator remains at a workstation and pallets or cases are moved to and away from the workstation under computer control" (Ackerman, 1997, p. 488). Goods to picker is used when it is inefficient for picker to travel long distance in order to pick small portion of the order (Rushton et al., 2014). Lastly, automated systems also known as Automated Storage Retrieval Systems (AS/RS) consists of "racks served by cranes running through aisles between racks" (Roodbergen and Vis, 2009) performing order picking operation in goods to picker style (Berg and Zijm, 1999). Examples of AS/RS include layer pickers (Zhang et al., 2012), dispensers (Berg and Zijm, 1999), and various robot applications (Le-Duc, 2005).

Warehouse's layout has significant impact on the order picking activity and optimising facility layout is a significant factor in reducing picking travel times (Karasek, 2013; Rushton et al., 2014). According to Caron et al. (2000)

the impact of the warehouse layout on picking productivity is estimated to be more than 60%. De Koster et al. (2007) point out the general factors that should be considered in designing the warehouse layout: number of storage blocks, facility dimensions, number of picking aisles, number and shape of cross aisles, racking height, and position of inbound and outbound gates. These factors should be also taken to account when planning layout of the picking area. Roodbergen and De Koster (2001) suggest that putting a cross aisle between existing parallel aisles in a rectangular warehouse significantly improves the order picking productivity and allows for more picker routing options. Similarly, Vaughan (1999) after investigating adding cross aisles to warehouse layout conclude that additional aisles result in shorter travel picking times and point out that greatest benefits are achieved when "length of main storage aisles increases relatively to the width of the cross aisles". Lastly, separation of order picking and stock reserve areas or keeping both functions combined is "one of the first decisions that need to be taken" (Rushton et al., 2014, p. 315) when designing layout of the order picking areas.

Picking routes, also known in literature as routing methods, have the objective of sequencing the items on the pick list to ensure most efficient travel through the warehouse (De Koster et al., 2007). Picking routing problem is a subset of the Travelling Salesman Problem in which salesman needs to find optimal route to travel between cities (Lawler et al., 1985). Seminal works on the subject of picking routing by De Koster et al. (2007) and Roodbergen (2001) surmise routing methods in a single block warehouse as follows, with examples presented in Figure 4.3:

- S-shape – Any aisle that contains at least one pick is entirely traversed by order picker and aisles without picks are not used.

- Return – Any aisle that contains at least one pick is entered and after picking worker leaves aisle from the same end.
- Mid-point – Warehouse is divided into two areas, picker enters aisles from the front and from the back until the midpoint. This method is more efficient than S-shape when number of picks is on average one per aisle (Hall, 1993).
- Largest gap – Order picker enters the aisle as far as the largest gap between two nearby picks. The gap is measured as distance between first and last pick, and front and back aisle respectively; it is a distance that the picker does not traverse. According to (Hall, 1993) the largest gap routing is always outperforming the mid-point method.
- Combined – Every aisle that contains at least one pick is entered only once and either traversed entirely or partially.
- Optimal – Picking route is optimised in order to minimise the traversing distance. Optimal solutions are based on algorithm presented by Ratliff and Rosenthal (1983).

Information systems also play important role in the order picking operation as they are conveying following information to the worker about the picking assignment: items, quantity, location, route, and other order details and instructions. There are numerous information systems that may be used in the warehouse that vary in complexity and technological advancement, as presented in Figure 4.4. Following descriptions of information systems are based on Richards et al. (2013) and Rushton et al. (2014), and other works as stated.

- Paper-pick lists – Worker receives a printed paper list of products,

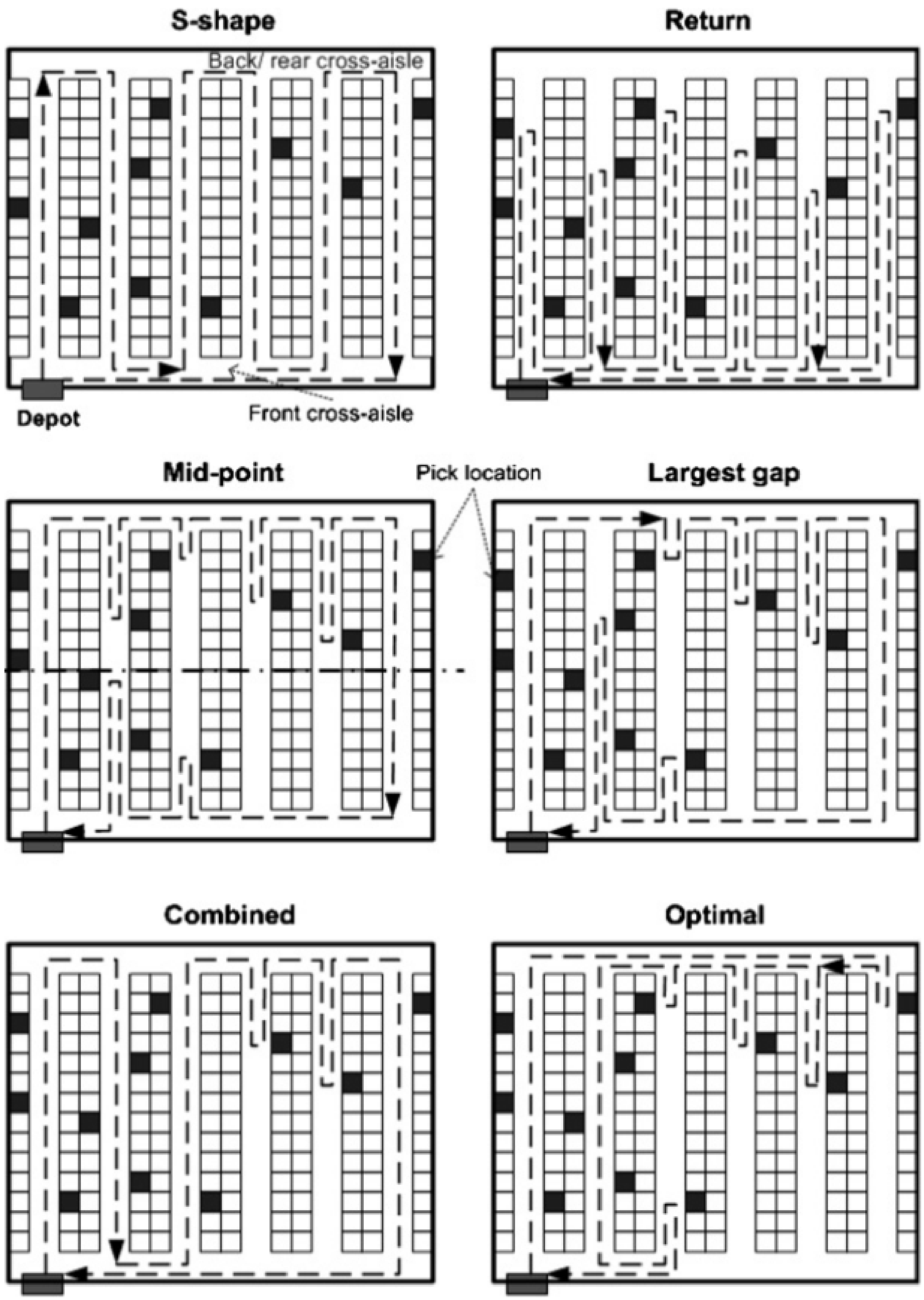

Fig. 4.3: Routing methods in a single block warehouse De Koster et al. (2007); Roodbergen (2001)

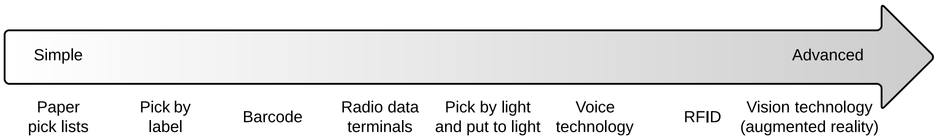

Fig. 4.4: Information systems used in order picking on technological advancement scale.

quantities, and locations. During picking any discrepancies are noted on the paper list. Paper-pick lists are applicable for most operations, especially where there is little IT support and number of picked lines is below 100 per hour. Benefits include: low cost, flexibility, instant implementation, picker decides their own path, and low maintenance. Disadvantages include: prone to error, pickers are not hands free, requires manual updates of order status, and lost time when picker needs further instructions from management desk.

- Pick by label – Picker receives the sequence of the items to be picked on a printed list as well as adhesive labels that have to be stuck to the picked items. At the end pick route any remaining labels will indicate errors in the picking process. Similarly to paper-pick list this method is suitable for most operations, especially where there is little IT support and number of picked lines is below 100 per hour. Pick by label is characterised by low running costs, reasonable accuracy, flexibility and low maintenance. Disadvantages include low pick rate, pickers are not hands free, need to print labels, labels may be difficult to read, product damage caused by adhesive label, and lost time when picker needs further instructions from management desk.

- Bar-code – It is most common method used nowadays to increase picking accuracy. Order pickers are given a bar-code scanning gun that is used to confirm the locations and identity of picked product by scanning bar-code labels on location and on a product. This method is suitable for most operations that require picking of less than 100 and is characterised by: improvements in accuracy over paper based methods, flexibility, almost real time-stock updates. Disadvantages include: low pick rate, pickers are not hands free, may take longer than paper based picking due to problems of barcode scanning, increased cost of hardware, requires IT support and maintenance.

- Radio data terminals – Also known as handheld computers, comprise of bar-code scanner, display, keyboard and network module for online communication with WMS. Terminals are often wearable allowing for hands free work. Radio data terminals are applicable for most of operations and allow typically for picking 150 lines per hour. Benefits include: paperless, improvement in productivity and accuracy, hands free operation, less strain on operators, real time stock updates, real time updates of picking tasks. Drawbacks are mainly connected to cost of hardware, IT support, and maintenance.

- Pick by light – Picking locations are fitted with the light emitting diode that indicates picking location and a digital display that shows number of items to be picked. Pick to light is used in conjunction with picking tunnels, which are racking structures providing higher density and cubic space utilisation and are used for single level picking operations. Picker enters the picking tunnel and is led step by step through picking process by light indicators. Pick by light is often applied in mail order and e-commerce warehouses where picking requirements range between 250–450 per hour. Main benefits of pick by light include high accuracy, high productivity, ease of training new staff, and real-time stock updates. Disadvantages of this solution are mainly in the area of system costs (i.e. hardware, maintenance, implementation) and operational issues, like limited only to certain product types, problems with items located at several locations and difficulty with clustering and batching orders.

- Put to light – This is a similar method to pick by light, but it is used during sortation process. Typically it is used in retail operations. Advantages of put to light are similar to those of pick by light and implementation and maintenance costs may be considered a disadvantage.

- Voice technology – This is a two way communication method in which picking requests are communicated to picker directly from WMS computer. Picker hears the picking instructions using headphones and in return confirms through the microphone details of the operation and its successful completion. Voice picking is typically used by food-service industry and grocery retailers with its temperature controlled warehouse areas (Matopoulos, 2011), but it is also applicable to other operations that require pick rate between 100–250 lines per hour and where heavy or awkwardly shaped products are handled. Advantages of voice picking technology include: paperless, flexibility, improved accuracy and productivity, short training, hands and eye free work. Disadvantages are mainly related to implementation costs (i.e software, hardware, maintenance), difficulties in voice recognition and possible long term health issues.

- RFID – RFID technology is discussed in detail in Chapter 3 and particular application in the warehouse is presented in Section 4.4. Advantages of using RFID in order picking include high accuracy, increased productivity and real-time stock updates, with main disadvantage being the cost of implementation.

- Vision technology (augmented reality) – Use of vision technology also known as augmented reality is the more recent addition to range of technologies aiding order picking. Picker's vision is enhanced by electronic display that shows relevant information like next task, directions, identification of product, aisle, and shelf (Puchta, 2013; Reif and Günthner, 2009; Schwerdtfeger and Klinker, 2008). As it is an emerging technology its direct benefits and drawbacks are yet unknown Parsons (2014), however it may be speculated that it will increase productivity and if coupled with identification technology like the RFID it may revolutionise the future of order picking.

Activities related to order picking include replenishment, sortation, and packing. Replenishment ensures that stock is present in picking location, while sortation and packing are stages before the despatching. In process of sortation items are sorted into their respective orders and subsequently packed, being made ready for despatching.

4.2.5 Value added activities

Value added activities, also called value added logistics, are the general name for various activities typically, but not exclusively, provided by the 3PL warehouse (Chua et al., 2009; Van Den Berg, 2011). Examples of value added activities include: labelling and relabelling, pricing, packaging and repackaging, bundling, reconfiguration, assembly, kitting, repair and refurbishment (Richards, 2011b). These activities may be applied to goods during the inbound or outbound processes, make-to-stock and make-to-order respectively (Van Den Berg, 2011).

Activities like (re)labelling, pricing, (re)packaging and bundling are executed in support of the downstream supply chain, for example retailers, by freeing staff from performing these monotonous tasks and focusing them on sales (Richards, 2011b). Chua et al. (2009) suggests that in order to execute these activities error free work organisation should be similar to a production line, with only one product handled at a time and exact number or labels/packaging/bundles should be issued.

Reconfiguration, assembly and kitting activities support the upstream supply chain, for example manufacturers who by production postponement try to better respond to customer requirements (Richards, 2011b). For example, laptop manufacturer delays installation of hard drive and graphic card and leaves a choice to the customer (Rushton, 2000, p. 176).

Lastly, value added activities include handling products returned for repair and refurbishment (Richards, 2011b), hence part of the warehouse is designated as the repair centre. These activities are along side return handling are part of the reverse logistics (Min and Ko, 2008) and become increasingly prominent with growth of e-retail (Richards, 2011b).

4.2.6 Despatching

Despatching, also known as dispatching, shipping, or releasing is the last activity in the flow of products in the warehouse (Van Den Berg, 2011). It is defined as "releasing of the goods to the transporter for delivery" (Chua et al., 2009, p. 94). In this process picked orders are checked for the last time, consolidated, despatching documents generated and goods are loaded into the truck or other mode of transport (Richards, 2011b; Van Den Berg, 2011). Despatching triggers deduction of shipped goods from the warehouse inventory (Chua et al., 2009).

Competitive market conditions require order cycle to be as short and efficient as possible, with many warehouses offering taking orders late into the evening for next day delivery (Richards, 2011b). Hence, despatching procedure needs to closely coordinated with order picking procedures. Moreover, if the facility has only one dock receiving and despatching should be time coordinated (Ackerman, 2004).

Consolidation process encompasses grouping picked orders by their destinations and splitting pallets for better load balance Van Den Berg (2007). Shipping documents accompany the orders and show the quantities of each product, they are printed after goods were presented at the despatching areas Van Den Berg (2011).

Prior to loading the vehicle is inspected if it is fit for carrying cargo, with special attention being paid to: cleanness, waterproof, strong odours that can contaminate the cargo, and correct temperature or humidity in case of environmentally sensitive products (Richards, 2011b).

Lastly, during loading procedure goods are loaded onto truck or other mode of transport with proviso that goods for customer who will be visited first should be loaded last (Richards, 2011b; Van Den Berg, 2007). Loading procedure may be done manually or with using various types of MHE like: pallet jacks, forklifts, conveyor belts or automated pallet loaders (Richards, 2011b). At loading, goods are deducted from the warehouse inventory (Chua et al., 2009).

Fig. 4.5: Challenges faced by warehouse managers.

4.3 Operational problems in a warehouse

Warehousing literature points to numerous problems faced by warehouse managers. These challenges can be categorised into four subsets: operational, inventory, technological, and environmental, as presented in Figure 4.5.

The main operational challenge faced by typical warehouse manager is improving efficiency and productivity while reducing cost (Richards, 2011b), especially in the area of quality and accuracy of order picking. Additionally, there is an operational complexity in handling multiple products from multiple customers, while sharing the same warehouse between various customers also poses significant coordination challenges (Cheung et al., 2009).

Inventory related challenges faced at warehouses include lack of physical storage space, which is limited by the size of facility and used racking, as well as lack of real-time information related to the product status and storage locations (Cheung et al., 2009). Lack of real-time information about inventory affects product expiry date management and accuracy (Richards et al., 2013).

Technological innovations aimed to alleviate some of warehousing operational complexities pose an additional challenge, as they require justification of return on investment (ROI) and are often accompanied by implementation issues (Qiu Sr and Sangwan, 2005; Richards, 2011b). For discussion on RFID implementation obstacles in the warehouse please refer to Section 4.7.

Lastly, warehouse managers are faced with environmental challenges that include impact of operation on environment and health and safety regulations. Environmental issues play increasingly important role due to to concerns about sustainability and customer's demand for "green logistics" (McKinnon et al., 2012). Health and safety regulations are imposed by government but also self imposed to limit occupational risks in the warehouse (Emmett, 2005; Richards, 2011b) and include: fire safety, preventing slips and trips, manual handling, working at height, use of vehicles/MHE or other warehouse equipment.

Concluding, "despite much progress made in the development and integration of systems and automation in warehouses... and distribution centers are still confronted with many formidable challenges in improving the efficiencies in operating a variety of warehouses" (Qiu Sr and Sangwan, 2005). Hence, in recent years attention of both logistics academics and practitioners was turned towards RFID technology and its application in warehousing (Bahr and Lim, 2009, 2010; Lim et al., 2013), which is the focus of the next section.

4.4 Use of the RFID in a warehouses

4.4.1 Operations in the RFID enabled warehouse

In order to gain competitive advantage the warehouse information should be as accurate as possible; hence inventory, safety stock and material handling operations can be precisely planned. RFID systems enable to track pallets, cases, cartons and individual items in order to achieve leaner inven-

Fig. 4.6: Operations in RFID the enabled warehouse

tories, increased automation and stock visibility. The typical installation of RFID system in a warehouse is presented in Figure 4.6 and discussed in the following subsections.

4.4.2 Receiving with the RFID

RFID tagged items arrive at the warehouse shipping dock, which is equipped with RFID reader. As pallet or cases are moved off the truck into receiving areas, their codes are wirelessly read and system verifies match between pallet/cases ID tags and source of product and purchase order. If there are no discrepancies, the receipt is confirmed, otherwise staff is alerted and discrepancy report is produced.

Using RFID in the receiving operation makes it fast and effective as identities of products are automatically verified, documentation can be instantly created, manual data entry is eliminated, and lastly manual labour is significantly reduced (no manual counting, breaking boxes and pallets, etc.).

4.4.3 Put-away and storage with the RFID

From the receiving area items are moved either manually or with use of equipment to their respective storage locations. Tag ID and location ID is being read to update the WMS about assigned storage bin.

Use of RFID in put-away and storage activities allows for visibility of inventory and locations, and real time tracking of materials (allows for random storage). Additionally, if items are put-away at incorrect locations by untrained staff, these errors are may be spotted and rectified immediately. Moreover, manual updates of tally sheets and WMS are eliminated, as data collected by RFID system. Lastly, stockouts are reduced, as inventory is complete and accurate.

4.4.4 Order picking with the RFID

During order picking when items are collected from their locations, their RFID tags are read in order for WMS to validate the picking quantities, update inventory and manages the order picking route.

Use of RFID in order picking leads to elimination of picking errors, as picker chooses right product in right quantity first time. Additionally, efficient picking routes are planned and are based on current stock availability. RFID also enables control over pickers straying from route and picking from not assigned locations (i.e. picking bulk from fast pick area). Lastly, increased storage accuracy ensures that stock is at expected locations.

4.4.5 Despatching with the RFID

As products enter shipping area their RFID tags are wirelessly read and checked against data in the WMS. The WMS will then update the inventory, confirm the order and delivery along with advice for staff on any specific loading sequence.

Use of RFID in despatching activity helps to achieve the error-free shipments of orders to customers (so called perfect order). As all the items needed to fulfil an order are present and packed before the order is dispatched. Additionally, with RFID the manual scanning is eliminated, documents can be automatically created.

4.5 Examples of the RFID implementation at a warehouse

Several studies have been carried out to establish the impact of RFID technology on the warehouse operations. Chow et al. (2007) tested the RFID system at the premises of a logistic company from Hong Kong. Active RFID readers were mounted on dock doors in order to read inbound and outbound items and track movements of material handling equipment. Active tags were installed on pallets and forklifts. Staff ID cards were tagged for tracking their movement around warehouse sections. Order pickers were issued with handheld computers to manage the picking route and order list. During the trial period the improvement in inbound and outbound operations were noted. Quality of service was significantly improved fewer shipping errors, which resulted in decrease in customers complaints. Authors reported an improvement in the warehouse operations. The weak point of proposed solution is the use of active tags to identify pallets. Active tags are significantly more expensive than passive ones. It is a common practice in warehousing that pallets and totes are not returned and left at customer's premises. Using active tags on non-returnable pallets, or even on returnable ones, would put a company on financial strain which could be higher than achieved the benefits.

Passive RFID tags were used by Poon et al. (2009) to tag products and racking system in order to realise the visibility of inventory. Time for retrieving information related to warehouse operation was significantly reduced, from 1 minute to 5 seconds. Similar results were obtained by García et al. (2007), where Spanish e-retailer installed RFID readers and tagged products at its warehouse. Significant decrease in shipping errors and improvements in order picking were noted. Poon et al. (2008) presents RFID system to track material handling equipment at manufacturer's warehouse. It resulted in average time for locating forklifts was considerably reduced from 3 minutes to 2 seconds.

As shown in practical studies, the application of RFID technology at warehouse facilities brings numerous benefits in managing the operations. Next section focuses on RFID benefits in the warehouse.

4.6 Benefits of using the RFID at a warehouse

Recent publication by Lim et al. (2013) comprehensively analysed benefits provided by RFID to the warehouse operations. Authors divided benefits achieved at warehouses into three categories: product/resource related, operational, and informational. Summary of these benefits is presented in Table 4.1.

Research community is called by Lee and Özer (2007) to provide more substantiated analysis and have more balanced view of RFID despite its numerous benefits. Hence, the next section is focused on difficulties of RFID technology implementation in warehousing.

4.7 Obstacles to using the RFID in a warehouse

Bahr and Lim (2009) and Lim et al. (2013) point out to five obstacles to successful implementation of RFID in the warehouse:

Benefit category	Benefits
Product / Resource related	• Reduced shrinkage • Product tracking • Space utilisation • Asset/resource management • Reduced stockouts • Lower inventory • Better expiry date management
Operational	• Reduced material handling • Faster exception management • Quality control • Supply and production continuity • Better customer service • Reduced labour • Lower costs • After sale services • Reduction in unofficial supply chains
Informational	• Increased data accuracy • Improved information sharing in supply chain • Better determining of arrival/despatch times • Tags can contain more information and be updated

Tab. 4.1: RFID benefits in the warehouse.

1. Uncertain return on investment
2. Integration with legacy systems
3. Failing RFID performance
4. Concerns about privacy and security
5. Standards development

Return on investment (ROI) is one of the crucial criteria for companies to consider when introducing a new technology as this will point to their expectation on quantifiable benefits Collins (2004). Industry leaders indicated their lack of trust in RFID providing satisfactory ROI (Attaran, 2007; O'Connor, 2005; Vijayaraman and Osyk, 2006; White et al., 2008). In order to justify ROI for RFID implementation in the warehouse, academics and professionals should look into the benefits of the RFID as provided by Lim et al. (2013). Additionally, new applications for RFID could be found, like for example RFID-TDABC which is proposed in this thesis.

Integration with legacy systems such as WMS, Enterprise Resource Planning (ERP), and Customer Relationship Management (CRM), which is indicated by Vijayaraman and Osyk (2006). However, integration of RFID even with very old IT systems is possible (Fleet, 2004). Seamless integration of systems is a great challenge, but it has the possibility to significantly benefit a wide range of business activities.

Failing RFID performance was indicated by several studies on RFID (Bosselmann and Rembold, 2006; Kabadurmus et al., 2007; Porter et al., 2004; Singh et al., 2009; Wu et al., 2006). These and similar studies may have impacted the perception of RFID as unreliable, despite claims from RFID vendors ensure about 100% reading accuracy (Swedberg, 2009). Perception of poor performance from earlier RFID experiences among practitioners may need time to overcome.

Concerns about privacy and security are especially expressed by general public, which understands RFID to track people and objects anywhere and any time Hardgrave and Miller (2006). There are also concerns about unauthorised readings (Roussos and Kostakos, 2009) and threats of job security (Curtin et al., 2007). These issues may be resolved by increasing the protection measures embedded in the RFID hardware and software, while public privacy concerns about RFID may be alleviated by education and legislation.

Standards development was pointed out since early years of RFID as the key issue for future growth of this technology (Vijayaraman and Osyk, 2006). Nowadays existing RFID standards are now more established (Finkenzeller, 2010) and RFID vendors are now complying with Gen-2 standard in order to promote wider interoperability, some vendors are still using their proprietary protocol for specific purposes/applications. Moreover, power regulations and certification procedures are still varied from country to country.

4.8 Summary

This chapter presented a warehouse and its operations: receiving, put-away, storage, order picking, and despatching. Operational problems in a warehouse are discussed and use of the RFID technology was given as a way to alleviate them. Examples of the RFID implementation at a warehouse were presented. Then benefits of using the RFID at a warehouse were evaluated and obstacles to using the RFID in a warehouse were addressed. Next chapter evaluates several approaches to costing in a warehouse.

5. COSTING IN WAREHOUSES

5.1 Introduction

This chapter evaluates several approaches to costing in warehouses. Firstly warehouse costs frameworks are discussed in Section 5.2. Their evaluation leads to proposing a combined perspective on warehouse costs in Section 5.3. Next, the traditional costing method and the alternatives are discussed in Section 5.4. Section 5.5 presents the activity-based costing (ABC) and contrasts the benefits and advantages of the ABC model with the problems, especially focusing on the logistics industry. Time-driven activity-based costing (TDABC) is a further development of the ABC model and the TDABC benefits and advantages are evaluated and compared with the ABC model in Section 5.6. Lastly, Section 5.7 provides a summary for this chapter.

5.2 Warehouse costs frameworks

Warehouses bear the costs of acquisition and the use of resources, such as people, equipment, materials, external services and facilities (Kaplan and Atkinson, 1998). Resources used to perform activities, are recorded as costs in organisation financial systems. The relationship between resources and costs is highlighted in a cost definition by Drury (2008), stating that costs are "monetary measures of the resources sacrificed or forgone to achieve a specific objective"[pg. 27].

Warehousing costs constitute about 22% of logistics company costs, leading to increasing concerns among warehouse managers regarding the financial aspects of warehousing (Richards, 2011b, pg. 212). Warehouse managers are responsible for cost reductions, meeting customers' requirements and proposing inventory reduction strategies. In order to successfully achieve these tasks, managers need to have a complete and accurate understanding of all warehouse costs and cost drivers. Only then they can keep a day-to-day operation costs under control and submit accurate figures to the company's general budget.

Warehouse costs are discussed in the literature from three complementary perspectives: warehouse activities (Roth and Sims, 1991), capital and operating costs (Napolitano, 2003) and total warehouse cost (Richards, 2011b).

5.2.1 Warehouse activities cost perspective

Roth and Sims (1991) present warehousing costs as they are incurred in each warehousing activity: receiving, storage, dispatching, "inventorying", deliveries, and value added activities such as: repackaging and relabelling. Costs of the receiving activity include manual and office labour, forklift time and use of pallets. Storage costs are the sum of items like building rent, depreciation on leasehold improvements, repairs, maintenance, and property taxes. Dispatching costs consist of office labour, office supplies and deliveries: cost of fuel, repairs, maintenance, depreciation and labour. Cost of value added activities accounts for: labour, warehouse and office supplies. Lastly, costs of general labour and other costs are added. Warehouse costs from activities perspective and their charge drivers are summarised in Table 5.1

Direct handling expense is considered to be all those costs associated with moving product into or out of the warehouse. The primary components are labour and equipment to handle the product (MHE), supplies, and other

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Fig. 5.1: Warehouse cost elements by operation.

items related to the handling, picking and dispatching. A wide range of warehousing activities from unloading vehicles to handling product returns is included in the category of handling expense. Examples of expenses in the warehouse are shown in Figure 5.1.

Handling equipment costs include the expenses for lift trucks and other material handling equipment, including the cost of fuel, maintenance, rental fees etc. With the increased optimisation of warehouse activities, including the use of RFID data, costs savings can be made, as less material handling equipment might be necessary.

Additional warehouse costs include expenses on pallets and supplies, demurrage costs, recouping warehouse damage and other costs. As well as costs incurred during value added activities, like: repacking, case breaking, re-labelling.

5.2.2 Capital and operating costs perspective

Another perspective of warehouse costing is offered by Napolitano (2003), where capital and operating costs are divided into two categories. Capital costs encompass all costs related to planning and designing new warehouse facility. As such, they include building or construction costs, material handling and storage equipment costs, as well as costs of IT systems included

Activity	**Costs**	**Charge drivers**
Receiving	manual/office labour, forklift time, use of pallets	labour-time, pallet-usage
Storage	building rent, depreciation on leasehold improvements, repairs, maintenance, property taxes	space used
Dispatching	office labour, office supplies	rate per bill of lading
Inventorying (maintaining stock records)	office labour and supplies	no direct charge
Deliveries	cost of fuel, repairs, maintenance, depreciation, labour	fixed fee and/or weight
Value added	labour, warehouse supplies, office supplies	labour time
Labour	staff wages, payroll taxes, employee benefits, insurances	labour time
Other costs	management salaries, commercial insurance, utilities, licenses, advertising, PR	

Tab. 5.1: Warehouse costs by activity and their charge drivers. Based on Roth and Sims (1991)

in other special costs and peripherals. Operating costs are associated with the daily costs of running the warehouse operation, and as such are specific to every warehouse. Typically, operating costs include costs of: direct storage, direct handling, and operating and general administration. Summary of capital and operation costs and examples of cost factors is presented in Tables 5.2 and 5.3.

Warehouse capital costs

Warehouse capital costs depend on the type of facility that is constructed or acquired. Building and construction costs depend on ceiling height, size of loading/unloading bays and their number, and type of materials used for flooring, walls and insulation. Warehouses tailored to specific industry requirements (i.e. temperature controlled environments) cost more. Additionally, location also may play a crucial role and warehouses in densely

Capital costs category	**Cost factors**
Building and construction	Ceiling height, location, bay size, floors, walls, insulation and temperature control.
Material handling equipment	Stacker cranes - costs are typically quoted as a part of total system due to their specific applications. Lift trucks - costs function of: load capacity, maximum lift height, duty cycles per hour, operating aisle width and normal operating hours. Conveyors - costs function of: type of a conveyor, linear length required and complexity: number of turns, sorts and mergers.
Storage equipment costs	Costs of purchasing new or used storage equipment like: pallet racks, stacking frames, cantilever racks, drum stacking racks, shelving system, flow racks, mezzanines etc.
Other special costs	Planning and design costs (consultancy), training costs, IT system and other miscellaneous costs.

Tab. 5.2: Capital costs of the warehouse

Operating costs category	**Cost factors**
Direct storage	Rent or depreciation and interest, real estate taxes, facility insurances, facility exterior and interior maintenance, grounds maintenance, storage equipment depreciation, interest and maintenance, utilities, security, pest control, other specific costs.
Direct handling	Warehouse labour (wages, bonuses etc.), handling equipment usage and maintenance, warehouse supplies (i.e. wrap, tape, packaging), demurrage, damage to merchandise, and other costs.
Operating administration	If particular warehouse closes, these expenses disappear: management and clerical salaries, "purchased" temporary workforce, office equipment (rental, maintenance, depreciation), office cleaning service.
General administration	Support overall business mission: Executive salaries, marketing salaries, other support staff, office space, data processing, taxes, legal and professional fees, travel expenses, donations, bad debt, other expenses.

Tab. 5.3: Operating costs of the warehouse

populated locations with limited space availability or in proximity to strategical transport networks carry higher costs.

Another element of warehouse capital costs is the material handling equipment, which depending on the operation requirements may include: stacker cranes, lift trucks and conveyors. Stacker cranes are priced as a part of the whole system, but cost of lift trucks is a function of their performance (i.e. load capacity). Conveyor prices depend on the complexity of the set up and number of turns, sorts and mergers used.

Warehouses are typically furnished with storage equipment, which also counts towards capital costs. The cost of storage equipment, for example: pallet racks, stacking frames, cantilever racks, drum stacking racks etc., may be lowered by purchasing used storage equipment.

Lastly, capital costs include expenses on consultancy in planning and designing of the facility, training, equipping warehouse with the IT system. These miscellaneous costs are incurred at the start of the the new or modernised warehouse facility.

Warehouse operating costs

Operating costs vary from warehouse to warehouse and depend on specifics of an individual operation. Operating costs are categorised into two groups: direct operating costs and administration costs. Direct operating costs include costs related to ownership (or rental) of the storage facility and handling costs. Administration costs relate to costs of operating and general expenditures.

Direct storage expenses include rent or depreciation and interest, real estate taxes and maintenance costs for facility exterior and interior, storage equipment, utilities, security, pest control and other specific costs. These types of costs are incurred even if the warehouse is not used for operation.

Conversely, direct handling costs are accrued when warehouses are operating and include wages and bonuses for warehouse labour, usage and maintenance of material handling equipment and warehouse supplies like boxes, wraps etc. Additionally, demurrage, accidental damage to handled merchandise may be added.

Similarly, the operating administration costs disappear if a warehouse closes its operation. These include: management and clerical salaries, temporary workforce, office equipment (rental, maintenance, depreciation), office cleaning service.

In contrast, the general administration costs exist independently from warehouse operation and are incurred in the process of supporting the overall business mission. General administration costs includes salaries of executives and other support staff (i.e marketing, HR, finance), office space, taxes, legal and professional fees, travel expenses, donations, debt management and other expenses.

5.2.3 Total warehouse costs perspective

A total warehouse costs perspective is presented by Richards (2011b) and similarly to classification provided by Napolitano (2003). It distinguishes between storage, handling and overhead costs, but also introduces new classification. Summary of this approach is presented in the Table 5.4.

Firstly, fixed and variable costs are identified. Fixed costs are not dependent on the level of services provided by the warehouse (i.e. basic salaries), whereas variable costs are a function of warehouse activity level (i.e. bonuses, overtime, equipment running costs).

Secondly, Richards (2011b) distinguishes direct and indirect categories

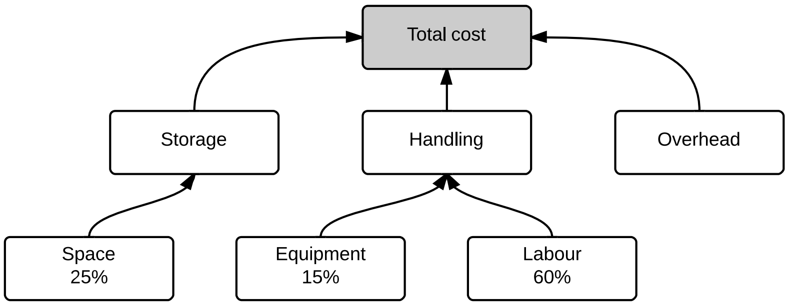

Fig. 5.2: Warehouse cost tree based on Richards (2011b).

for labour costs. Direct labour costs relate to warehouse operators, their wages, insurances, safety wear, welfare and training. The indirect costs include the same elements but for warehouse managers, supervisors and administrators.

Lastly, a separate category for material handling equipment is introduced and split into fixed and variable costs. This approach is opposed to categories by Napolitano (2003), where such costs are part of direct handling.

Each of these aforementioned categories (see Table 5.4) adds up to the warehouse total cost. Total cost elements are illustrated by Figure 5.2. According to Richards (2011b) the labour (i.e. wages) is the most expensive element constituting approximate 60%, followed by space costs (i.e. rent/lease on facility) at about 25% and equipment costs (i.e. depreciation/rental and running costs) at 15%. It should be noted that these estimations are for typical warehouse that receives/dispatches goods on pallets and stores them at ambient temperature without automation (Emmett, 2005; Richards, 2011a).

Costs category	**Cost factors**
Space costs	Rent/leasing costs on building/land; building depreciation; insurance; rates; utility costs; fixtures and fittings depreciation; racking depreciation; refrigeration plant depreciation; repairs and maintenance; cleaning, security, other building equipment depreciation; waste disposal.
Direct labour costs (fixed)	Warehouse operators: wages including on-costs; personnel insurance; safety wear; welfare; training.
Indirect labour costs (fixed)	Warehouse management including supervisors and administrators: wages including on-costs; insurance; safety wear; welfare; training.
Labour costs (variable)	Overtime and bonuses.
Equipment costs (fixed)	Depreciation/lease costs or rental costs.
Equipment costs (variable)	Running costs, eg fuel, tyres, lubricants; packaging, pallets, stretch wrap.
Overhead costs	Management, finance, HR, IT and administration: salaries and on-costs plus benefits like mobile phones, accommodation, etc.; company cars and running costs; office equipment and furniture depreciation/lease/rental costs; cost of IT software and hardware.
Overhead costs	Sales and marketing: salaries and on-costs plus benefits like mobile phones, accommodation, etc.; company cars and running costs; marketing spend, i.e. advertising, exhibitions, brochures, etc.
Miscellaneous costs	Communication costs; postage; bank charges and interest payments; funding costs/cost of finance; insurance; legal and professional fees.

Tab. 5.4: Total warehouse costs categories according to Richards (2011b)

5.3 Combined perspective on warehouse costs

Three perspectives on warehouse costs discussed in a previous Section lack adequate integration. In order to address this problem a combined perspective on warehouse costs is proposed. This combined perspective on warehouse costs combines: warehouse activities (Roth and Sims, 1991), capital and operating costs (Napolitano, 2003) and total warehouse cost (Richards, 2011b).

A combined perspective on warehouse costs enables quick identification of cost categories and subcategories. The combined perspective is pictured in Figure 5.3.

Total cost of the warehouse consists of the sum of capital and operating costs. Capital costs are sum of following elements: building & construction, material handling equipment, storage equipment and other special costs. Building & construction and storage equipment costs are made up of space costs defined in Table 5.4. Material handling equipment costs consists of fixed equipment costs (see Table 5.4).

Operating costs are costs incurred during the warehouse activities - basic activities are illustrated in Figure 5.3. Operating costs are the sum of the following elements: direct storage, direct handling, operating and general administration. Direct storage consists of space cost elements relating to storage systems and their maintenance. Direct handling has several elements such as: direct labour costs (fixed), variable labour costs and variable equipment costs. Operating administration consists of fixed indirect labour costs. Lastly, general administration is made up of various overhead and miscellaneous costs.

Warehouse cost elements adding up to the total cost of warehouse can be measured in several ways. Techniques to calculate warehouse costs are

Fig. 5.3: Warehouse cost tree in combined perspective.

introduced in the next section.

5.4 Techniques to calculate warehouse costs

5.4.1 Traditional costing techniques

Traditional costing techniques were developed before mass globalisation and the ubiquity of computer technologies. At that time companies did not operate in a global environment and use of automation technologies was not widespread. Decision making was based predominately on calculations of direct labour cost and direct production costs. Auxiliary costs and overhead costs were assigned on an arbitrary basis by a volume-based costing technique, which used labour hours or machine hours as criterion (Richards, 2011b). Such approaches were traditionally used by logistics companies (Somapa et al., 2012).

An increase in automation in manufacturing, logistics, and retail not only led to more available capacities but also allowed for more detailed data collection. Automation reduced the impact of direct labour costs on a product or activity and costs that could be attributed to overheads increased. Indirect costs and overheads started to increase and traditional volume-based costing techniques became increasingly inaccurate (Themido et al., 2000).

Eventually, as conventional techniques stopped accurately reflecting costs of diversified operations (No and Kleiner, 1997), other methods of costing were introduced.

5.4.2 Alternative approaches to costing

There are several alternative approaches to traditional costing:

- Economic value added (EVA)
- Supply-chain operations reference-model (SCOR)
- Balanced scorecard
- Activity-based costing (ABC)
- Time-Driven activity-based costing (TDABC)

Economic value added (EVA) is an indicator of financial performance and it monitors the level of value created by a firm and is regarded as a mega-trend revolutionizing supply chain logistics (Bowersox et al., 2000). Bowersox et al. (2000) explains: "EVA is used by stockholders to determine whether management is creating or destroying wealth. EVA is calculated as annual operating profit after tax, minus a cost of capital charge." An examination of 566 companies conduced by Chen and Dodd (1997) concluded that "improving EVA performance is associated with a higher stock return" and that "EVA is more powerful than traditional measures of accounting profit in explaining stock return". Young (1997) points out to problems using EVA with transfer pricing in vertically integrated companies and cost allocation in a financial system. Young (1997) summarises EVA in following words: "EVA, by itself, does nothing to resolve the dilemmas that often plague divisional performance measurement in large firms".

Supply-chain operations reference-model (SCOR) is a standardized process reference model of the supply chain developed by The Supply-Chain Council in 1996 (Poluha, 2007). SCOR models allow the comparison of supply chains across a wider range of industries and are used to: evaluate and compare supply chains' performance potential, analyse and optimize integrated supply chains within the logistics chain, and to determine suitable places for the assignment of software and its functionality within the supply chain (Poluha, 2007). The SCOR model uses four distinct processes: source, make, deliver, and plan (Huan et al., 2004). The benefits of SCOR are well established in the literature and include the following results (Bolstorff and Rosenbaum, 2003; Huang et al., 2005): 1)cost reduction and customer service improvement, offering on average 3% rise in total operating income; 2) within 12 months of project implementation, almost 26% improvement in return on investment (ROI); 3) noticeable improvement in return on assets (ROA) because of cognizant decisions in capital investment; 4) standard supply chain definitions and interpretations facilitating use of standard features of IT systems, reducing the operating costs drastically; 5) 13% profit step up through continuous improvements in supply chain management.

Balanced scorecard is described by Kaplan and Norton (1995) as a tool to help "managers be able to view performance in several areas simultaneously" and covers four areas:

- How do customers see us? (customer perspective)
- What we must excel at? (internal perspective)
- Can we continue to improve and create value? (innovation and learning

perspective)

- How do we look to shareholders? (financial perspective)

Balanced score card is often used to measure the strategic supply chain performance (Bhagwat and Sharma, 2007; Brewer and Speh, 2000).

Activity-based costing (ABC) and time-driven activity-based costing (TDABC) are discussed and evaluated in their respective Sections 5.5 and 5.6.

5.5 Activity-based costing (ABC)

Activity-based costing (ABC) was introduced in the late eighties in a response to weaknesses of the traditional accounting methodology. Firstly it was defined by Johnson and Kaplan (1987) and further defined by Cooper (1988). Among several explanations of the ABC, the description provided by Hicks (1992) is said to be the clearest and most concise (Griful-Miquela, 2001). It states: "Activity-based costing is a cost accounting concept based on the premise that products (and/or services) require an organization to perform activities and that those activities require an organization to incur costs. In activity-based costing, systems are designed so that any costs that cannot be attributed directly to a product, flow into the activities that make them necessary. The cost of each activity then flows to the product(s) that make the activity necessary based on their respective consumption of that activity."

A simple illustration to the aforementioned definition of the ABC is presented in Figure 5.4. Various costs that cannot be attributed directly to products or service are related to activities that make them necessary. Subsequently, these activities are associated with products or services that make the activity necessary. Hence, the ABC methodology allocates the

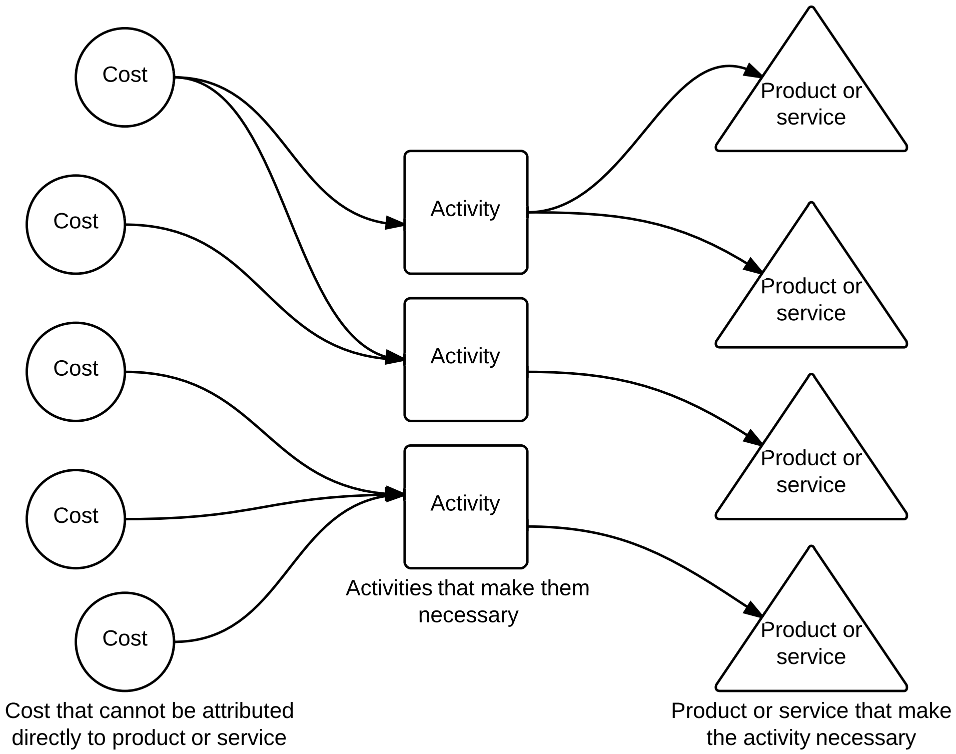

Fig. 5.4: Flow of costs in Activity Based Costing.

indirect costs to processes in a way that accurately reflects how these costs are incurred (Richards, 2011b).

Table 5.5 defines terminology used in ABC methodology: activities, cost objects, resources and cost drivers.

5.5.1 Steps to implement the ABC model

Steps to design and implement the ABC model are presented in a Figure 5.5. The first step is identification and it requires a comprehensive knowledge of the business, its operations and roles performed by members of staff. Identification of relevant activities is done by observation and record keeping (Richards, 2011b). At this step, Pirttil and Hautaniemi (1995) suggests to document material flows in order to capture activities and used resources.

Term	Definition
Activities	Tasks or sets of tasks that require the consumption or utilisation of resources and result in the completion of a specific service, or in the physical transformation of a product from one state to another.
Cost object	Final product or service created as a result of the performance of an activity, or of a chain of activities.
Resources	Ingredients required for the production of a good or of a service. In their most basic form understood as: labour, material, and capital.
Cost driver	Variable that demonstrates a logical and quantifiable cause and effect relationship between the utilisation of resources, the performance of activities, and the final cost object(s).

Tab. 5.5: ABC terms and their definitions. Based on Themido et al. (2000).

In the next step the major cost elements should be identified. This is typically achieved by analysing the line items on a budget or expense ledger (Griful-Miquela, 2001). Once activities and major costs are established, the relationships between activities and costs should be determined.

A subsequent stage then identifies cost drivers. Cost drivers are used to assign costs to activities and activities to cost objectives (like: products, services, or customers). This allocation is based on the usage of the activity (Griful-Miquela, 2001). In order to establish accurate cost drivers Richards (2011b) suggests asking staff about what would increase or decrease the time and effort to perform activities. This complements questions posed by Cooper (1990) about ease of obtaining the data required by the cost driver; correlation between actual consumption of the activity and the consumption implied by the cost driver; and behaviour induced by the cost driver. A sample of cost drivers and activities that they impact are presented in Table 5.6.

Next steps in designing ABC model is to plan a cost accumulation model and to begin data collection that will feed into the model. Griful-Miquela (2001) point out that the aim of the exercise should be accuracy and not precision. Successively, the simulation of the organisation's cost structure

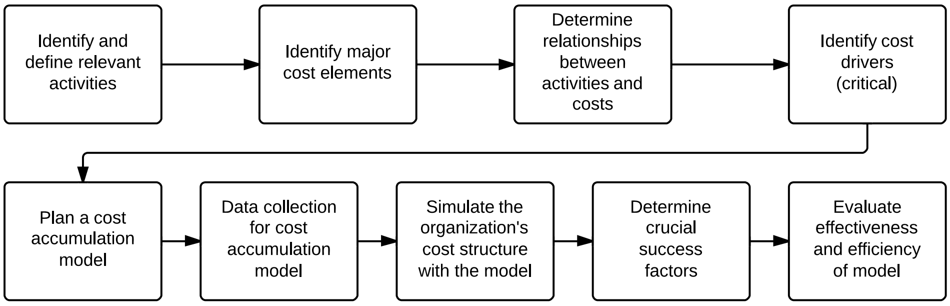

Fig. 5.5: Steps to design the ABC model (based on Griful-Miquela (2001))

Activity	**Cost drivers**
Receiving	Order volume and order source, quantity and unit load
Put-away	Quantity, cubic volume, weight
Storage	Quantity, cubic volume
Picking	Number of pick locations, number of order lines, number of units to pick
Despatching	Unit load quantity

Tab. 5.6: Warehouse activities and their cost drivers adapted from Griful-Miquela (2001) and Richards (2011b).

takes place. Completing calculations of operational and overhead costs along with documenting use of services by each customer allows for establishing client's profitability and their impact on the business (Richards, 2011b).

Lastly, success factors are determined and the model is evaluated for its effectiveness and efficiency. As some researchers indicate that ABC models are too expensive to maintain (Barrett, 2005; Everaert and Bruggeman, 2007; Kaplan and Anderson, 2007) these last steps should not be overlooked.

5.5.2 Benefits and advantages of the ABC model

Since its inception ABC models have gained considerable interest from businesses due to their benefits (Gunasekaran et al., 1999). These benefits have been widely discussed in the literature (Bellis-Jones and Develin, 1995; Innes and Mitchell, 1990; Malmi, 1997) and their summary is found in Table 5.7.

Firstly, ABC methodology allows for more accurate product and service costing as opposed to aforementioned conventional method. Such accuracy is especially demonstrated where business have significant non-volume-related overheads.

Granularity of cost data provided by the ABC methods allows analysis of costs by management and customers. In this way ABC helps to improve the company's bottom line by identifying customers that directly affect cost structure and therefore is utilised in customer profitability analysis.

Moreover, during work on ABC model, activities creating value for customer are identified. This allows to identification of activities that do not add value or streamline the operation.

ABC allows also for easier capacity analysis, as it measures the cost of used resources. After deduction from total resources supplied it is easy to establish the spare or excess capacity. In traditional models unused capacity was assigned to customers, but ABC allows the identification of the maximum level at which companies can efficiently operate.

Lastly, the use of ABC reduces uncertainty regarding the cost model, as it provides correct diagnosis of state of business. Hence, strategic decisions regarding can be made confidently.

Next section shows how benefits of ABC methodology are realised in the field of logistics and supply chain management.

5.5.3 Use of the ABC model in logistics

The ABC model was enthusiastically received by the logistic industry with many companies implementing it to asses their costs (Pohlen and La Londe, 1994). Beginning with implementation trials, the ABC later became an industry standard as it seems to be well suited to asses consumption of

Benefit	Description
Accuracy	More accurate product and service costing, especially where non-volume-related overheads are significant.
Granularity	Allows to to analyse costs by areas of managerial responsibility and customers.
Improved bottom line	Allows to recognise, which customers directly affect the cost structure of the business and therefore helps to analyse customer profitability.
Understanding of costs	Provides better understanding of cost behaviour. Identifies changes in costs due to customisation of product or service to customer requirements.
Streamline activities	Allows to focus on activities creating value for customer and identify for elimination the activities that do not add value.
Easier capacity analysis	ABC measures the cost of used resources and after deduction from total resources supplied it is easy to establish the spare/excess capacity.
Reduced uncertainty	ABC provides correct diagnosis of state of business, which is a solid basis for strategic decisions.

Tab. 5.7: Benefits of ABC methodology adapted from Griful-Miquela (2001).

logistical resources (Pirttil and Hautaniemi, 1995; Pohlen and La Londe, 1994; Richards, 2011b).

Roth and Sims (1991) state that planning, measuring, allocating and reporting of warehouse costs is a vital component in successful warehouse management. Hence it is argued that the ABC is well suited for warehouse and distribution environments based on this premise: costs are caused by activities. With the application of the ABC, the cost of every warehouse activity can be estimated.

According to Pirttil and Hautaniemi (1995) application of the ABC in logistics results in more accurate cost estimates than traditional systems. The biggest benefits of cost accuracy are envisaged in the areas of logistics strategy and policy making, control of the activities and pricing decisions.

In order to evaluate these benefits the ABC methodology was implemented at the Portuguese 3PL company (Themido et al., 2000). Implementation of the ABC helped to establish unit costs of handled and transported items in distribution regions and played role in improving logistic services. Moreover, precise knowledge of unit costs was used for contract negotiations and adjustments in the service that were satisfactory for 3PL and their client.

Similar application of ABC is made at land transportation company in Turkey (Baykasoğlu and Kaplanoğlu, 2008), where ABC was integrated with business process modelling. Study highlights a striking difference between the results obtained by traditional cost accounting practice and results calculated with ABC methodology. For example, on one route traditional method indicated \$143 profit, whereas ABC shown \$1140 loss on the same service. These differences are attributed to correct distribution of overheads in ABC methodology.

Another area where ABC was applied is reverse logistics in the supply chain. Goldsby and Closs (2000) used ABC to re-engineer the reverse logistics channel and provide robust methodology for tracking the operational costs. Study focused on reverse logistics of beer bottles from retailers to distributors, which is required by law in Michigan (USA) and has a long practice there. Results of ABC analysis demonstrated several gains that were achievable for supply chain participants. By foregoing competition concerns and using the third party for bottle collection companies saved on time, retail space and activities performed bringing the estimated saving to \$11.4 million per year. Study demonstrated value of ABC in increasing operational profitability.

Sometimes cooperation between companies emerges into a logistics alliance, which is studied by (Chao et al., 2010). The ABC methodology is proposed as an accurate cost accounting method for alliances, which alleviates issues with disproportional distribution of indirect costs, vague fee structure and generally poor cost management.

A particular area for application of ABC is airline logistics, which is analysed by Banker and Johnston (1993). Findings show that although output capacity and volume are important cost drivers, the significance of operations-based drivers should not be overlooked. Operations-based drivers are related to both product diversity and production process complexity. Practicality of ABC for airline logistics is shown in study by Tsai and Kuo (2004), which demonstrates ABC calculations for establishing costs of operating aeroplanes and flight routes. ABC is found not only to be suitable for calculations of industrial cost indicatives such as cost per available seat kilometres, but also useful for calculations of production and marketing variances and idle passenger capacity. The ABC is not only found to be useful for in the air cost calculations, but also for establishing cost controls in airport operations and ground handling (Koch and Weber, 2008).

Presented studies shown that ABC is suitable for the use in wide range of logistics applications: warehousing, land transportation, 3PL, complicated supply chains and airline logistics. However, these successful implementations indicated also several deficiencies with the ABC. These issues are discussed in the next section.

5.5.4 Problems with the ABC model

Early surveys of ABC model found several issues with this technique: unavailability of data, shortage of resources to carry out surveys, managers resistance to change and lack of senior management commitment, lack of training and IT inadequacy, as well as difficulties in linking cost drivers to individual products and collecting quantitative information on cost drivers (Armitage and Nicholson, 1993; Innes et al., 1992; Nicholls, 1992; Pohlen and La Londe, 1994). As some of these issues were resolved with maturity of ABC methodology, developments in IT technologies and more committed management, more recent literature presents also other concerns.

Researchers indicate that using ABC methodology leads to complexity and increased costs of model creation, implementation and maintenance (Mena et al., 2002). Pirttil and Hautaniemi (1995) suggest that size of ABC model may be a result of large number of implemented exceptions. Creation of ABC model is also found to be time consuming and laborious (Barrett, 2005), especially due to long surveys with employees and high demand for data processing (Öker and Adigzel, 2010). Such in-depth studies to establish relationship between overheads, services and customers require a lot of work and cost, especially that data may be difficult to obtain (Richards, 2011b).

Once the model is established, modifying it and adapting to changes in the organisation is also considered costly, complex and difficult (Everaert and Bruggeman, 2007; Kaplan and Anderson, 2007). Modifications become an issue when the model needs to be calibrated frequently as the volumes of sales and ranges of product change (Themido et al., 2000).

There are also issues with the ABC methodology itself. Firstly, process of translating costs to activities carries a risk of subjectivity (Mena et al., 2002). Subjectivity may be a result of interdepartmental politics (Mena et al., 2002) or behavioural hurldles during interviews, i.e. employees exaggerating their performance (Öker and Adigzel, 2010). Secondly, the created ABC cost models are organisation specific and are not transferable (Themido et al., 2000). Lastly, Goldsby and Closs (2000) suggests using ABC with caution to avoid cost distortions caused by similar cost centres executing different activities.

Aforementioned problems may explain why significant number of early adopters of ABC methodology did not implement it and relatively few companies fully employ it (Gosselin, 2006; Somapa et al., 2012). Number of large companies using ABC to some extent in Europe and United States is estimated to be only about 20% (Gosselin, 2006). Gosselin (1997) even argues that there is an paradox in regards to ABC implementation. ABC is widely popularised in academic world through journal articles and textbooks, but it is not widely used by the companies. It may be suggested that traditional ABC model is inadequate to accurately capture complex nature of companies, like it is the case with real-life logistics operations (Somapa et al., 2012).

In response to the ABC's weaknesses the time-driven activity-based costing (TDABC) was proposed as "a simpler and more powerful path to higher profits" (Kaplan and Anderson, 2007). The TDABC is discussed and evaluated in the next section.

5.6 Time-driven activity-based costing (TDABC)

Many companies discontinued their interest in the ABC as it did not capture complexity of their operations, was tedious to implement and high cost to build and maintain models were unjustifiable (Gosselin, 2006; Somapa et al., 2012). In order to avoid these issues the Time-Driven Activity-Based Costing (TDABC) was proposed by Kaplan and Anderson (2004). The concept of TDABC was initially developed by Steven Anderson in 1997 and used in his company Acorn Systems Inc and since 2001 it was further developed in cooperation with a Harvard Business School professor Robert Kaplan (Diaconeasa et al., 2010; Öker and Adigzel, 2010). Kaplan and Anderson addressed issues that were problematic in ABC models: scalability, granularity and coordination between multiple sites. TDABC being a revised version of ABC was successfully implemented in over 100 companies (Kaplan and Anderson, 2004) and applied for example at financial institutions, medical sector, libraries, manufacturing and logistics (Everaert et al., 2008; Kaplan and Anderson, 2007; Öker and Adigzel, 2010; Pernot et al., 2007).

The basic premise of the TDABC methodology is that it only requires two parameters for each group of resources:

1. cost per time unit of supplying resource capacity
2. unit times of consumption of resource capacity by products, services, and customers.

For example, calculating department costs with the TDABC requires:

1. capacity cost rate (the unit cost of supplying capacity) for the department
2. capacity usage by each transaction processed in the department

Using only two estimates simplifies the model and allows management to directly estimate demand for resources levied by each transaction, product or customer. Such simplicity contrasts with a typical ABC model, where resource costs would be first assigned to activities and then to product or customers (Kaplan and Anderson, 2004).

5.6.1 Time equations in the TDABC model

Everaert et al. (2008) argues that the breakthrough of the TDABC model is in the time estimation. Each activity has its duration time estimated depending on its characteristics. These characteristics are called "time drivers", because they increase or decrease duration of activity. Time equations model how time required per activity is affected by several drivers.

Example of a time equation for order processing is presented in an Equation 5.1

Order processing time expressed in an Equation 5.1 depends on number of time drivers (X_1, X_2 and so on). Time drivers may depend on number of lines (X_2) or number of price quotes (X_3) that need to be prepared. Other time drivers ($X_1, X_4 ... X_8$) take the value of 1 or 0 depending on the case. For instance, company received an order from a new international customer with 5 line items, requiring 5 price quotes, requiring completing forms for customs, shipping, and clearance. Such order will be processed in 62 minutes ($5 + 5 + 2 * 5 + 5 * 5 + 3 + 6 + 8 + 0 + 0$).

Use of time equations is an improvement over the ABC methodology. Time equations in the TDABC may contain many parameters that increase size of the model in a linear way, not exponentially as it was the case in the ABC (Kaplan and Anderson, 2007).

Although simplicity of time equations is considered to be the biggest advantage of the TDABC (Everaert et al., 2008) there are several additional benefits of using TDABC, which are discussed in the next section.

$$
\begin{aligned}
&\text{Order processing time (minutes)} = 5 + 5X_1 + 2X_2 + 5X_3 \\
&+ 3X_4 + 6X_5 + 8X_6 + 4X_7 + 15X_8, \text{ where:} \\
&X_1 = 1, \text{ if new customer, otherwise } 0 \\
&X_2 = \text{number of line items} \\
&X_3 = \text{number of price quotes} \\
&X_4 = 1, \text{ if customs form required, otherwise } 0 \\
&X_5 = 1, \text{ if shipping declaration required, otherwise } 0 \\
&X_6 = 1, \text{ if clearance required, otherwise } 0 \\
&X_7 = 1, \text{ if same day delivery required, otherwise } 0 \\
&X_8 = 1, \text{ if credit on hold, otherwise } 0
\end{aligned} \tag{5.1}
$$

5.6.2 Steps to implement the TDABC model

According to Kaplan and Anderson (2007) a typical implementation process of the TDABC model at a company should consist of four stages: preparation, analysis, pilot model, and a rollout. Figure 5.6 presents typical TDABC implementation.

Preparation phase starts the implementation process with a purpose of creating a plan of action and gathering the team members. Team members should have backing of senior management staff, as otherwise it may be a hindrance to implementation Somapa et al. (2012). Next, the TDABC model outline should be created with its data requirements and availability.

Analysis phase ensues afterwards. This phase is characterised by gathering data and conducting department interviews. Depending on data availability, especially with companies employing the CRM and the ERP systems, interviews with regular employees may be avoided Kaplan and Anderson (2007). Meanwhile, estimated time equations and corresponding capacity cost rates should be established. Analysis phase concludes with finalising data requirements and completing the pilot model.

Third phase starts when the aforementioned pilot model is completed. This phase focuses on building the TDABC model and validating it. Öker and Adigzel (2010) suggest at this stage following steps to build the TDABC model:

1. Groups of resources (departments) that perform activities are identified. Costs of these groups are determined from the trial balances of the company.

2. Capacity cost rates are calculated for each department. To calculate these, total departmental costs are divided by the practical time capacity of each department.

3. Time equations are developed for each department. To develop time equations, processes within departments and activities within processes are analysed.

4. Total capacity demanded from the departments by the products is calculated. Time drivers and amounts of time drivers are determined and placed in the time equations.

5. Total costs of the resources demanded by the products are calculated by multiplying the capacity cost rates of each department by the total capacity demanded by the products.

Once the TDABC model is built, the next step is to run it and validate it (Kaplan and Anderson, 2007).

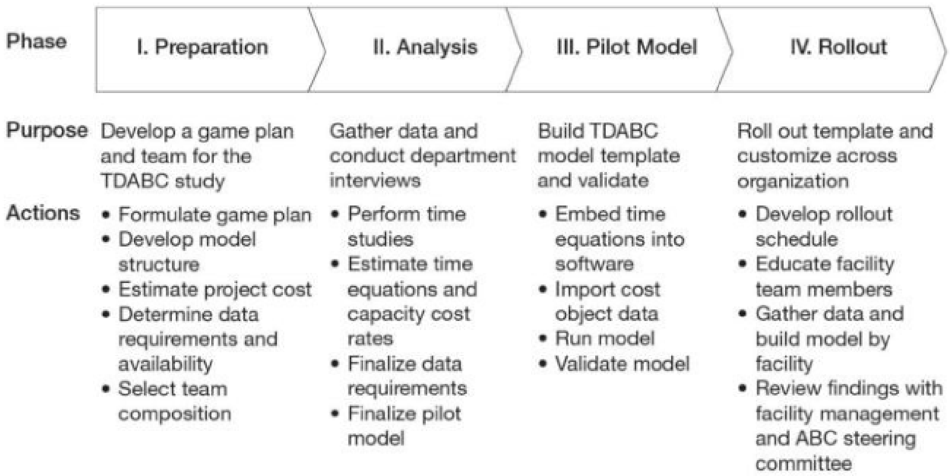

Fig. 5.6: Typical Time-Driven ABC Implementation (from Kaplan and Anderson (2007))

Rollout is the final phase of the implementation process. At this stage the validated TDABC model is ready to be used across the organisation subject to its customisation. Meanwhile, regular employees are educated about use of the TDABC in the organisation. Employees should be explained that the TDABC is not a time measurement system, but a costing model (Everaert et al., 2008). Lastly, findings from the rollout should be analysed between the management and the implementation team.

5.6.3 Benefits and advantages of the TDABC model

Kaplan and Anderson (2007) identify numerous benefits of TDABC methodology, which can be summarised by their book tag line "a simpler and more powerful path to higher profits". The numerous TDABC benefits are presented in a Table 5.8.

Foremost advantage of the TDABC is that building an accurate model is easier and faster comparing to the ABC because only two parameters are needed: capacity cost rate and capacity usage. Case study by Öker and

Adigzel (2010) at manufacturing company demonstrates that the TDABC models are easier to use than standard costing models. Additionally, TDABC models are not as easily affected by changes as ABC models. Everaert et al. (2008) examines depreciation increase at a company and how it affects ABC and TDABC models. ABC required change of eleven activity-cost drivers rates, whereas TDABC required only one. Similarly, case study by Stout and Propri (2011) revealed that TDABC models are more accurate than traditional ABC models.

Data and parameters required by the TDABC model are already available from enterprise resource planning (ERP) and customer relationship management systems (CRM) (Stout and Propri, 2011). Hence, the TDABC model is not based on employee guesses regarding the proportion of time spent on activities (Kaplan and Anderson, 2007). Furthermore, TDABC models are easily scalable to enterprise wide models via enterprise-scalable software and database technologies (Kaplan and Anderson, 2007).

Costs in the TDABC model are driven to transactions or orders using their specific characteristics, i.e. orders, processes, suppliers, and customers. Such fine granularity is found to be especially appropriate for environments where the operations and processes are fast changing, i.e. warehouses (Everaert et al., 2008) or in any industry or company with complexity in customers, products, channels, segments, and processes (Kaplan and Anderson, 2007). Granular information provided by the TDABC may also assist users with identifying the root cause of problems as reported by Everaert et al. (2008), where employing the TDABC gave better understanding of the profitability of logistics service strategies. It should be noted that TDABC model can be broadly defined and still capture operations in detail Everaert et al. (2008).

Another advantage of the TDABC model is that it does not have to be run daily, but periodically. Kaplan and Anderson (2007) suggest running monthly calculations to capture the economics of the most recent operations.

Results of the TDABC model provide visibility required to analyse and improve processes and capacity utilisation, and according to Öker and Adigzel (2010) the results are more relevant for improvements in profitability and capacity management. Moreover, use of the TDABC helps to forecast resource demands, which allows companies to budget for resource capacity on the basis of predicted order quantities and complexity. For example, improved capacity planing linked to use of the TDABC was noted in case study by Everaert et al. (2008).

Lastly, use of the TDABC models enables fast and inexpensive model maintenance (Kaplan and Anderson, 2007). The TDABC may be even implemented and maintained with the popular spreadsheet programs (Somapa et al., 2012). Likewise, Stout and Propri (2011) suggests that though for companies with uncomplicated business models the TDABC may be "virtually maintenance free" even large corporations may benefit from its easy maintenance.

All aforementioned benefits are available to organisations that decide using the TDABC model. Process of creating the TDABC model and implementing it in a organisation is outlined in the next section.

Next section discusses and evaluates use of the TDABC model in logistics.

5.6.4 Use of the TDABC model in logistics

To date, there are relatively few studies on use of the TDABC in logistics and it may be asserted that it is due to newness of this cost calculating

Benefit	Description
Easier and faster model building	Requires only two parameters: capacity cost rate and capacity usage.
Data accessible from ERP, CRM	Data collection typically does not require interviews and employees guesses.
Scalable models	Models can be extended to whole organisation.
Periodical model calculations	Model can be run on weekly, monthly basis.
Meaningful results	Results provide chance to improve profitability, capacity management, and forecasting.
Simple implementation	Models can be implemented even in spreadsheet software.

Tab. 5.8: Benefits of TDABC methodology.

methodology. However, existing studies find the TDABC well suited to capture inherent complexity of logistic activities (Everaert and Bruggeman, 2007). The TDABC is also found to be favourable received by logistics managers due to its simplicity (Somapa et al., 2012) and easy calculations expressed in time units (Kaplan and Anderson, 2007).

Literature extensively analyses the TDABC implementation at a Belgian wholesaler (Everaert and Bruggeman, 2007; Everaert et al., 2008), which brings favourable results to the TDABC method. Comparison between costs calculated with the TDABC and the ABC shown that the ABC oversimplified 64% of the activities and incorrectly allocated 55% of all indirect costs (Everaert et al., 2008). Moreover, the TDABC was found to give better understanding of the profitability of logistics service strategies and lead to improved profitability management.

Corresponding successful results in the TDABC implementation are discussed by Varila et al. (2007), where an electronics wholesaler is an object of action research case study. The TDABC is employed to measure costs of picking operation and time equations are used to established estimated picking times for product categories. Results suggest suitability of The TD-ABC for warehouse environment and further extending it with automatic data collection methods. Proposition of using the TDABC with the RFID technology, which is a subject of this Thesis, is discussed in a Chapter 6.

Another study that applies the TDABC methodology in logistics is done by Diaconeasa et al. (2010) and it is focused on company in Romania. Comparison between the ABC and the TDABC model finds maintenance of the ABC too time consuming and unable to capture complexities of logistics operations of goods receipt. Authors conclude that the ABC is suitable to establish cost of uncomplicated activities and the TDABC is the right methodology for the dynamic and complex ones.

The TDABC was also combined with the theory of constraints and applied by Zhang and Yi (2008) to a small Chinese distribution centre. Calculation of resources capacity utilisation reveals spare capacity between order picking and shipment checking. Authors suggest distributing workforce more equally between these operations to avoid bottlenecks, which will lead to cost savings and more optimised operation.

More recently, work by Somapa et al. (2012) claims to unlock the potential of the TDABC for small logistics companies. The research focuses on implementation of the TDABC at a small transportation company in Thailand. Use of the small sized company is especially interesting as it proves that simplicity of the TDABC does not require large size or abundant corporate resources. Successful implementation of the TDABC at this company reveals several difficulties in employing the TDABC at small enterprises. Foremost issue is the lack of quantitative data to build time equations and estimate capacity costs. It is suggested that required data may be obtained from financial statements, bill of orders and discussions with management. It is however suggested that even coarse data should be captured regularly in order to increase accuracy of the model. Secondly, small enterprises may have activities that are not running continuously and these are found to be difficult to estimate with the TDABC. Nevertheless, it is advised to treat the TDABC as a tool to achieve even light accuracy rather then precision (Kaplan and Anderson, 2007). Lastly, small companies that introduce the TDABC may have problem with estimating time allocation for consolidated services, for example multi drop deliveries, full truck loads versus less than truck load. Authors state that joint costs for transport operations are a important challenge in building the TDABC model for logistics companies. Despite these limitations, Somapa et al. (2012) recommend the TDABC as a simple and effective tool for cost calculations at logistic companies.

Literature review on using the TDABC in logistics revealed its suitability for this industry. Implementation studies also revealed some weaknesses of the TDABC model. Challenges facing the TDABC are discussed in the next section.

5.6.5 Problems with TDABC model

The literature discusses several issues with the TDABC model that mainly focus on the errors in estimates and especially overestimations in time equations.

Cardinaels and Labro (2009) argue that errors in the time estimates happen the during data collection stage. When people are asked about their working time, they overestimate the real time by up to 37%, a study revealed. Hence, the TDABC is critiqued for its reliance on employees' memory to estimate the timing for activities. Therefore Barrett (2005) states that such time measurements are based on assumed estimates and as a result may lead to increased cost figures. Similarly, Somapa et al. (2012) also caution about time measuring errors. It is also suggested that due to cognitive limitations measurement errors increase when activities are less aggregated Cardinaels and Labro (2009).

According to Cardinaels and Labro (2009) people are more confident about estimates expressed in percentages then in absolute estimates like minutes. It is asserted that this may lead to a rejection of results obtained by using the TDABC method, especially when it comes to performance evaluation or decision making. Although worker's submission of their estimates in percentages rarely includes their idle time, Cardinaels and Labro (2008) conclude that the presence of large overestimation bias will more likely remove any benefits intended by the TDABC, when using time measurements (i.e. minutes).

Another problem raised with the TDABC technique, especially at it's early stage, was that its claim to maximise benefits of implementing activity based costing initiatives are debatable (Barrett, 2005). It was also pointed out that in order to be accurate the TDABC needs as much data collection as ABC method. Furthermore, some researchers suspected TDABC to be a repackaged ABC model and claimed that similar methods were used before in corporations (Barrett, 2005). The TDABC is questioned as a "new wine or just a new bottle" (Gervais et al., 2009).

Lastly, a few concerns about TDABC suitability for logistics should be reiterated. According to Somapa et al. (2012) the weaknesses of TDABC are shown when it comes to calculate joint costs for transportation as it is unable to accurately capture issues related to service consolidation.

Despite the apparent limitations of TDABC implementation case studies show that it is a suitable system for use in logistics. The weaknesses attributed to TDABC, especially inaccuracies with time estimates, are addressed by the proposition of RFID-TDABC in Chapter 6.

5.7 Summary

This chapter evaluated several approaches to costing in warehouses. Firstly warehouse costs frameworks were discussed and their evaluation led to proposing a combined perspective on warehouse costs. Next, the traditional costing method and the alternatives (such as EVA, SCOR, balanced scorecard, ABC, TDABC) were discussed. A detailed presentation and evaluation of the activity-based costing (ABC) was conducted alongside contrasting the benefits and advantages of the ABC model with the problems with a focus on the logistics industry. Time-driven activity-based costing (TDABC) was presented as a further development of the ABC model and TDABC benefits and advantages were evaluated and compared with the ABC model. Evaluation of TDABC led to enumerating several weaknesses of the TDABC model. Problems with using the TDABC model are addressed by the proposition of the RFID-TDABC in a next chapter.

6. THE RFID-TDABC MODEL: A NEW WAY TO CALCULATE WAREHOUSE COSTS

6.1 Introduction

This chapter introduces the RFID-TDABC model as a new way to calculate warehouse costs. Section 6.2 gives a short overview of the RFID-TDABC model followed by a theoretical background of the RFID-TDABC model in a Section 6.3. Next, the research value of the RFID and the TDABC integration is considered in a Section 6.4. Then the RFID-TDABC model at work is explained in a Section 6.5. The numerous benefits of using the RFID-TDABC model are presented in a Section 6.6. Lastly, Section 6.7 provides a summary for this chapter.

6.2 Short overview of the RFID-TDABC model

The RFID-TDABC is an extension of the TDABC methodology with the RFID data. Concept of the RFID-TDABC was proposed by (Bahr and Lim, 2010), the author of this Thesis, as a way to maximise the benefits of the RFID implementation at the warehouse and opened a new area for application of the RFID technology within the warehouse environment. Hence the RFID is not only used to alleviate operational problems, but the RFID generated data in connection with the TDABC model allows for accurate costing of warehouse activities. The RFID-TDABC model is a response to requirement from the wholesalers for an instrument capable of linking logistics process information and financial data (van Damme and van der Zon, 1999). Next sections discuss the theoretical background of the RFID-TDABC model, explain how the RFID-TDABC model is used to calculate warehousing costs and how its use benefits the warehouse management.

6.3 Theoretical background of the RFID-TDABC model

Theoretical background of the RFID-TDABC model has its foundations in the warehouse management and cost accounting.The RFID-TDABC model is also an answer to several indications of research directions.

Warehouse managers are under a lot of stress to keep the warehousing operations costs low (Frazelle, 2002). Low operational costs are important especially in the competitive 3PL market, where new contracts are often awarded on the basis of the lowest price (Richards, 2011b) and every penny needs to be accounted for (Varila et al., 2007). In order to achieve better operational and cost advantage the RFID technology is employed to improve the warehouse operations, stock identification, material handling, tracking of equipment, locations and personnel as well as managing exceptions. For the sake of extending these benefits this Thesis proposes the RFID-TDABC model where the RFID data is used for accounting purposes, helping the company to better understand and calculate costs and expenses of the warehouse operations.

According to Cross (2011) warehouse managers should have access to processes' cost records and generate charging and billing information based on performed activities as every warehouse activity gives a potential for charging. The RFID-TDABC responds to these requirements by giving a way to recording operating costs and form a robust costing model. As such, the RFID-TDABC model is able to provide costing data useful in contract negotiations and renewals, and indicate areas with high costs were improvements and savings may be made (Cross, 2011).

Accounting techniques presented in Chapter 5 aimed to capture warehousing costs and give warehouse managers better understanding of costing issues. Despite move from traditional accounting techniques to the ABC model and more recently to the TDABC model, there is still a reliance on measuring operational times with interviews and chronometers. Conducting such measurements openly affects performance of warehouse workers and is explained by Hawthorne effect – people usually are more productive when watched (Adair, 1984). Inaccurate time calculations for the TDABC technique are avoided in the RFID-TDABC model, where the RFID technology is employed to measure time. According to Barrett (2005) problems with the TDABC can be solved with robust and accurate data. Use of the RFID-TDABC model that provides objective time measurements helps to avoid the TDABC pitfalls in this area.

Using Automated Data Collection (ADC) as tools for building the TD-ABC model was discussed by (Varila et al., 2007). At that time, barcodes were the most popular form of the ADC and the RFID technology was slowly emerging as part of the ADC. Nowadays the RFID market is more mature and the number of the RFID implementations in warehouses increases. Hence, proposition of the RFID-TDABC as an "automatic accounting of the future" fits into Varila et al. (2007)'s vision as it enables to follow the SKU paths around warehouse and record the RFID data in real time.

6.4 Research value of the RFID and the TDABC integration

Research value of the RFID and the TDABC integration is highlighted by the RFID-TDABC model being an answer to a numerous research questions posed in a literature.

The RFID-TDABC model was developed in a response to three research questions posed in a literature: if the RFID can provide "automatic accounting of the future" (Varila et al., 2007), if and how the RFID can be used in conjunction with TDABC (Everaert et al., 2008), and what is the impact of measuring time with the RFID on the TDABC model (Somapa et al., 2012).

Merging the TDABC with the RFID technology was mentioned in passing by Everaert et al. (2008), while discussing experiences in using the TDABC for cost modelling at a wholesaler. The RFID-TDABC model fills this research gap and shows how actual times spent on each operational subtasks are measured using the RFID technology.

The RFID-TDABC model answers question posed by Somapa et al. (2012) on impact of the measurements of time with the RFID on the TDABC model. Time measurements obtained from the RFID data are easily fed to the TDABC model and allow for accurate time and cost estimates at granular level. Hence, the RFID-TDABC model alleviates the TDABC problem with inaccurate measurements.

Integration between the RFID and the TDABC model is a direct response to the weaknesses of the TDABC and its inaccuracies with time estimates. Cardinaels and Labro (2009) argues that errors in the time estimates happen during data collection stage. Likewise, Cardinaels and Labro (2008) there is a presence of a large overestimation bias when using self-reported activity time measurements. The RFID-TDABC model directly addresses this weakness of the TDABC by collecting time estimates without a human intervention, thus eliminating bias and errors.

In conclusion, the RFID-TDABC model fills the research gap indicated by warehousing and accounting literature to link logistics process information obtained with the RFID technology and financial data. Next section presents how the RFID-TDABC model works.

6.5 The RFID-TDABC model at work

Concept of using the RFID data in conjunction with the TDABC accounting methodology, namely the RFID-TDABC model, arises from information trail that is available when the RFID tags are traced in a warehouse. Early studies of the RFID called it "avalanche of data" (Jones et al., 2005) and indicated that business applications need upgrades to allow for seamless integration with the RFID (Bahr and Lim, 2009). Nowadays, due to developments in computer technology such issues are less of a problem (Wu et al., 2013). Hence, companies that decide to implement the RFID technology can not only benefit from tracking the items, but also make use of the RFID data.

Gonzalez et al. (2006) explain that the RFID data generated during the operation is a stream of tuples that are defined as $(EPC, location, time)$. EPC, which stands for Electronic Product Code, is an individual RFID tag number. *Location* indicates area where tag was read by the reader and *time* denotes time of the reading. Readers scan tags on interval or continues basis and one tag can be read several times in the same location (Dua and Meyers, 2007), which creates aforementioned "avalanche of data". By using data cleaning techniques, as indicated by Gonzalez et al. (2006), the RFID data can be presented as $(EPC, location, time_{in}, time_{out})$, where $time_{in}$ is time when the RFID tag was first read at $location$, and $time_{out}$ is time when tag left the $location$. This allows to establish time spent in each location and duration of activity.

In order to explain how the RFID-TDABC combines the RFID data captured during warehouse operation and the TDABC time equations lets take a warehouse with five operational stages: receiving, put-away, storage, order picking, and despatching. Figure 6.1 illustrates these operations and the RFID data records. The RFID data is recorded as a tuple $(EPC, location, date, time)$, where *time* is recorded as hh:mm (hh-hours, mm-minutes) and *date* of reading is recorded in format DD/MM/YY (DD-day, MM-month, YY-year). As an example, a pallet tagged with the RFID with code tag_1 arrives at the warehouse and is processed at receiving area called $location_1$ on 13/3/2012 at 11:03.

First recorded data tuple is $(tag_1, location_1, 13/3/12, 11:03)$. After processing at receiving, the pallet is put away on forklift truck to storage, during this time installed the RFID reader identifies the pallet as tag_1 and new data is recorded. Then first occurrences of entering into storage area, being picked as part of an order, and entering despatching area are respectively recorded. Gathered information allows to calculate processing times at each activity – for example, put-away procedure was the shortest: 4 minutes, and storage was the longest 196,939 minutes. These time measurements indicated as t_1, t_2, t_3, t_4 become part of time equation for processing pallet with tag_1 as illustrated in Figure 6.1.

In addition to that, time measurements with the RFID allow also for greater granularity and subsets of warehousing processes may be tracked as well. Would require time equations defined at process level and indicating beginning and end of each sub-process within the RFID data tuple.

The purpose of the RFID-TDABC is to aid warehouse manager with a tool to make use of the RFID beyond simple tracking of items, which is the most common benefit of this technology (Lim et al., 2013). Implementation

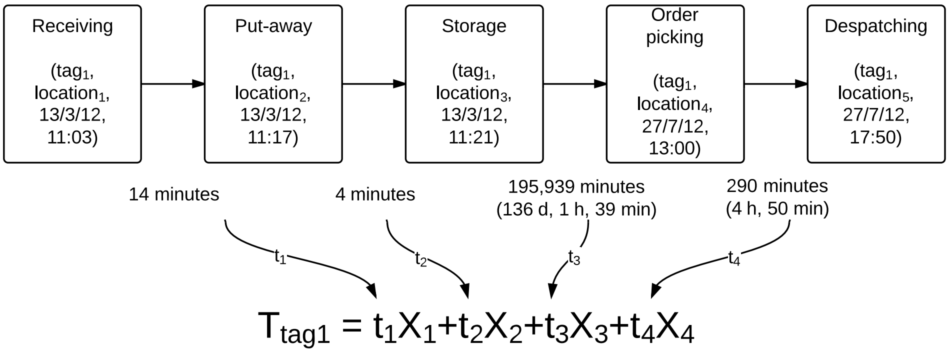

Fig. 6.1: Example of RFID data captured in warehouse and its relation to TDABC time equation.

of the RFID-TDABC does not require additional hardware resources, i.e. more RFID readers or special RFID tags, as existing RFID infrastructure may be used. The RFID-TDABC may be promptly implemented at the warehouse that already uses the RFID based track and tracking. In order to make use of the RFID data, the RFID-TDABC requires the host system business application to be able to analyse data tuples and extract information about time spent at each location, or duration of activity. This may require adding additional data management layer to extract and analyse timings, but additional computing power (i.e. adding mainframe computers) may not be needed as indicated by (Gonzalez et al., 2006).

6.6 Benefits of using the RFID-TDABC model

Implementation of the RFID-TDABC model at the warehouse has several benefits that transpire from merging logistical and financial accounting techniques. The RFID-TDABC being a combination of the RFID and the TDABC links advantages and robustness of both techniques while moving to a new area of application.

Firstly, warehouse that implements the RFID-TDABC benefits from capabilities provided by the RFID technology in areas of product/resource tracking, operational optimisation, and its information capabilities (Lim et al., 2013). Wireless identification of objects and full visibility of products and resources is extended with implementation of the TDABC as a costing methodology (Bahr and Lim, 2010). Intelligent use of the RFID data to track time and feed it to the TDABC model alleviates problems with accuracy of the TDABC time estimates. Hence, warehouse benefits from easier and faster accounting model building with the TDABC, its scalability and meaningful results. Moreover, the TDABC becomes more robust and reliable as data human factor is eliminated from time measurements due to the RFID.

Additionally, merge of logistic and financial data provided by the RFID-TDABC gives warehouse manager a better understanding of incurred costs. The TDABC is well suited to capture inherent complexity of logistics activities and has been successfully implemented in warehouses (see Section 5.6.4). With added robustness of the RFID time measurements model of the TD-ABC gains more confidence not only of managers, but also it becomes easier to accept by warehouse staff. It is also possible to constantly review the costs, as the the RFID data is continuously being collected during the warehouse operations (Bahr and Lim, 2010). Findings from the RFID-TDABC model will enable warehouse managers to take necessary operational improvements, which combined with the RFID technology already existing at the warehouse may bring even greater savings of time and money.

Capability of the RFID-TDABC to exactly identify cost of each activity may be especially interesting to 3PL operators running warehouses. Bahr and Lim (2010) indicate that greater insight into the running costs of the 3PL business, gives warehouse managers possibilities of setting the price at the fair level, in order to benefit their company and the customer.

In addition to that, with abundance of possible time measurements obtained with the RFID-TDABC new key performance indicators (KPI) can be constructed. New KPIs may bring better understanding of the warehouse activities and help to improve the operation, as well as help to track and motivate staff to better performance.

Summing up, implementation of the RFID-TDABC as a way to calculate costs, brings benefits of the RFID technology and the TDABC as an accounting technique. Adding to that ease of implementation at business application level the RFID-TDABC is a solution for organisations that want to make better use of an already installed RFID technology or those who consider introducing either the RFID or the TDABC.

6.7 Summary

This chapter introduced the RFID-TDABC model as a new way to calculate warehouse costs. A short overview of the RFID-TDABC model was followed by a theoretical background of the RFID-TDABC model. Next, the research value of the RFID and the TDABC integration was considered, which highlighted alleviating weaknesses of the TDABC model. Then the RFID-TDABC model at work was explained. The numerous benefits of using the RFID-TDABC model were presented. A case study implementation of the RFID-TDABC model is presented in the next chapter.

7. CASE STUDY

7.1 Introduction

This chapter presents a case study of a warehouse operstion used by a company called Exquisite Bathrooms. Firstly, the case study company is introduced in Section 7.2 and its current state and accounting methodology is outlined. Next, warehouse activities are analysed in Section 7.3. Analysis of warehouse activities leads to implementation of the TDABC method throughout warehouse activities in Section 7.4. The next building block of this case study is setting up an RFID system at the warehouse. The RFID equipment and associated investment costs are presented in Section 7.5. Following from the implementation of TDABC and RFID, Section 7.6 describes use of RFID-TDABC in four warehouse activities: receiving, put-away, order picking, and despatching. A results overview is provided in a Section 7.7. Lastly, Section 7.8 provides conclusions for this chapter.

7.2 Exquisite Bathrooms: company overview

Exquisite Bathrooms is a distributor of bathroom products and was set up in 2008. The company imports a wide range of products from a limited number of key suppliers in China and operates mainly in the United Kingdom market (about 15 regular customers), with some export to Ireland, France, and Turkey. Key four product categories are: bathroom furniture, brass-ware, accessories, and tiles. Products are divided into 300 sub-categories. The

Cost category	Costs Itemised	Resource pools	Month	Year
Space costs	Rent/leasing costs incl council tax	Warehousing unit	£ 2,666.67	£ 32,000.00
	Insurance	Warehousing unit	£ 166.67	£ 2,000.00
	Utility costs (gas & electricity)	Warehousing unit	£ 350.00	£ 4,200.00
	Repairs and maintenance	Warehousing unit	£ 41.67	£ 500.00
	Cleaning	Warehousing unit	£ 100.00	£ 1,200.00
	Security	Warehousing unit	£ 100.00	£ 1,200.00
	Waste disposal	Warehousing unit	£ 40.00	£ 480.00
Direct labour costs	Wages	Warehousing unit	£ 4,000.00	£ 48,000.00
	Safety wear (PPE)	Warehousing unit	£ 83.33	£ 1,000.00
Indirect labour costs	Wages	Management/admin unit	£ 8,000.00	£ 96,000.00
Equipment costs (variable)	MHE Running costs (i.e. fuel, tyres, lubricants)	Warehousing unit	£ 166.67	£ 2,000.00
	Vehicle running costs (i.e. fuel, tyres, lubricants), 2 vans	Transport unit	£ 2,000.00	£ 24,000.00
	Packaging	Warehousing unit	£ 100.00	£ 1,200.00
	Pallets	Warehousing unit	£ 50.00	£ 600.00
	Tooling	Warehousing unit	£ 25.00	£ 300.00
Overhead costs (management, finance, HR, IT and administration)	IT costs (hardware/software)	Management/admin unit	£ 416.67	£ 5,000.00
	Finance/accounting	Management/admin unit	£ 250.00	£ 3,000.00
	Marketing spend (i.e. advertising, brochures, etc.)	Management/admin unit	£ 1,666.67	£ 20,000.00
	Sales expenses, i.e. travels	Management/admin unit	£ 833.33	£ 10,000.00
Miscellaneous costs	Communication costs (mobile, internet, fax)	Management/admin unit	£ 600.00	£ 7,200.00
	Insurance	Management/admin unit	£ 83.33	£ 1,000.00
	Legal and other proffesional fees	Management/admin unit	£ 166.67	£ 2,000.00
	Courier services (parcels)	Transport unit	£ 2,000.00	£ 24,000.00
Equipment costs (one off)	Purchase price - forklift - £3,000			
	Purchase price - 2 delivery vans - £10,000			
Total			**£ 23,906.67**	**£ 286,880.00**

Fig. 7.1: Warehouse costs for year 2013.

company sells products to local independent bathroom-ware distributors, which constitute a sizeable part of the UK bathroom-ware market. There is some seasonal variations in demand for their products with the highest demand being in summer and autumn.

Sales for 2013 were approximately £500,000 which according to managers was a slight increase on the previous year. The company fleet consists of two delivery vans, and one forklift truck used at the warehouse. The warehouse size is 12,000 square feet and its schematic layout is presented in Figure 7.2. Exquisite Bathrooms has 15 staff, including 10 warehouse operators (5 permanent and 5 temporary workers). Figure 7.1 presents warehouse costs of Exquisite Bathrooms for year 2013, specifically cost categories, groups of resources, and costs incurred by month and year.

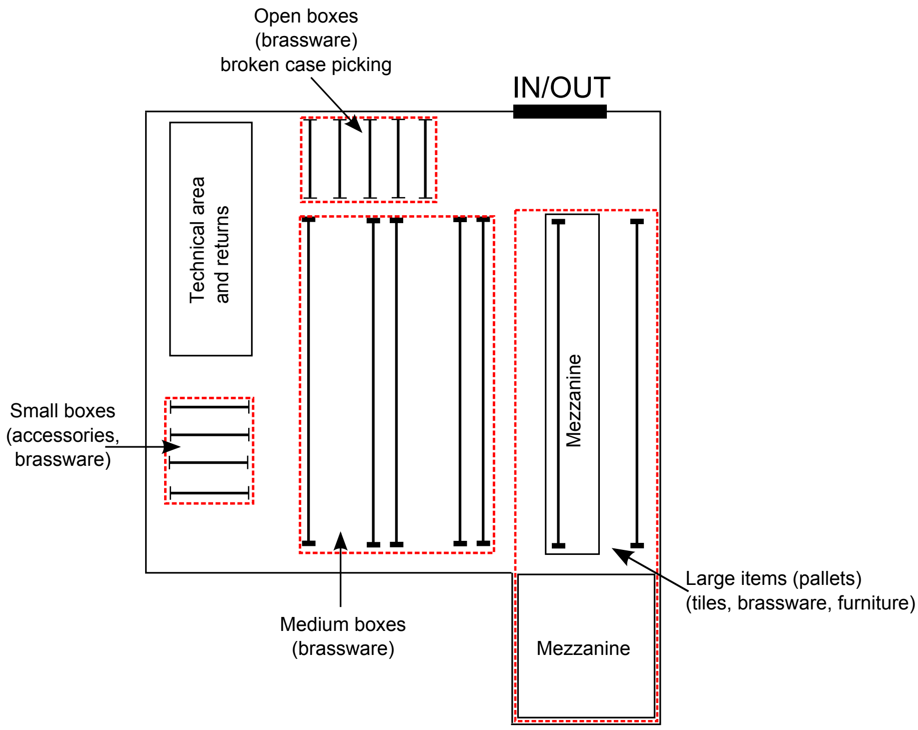

Fig. 7.2: Schematic warehouse drawing.

Product category	Description
S	Small products, with weight below 20kg. Picked up and handled by one person.
M	Medium products, with weight between 40kg to 60kg. Picked up and handled by two persons.
L	Large products, with weight above 60kg and up to 1,000kg. Handled with a forklift, typically it is a pallet with goods.

Tab. 7.1: Product categories at Exquisite Bathrooms warehouse

7.2.1 Accounting at Exquisite Bathrooms

The company uses a traditional costing model using MS Excel and Sage to manage its costs. An external accounting firm is used for consolidating the final accounts. During interviews with a manager it was stated that Exquisite Bathrooms has a ”very poor insight into its warehouse activity costs”. Therefore there is a perceived need to improve cost control in their operations. Next section discusses activities in the company’s warehouse.

7.3 Exquisite Bathrooms: overview of warehouse activities

Warehouse activities at the Exquisite Bathrooms company follow a typical warehouse operation: receiving, put-away, storage, order picking, despatching. In order to gain a better understanding of these activities direct observations were carried out at the warehouse and activity flowcharts created. Starting from receiving, these are discussed in the following subsections.

7.3.1 Product types

While discussing warehousing activities with the management it emerged that apart from the product categories, SKUs are also divided into three groups based on their weight and mode of handling. The three categories are small (S), medium (M), and large (L). Table 7.1 describes the product categories.

7.3.2 Receiving

Typically there are two to four deliveries to the Exquisite Bathrooms warehouse per month. Goods arrive by truck in fully loaded 40'ft containers. When the truck arrives delivery documents are checked, and in the case of a discrepancy management is called to investigate. Next, an unloading document is printed off and a team is assigned to unload the container. When all goods are unloaded items are manually counted to check if their type and quantity match. In the case of a discrepancy a manual count is repeated, and if there is a mismatch a discrepancy report is created. After this, storage locations are assigned and records in the computer system are manually updated, while the truck departs from site. Figure 7.3 presents a schematic flow of the receiving activity. Receiving is followed by a put-away activity.

7.3.3 Put-Away

Putting away the SKU items into the assigned storage locations is done manually (categories S and M) or in a case of large items (category L) with the use of a forklift truck. A put-away documented is printed out with assigned storage locations. The location assignment takes into account the following considerations: zoning (random storage within zone), size/weight (large heavy items at the bottom), and a product type or affinity (similar designs grouped together). Warehouse operators distribute the S, M, and L items to the assigned storage locations. If the assigned storage location is already occupied, the manager is alerted and an investigation is carried out. Product details are updated on the document with a new location. After leaving a product at the location, the worker updates their document, and the put-away cycle continues until all products are put-away. At the end of this process, the computer system is manually updated with actual storage

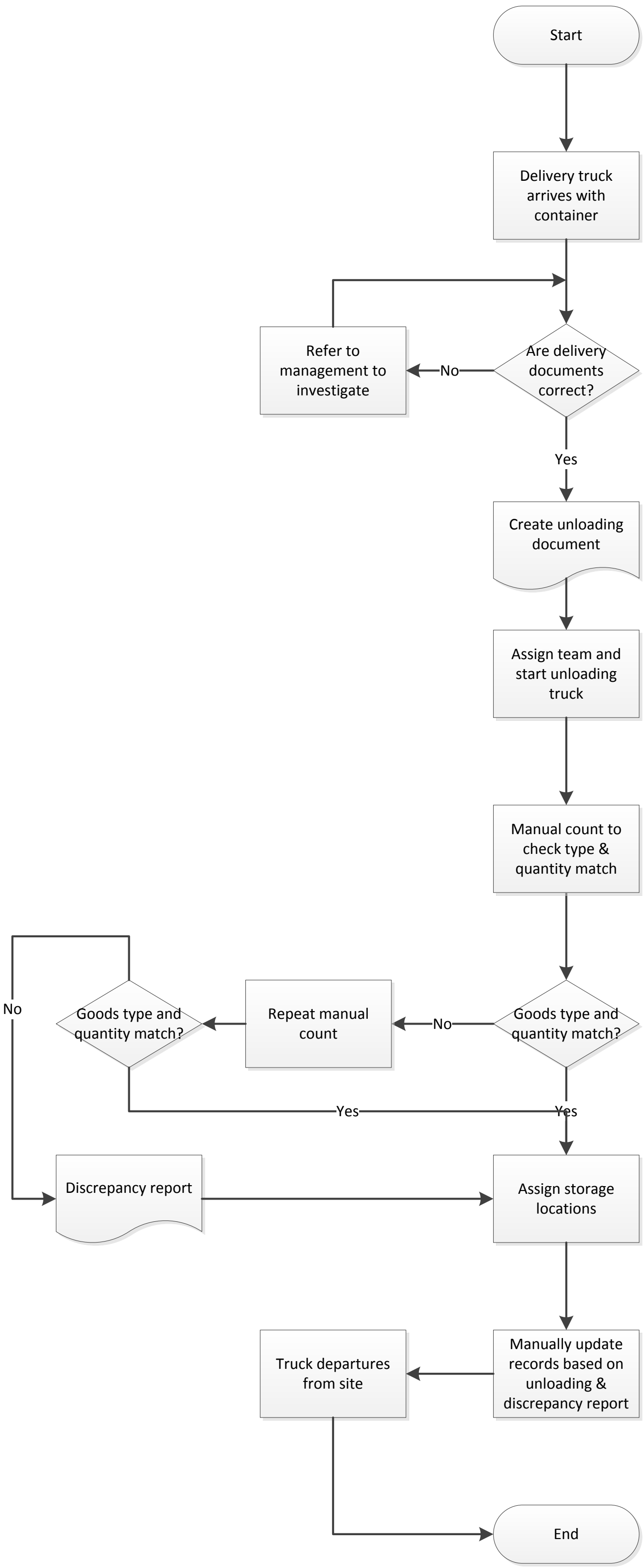

Fig. 7.3: Schematic flow of receiving activity.

locations. Figure 7.4 presents a schematic flow of a put-away activity. Put-away is followed by the storage activity.

7.3.4 Storage

During the storage activity items remain at their locations until they are picked up as required by the customers. Additionally, products may be moved between zones, or opened as part of break bulk. Changes of locations are recorded in warehousing documentation. While products are in storage a cycle-count is performed. Storage activity is not taken into further considerations since products remain stationary.

7.3.5 Order picking

An order picking list is based on a single order, hence each picker completes a full order for a customer. According to Exquisite Bathroom managers this system provides simple transparency on workers activity and increases personal responsibility for delivering a perfect order. Picking lists are distributed among the workers. At the first location a picker checks if an item is at a designated location and if it is the correct product (matching description, barcode on packaging), in the case of a discrepancy, management is consulted. The picker takes the required quantity, but if quantity of product is less than required then a note is made on the picking list and a maximum available quantity is taken to meet a customer's demand. After this, a picking list is annotated and if there are more products to pick the cycle continues. In the case of the picker's "basket" being full, but an order is not completed, it is brought to the despatching area and the picker continues the cycle. If there are no more products left on the picking list, the order is brought to the despatching area. Documents are collected by an

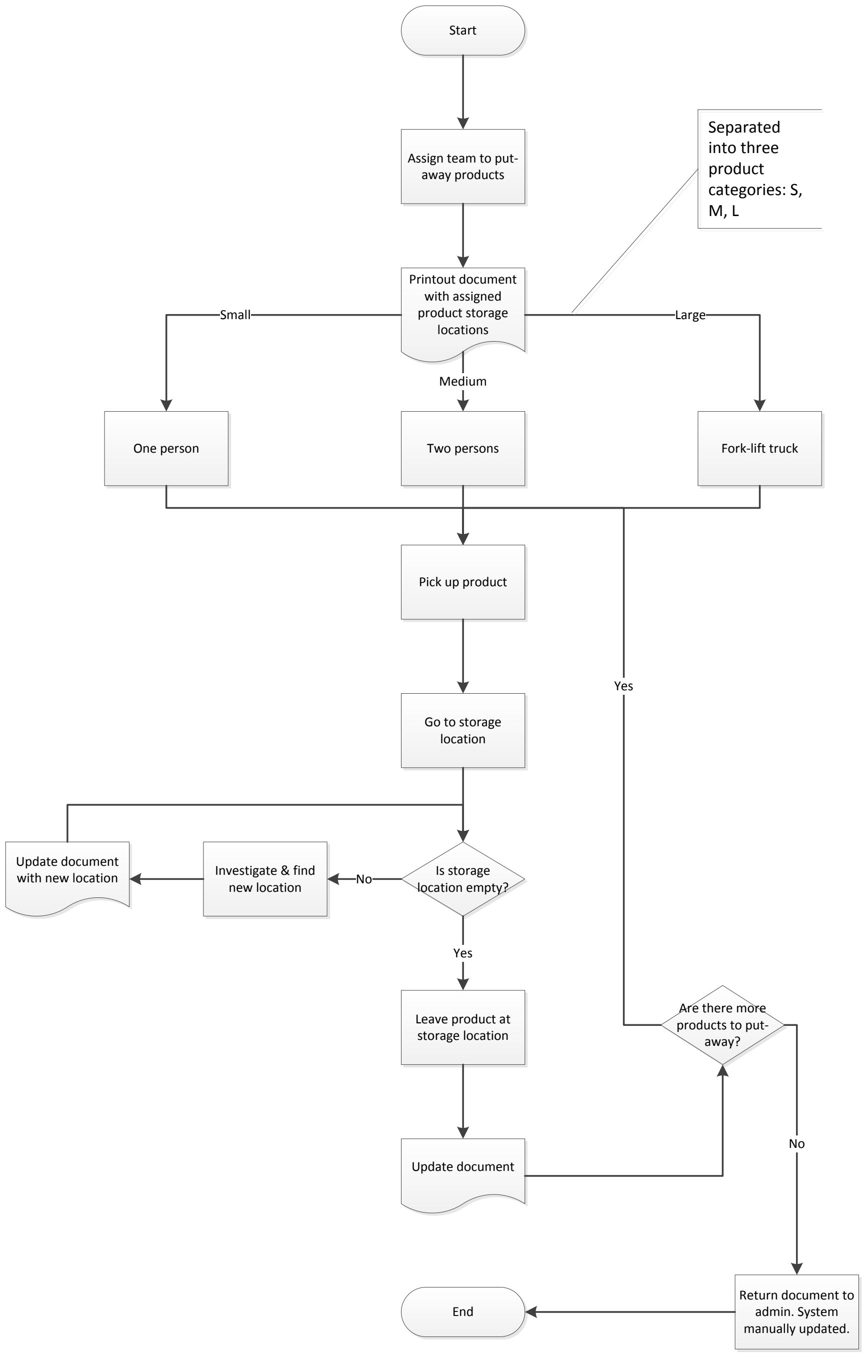

Fig. 7.4: Schematic flow of putaway activity.

admin and the computer system is manually updated. If orders are partially completed due to insufficient quantities, an admin advises this to the customer. Figure 7.5 presents a schematic flow of order picking activity. Order picking is followed by despatching products to customers.

7.3.6 Despatching

Despatching is the last activity in the warehouse cycle. Firstly completed orders are checked and verified against customer's order. If there is a discrepancy it is rectified by picking the required item/quantity from storage. If everything is correct, the order is marked as completed. Completed and checked orders are grouped depending upon the destination and route. Completed orders are loaded onto a truck and the computer system is manually updated. Figure 7.6 presents a schematic flow of the despatching activity.

7.4 Implementing TDABC at Exquisite Bathrooms warehouse

In this section the TDABC model is implemented at Exquisite Bathrooms warehouse. Firstly, the required resources and the practical capacity are identified, and then the activity times are estimated. Lastly the time equations are built. Figure 7.7 presents procedure for implementing TDABC.

7.4.1 Resources and practical capacity

Departmental divisions at Exquisite Bathrooms are not strictly defined, but resource pools are established based on functions. There are four resource pools: a warehousing unit, a management unit, an admin unit, and a transport unit. Each unit consumes resources and generates expenses at every activity or transaction. There are four resource types: warehouse, personnel, corporate sustenance, and vehicles. Use of corporate sustenance expenses

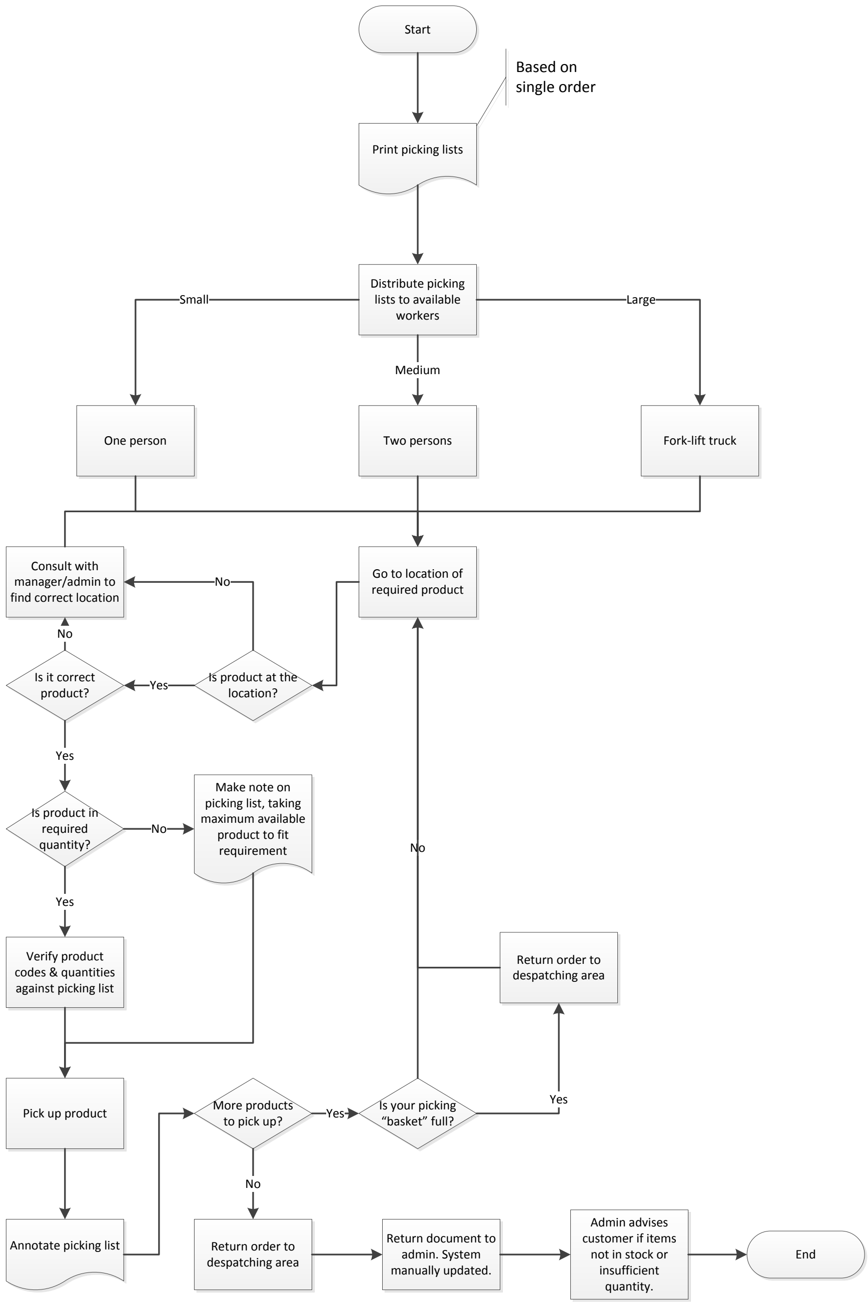

Fig. 7.5: Schematic flow of order picking activity.

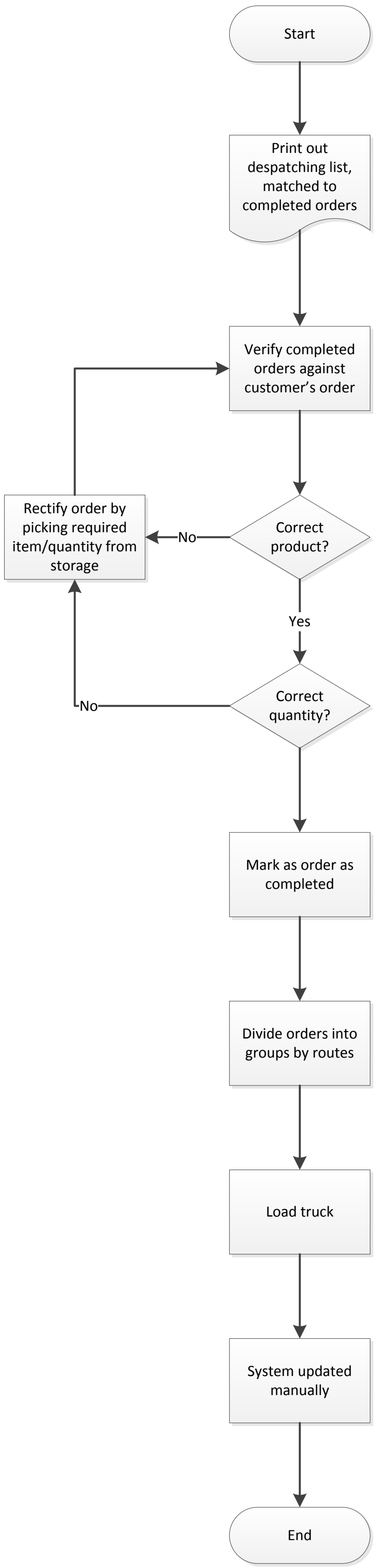

Fig. 7.6: Schematic flow of despatching activity.

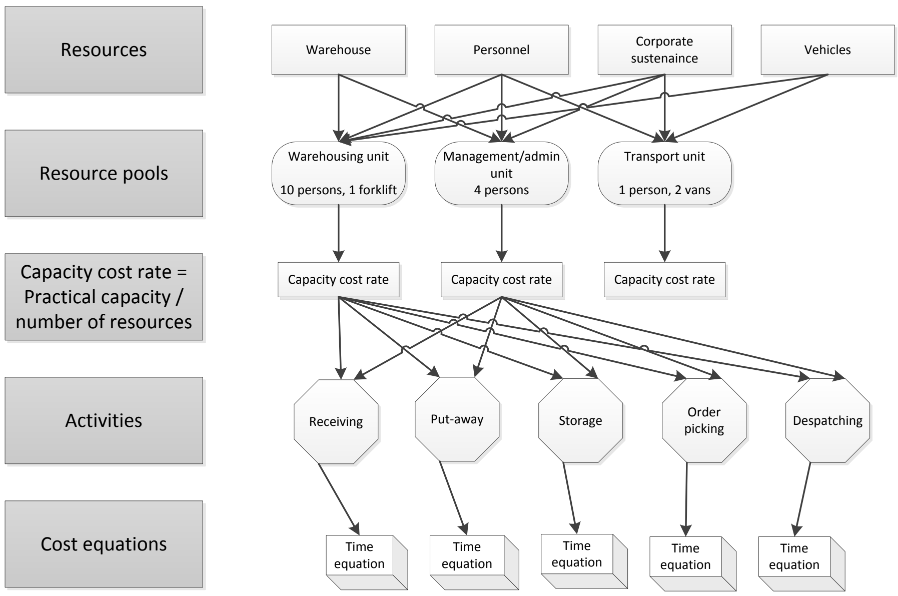

Fig. 7.7: Procedure of implementing TDABC.

is recommended by Kaplan and Anderson (2007) for expenses not related to other resources, which can't be attributed to a particular function. Resource capacities are reported in working hours. After a consultation with the company's management an assumption was made about working capacity of vehicles and personnel. Their working capacity is set at 80% of their available time. The 20% down time for the personnel includes a rest room and a cigarette breaks, while a down time for the vehicles includes maintenance and repair breaks.

Capacity cost calculations are explained in the Table 7.2 and resulting cost rates are presented in Figure 7.8.

It should be noted that in the rest of the chapter a capacity cost rate is used that utilizes both warehousing and management/admin resource pools. A combined capacity cost rate 0.47(£/min) for warehousing activities is obtained by summing up a warehousing unit capacity cost rate (0.10£/min)

Cost element	**Calculations**
Capacity per year	= no.of employees * working hours * working days
80% Capacity per year	= Capacity per year * 0.8
80% Capacity per year in minutes	= 80% Capacity per year in hours * 60 minutes
Aggregated costs (£)	= sum of relevant resource pool yearly costs from Figure 7.1, i.e. sum all warehousing unit costs per year
Capacity cost rate (£/hour)	= aggregated costs / 80% capacity per year (h)
Capacity cost rate (£/minute)	= aggregated costs / 80% capacity per year (m)

Tab. 7.2: Capacity cost rates calculations.

	Practical capacity								
	No. of employees	Normal working hours per day	Working days per year	Capacity per year (h)	80% Capacity per year (h)	80% Capacity per year (minutes)	Aggregated costs (£)	Capacity cost rate (£/h)	Capacity cost rate (£/minute)
Warehousing unit	10	8	253	20,240	16,192	971,520	£ 94,680.00	£ 5.85	£ 0.10
Management/admin unit	4	8	253	8,096	6,477	388,608	£ 144,200.00	£ 22.26	£ 0.37
Transport unit	1	8	253	2,024	1,619	97,152	£ 48,000.00	£ 29.64	£ 0.49

Fig. 7.8: Capacity cost rates.

and a management/admin unit capacity cost rate (0.37£/min).

7.4.2 Time estimates

There are five activities or processes at the Exquisite Bathrooms warehouse: receiving, put-away, storage, order picking, and despatching. Times estimates for these activities were obtained using a Casio watch and the estimates provided by management. Figures obtained by the time measurement were validated through discussion with the management and if it was necessary through a consultation with a relevant warehouse staff. Combining a 'top-down' approach with direct measurements by the observer provided a quick access to data and reduced discomfort felt by employees when asked to provide their assessment of the exact activity times. Confidence in time measurements was increased by taking ten measurements for each activity. Time measurements are presented in Figure 7.9.

Receiving

#	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12
	Time variable											
1	00:04:51	00:15:27	00:00:09	00:00:16	00:12:55	00:00:08	00:00:12	00:05:47	00:00:03	00:00:05	00:02:55	estimate:
2	00:02:24	00:08:11	00:00:07	00:00:16	00:12:48	00:00:08	00:00:12	00:04:04	00:00:04	00:00:04	00:01:48	00:15:00
3	00:03:17	00:13:45	00:00:07	00:00:15	00:09:01	00:00:05	00:00:09	00:04:56	00:00:04	00:00:05	00:01:57	
4	00:02:32	00:15:46	00:00:10	00:00:14	00:11:27	00:00:08	00:00:09	00:07:47	00:00:04	00:00:04	00:01:43	
5	00:03:27	00:07:11	00:00:09	00:00:17	00:10:48	00:00:08	00:00:11	00:07:26	00:00:04	00:00:05	00:01:52	
6	00:02:12	00:12:37	00:00:07	00:00:17	00:08:05	00:00:05	00:00:09	00:04:04	00:00:04	00:00:04	00:02:20	
7	00:03:50	00:07:51	00:00:07	00:00:16	00:08:20	00:00:07	00:00:11	00:05:36	00:00:03	00:00:05	00:02:40	
8	00:02:57	00:15:17	00:00:09	00:00:18	00:08:41	00:00:07	00:00:11	00:05:21	00:00:04	00:00:05	00:01:14	
9	00:04:21	00:18:02	00:00:04	00:00:15	00:09:38	00:00:07	00:00:10	00:06:36	00:00:03	00:00:04	00:01:23	
10	00:04:34	00:14:21	00:00:07	00:00:16	00:12:08	00:00:06	00:00:11	00:07:44	00:00:04	00:00:03	00:02:27	

Put-away

#	T13	T14	T15	T16	T17	T18	T19	T20	T21	T22	T23
	Time variable										
1	00:01:37	00:02:27	00:03:12	00:02:21	00:03:00	00:05:48	00:04:07	00:07:00	00:11:21	estimate:	estimate:
2	00:01:04	00:02:33	00:03:27	00:02:25	00:03:26	00:05:55	00:04:41	00:06:14	00:11:54	00:10:00	00:01:00
3	00:01:53	00:02:21	00:03:27	00:02:18	00:03:50	00:05:31	00:04:54	00:07:43	00:10:04		
4	00:01:29	00:02:41	00:03:40	00:02:40	00:03:11	00:05:53	00:04:56	00:08:20	00:09:24		
5	00:01:44	00:02:52	00:03:43	00:02:45	00:03:33	00:05:11	00:04:33	00:09:48	00:10:52		
6	00:01:13	00:02:18	00:03:44	00:02:10	00:03:58	00:05:52	00:04:43	00:09:19	00:11:27		
7	00:01:25	00:02:28	00:03:28	00:02:12	00:03:36	00:05:32	00:04:14	00:07:44	00:10:20		
8	00:01:40	00:02:56	00:03:40	00:02:20	00:03:48	00:05:38	00:04:50	00:08:22	00:12:08		
9	00:01:06	00:02:07	00:03:36	00:02:40	00:03:50	00:05:46	00:04:36	00:07:18	00:09:29		
10	00:01:51	00:02:11	00:03:57	00:02:19	00:03:05	00:05:19	00:04:28	00:08:18	00:12:45		

Order picking

#	T24	T25	T26	T27	T28	T29	T30	T31	T32	T33	T34	T35
	Time variable											
1	00:01:35	00:02:34	00:04:04	00:03:03	00:03:43	00:06:02	00:05:29	00:08:42	00:12:53	00:00:20	estimate:	estimate:
2	00:02:16	00:02:44	00:03:51	00:02:45	00:03:31	00:06:08	00:04:35	00:07:17	00:12:19	00:00:22	00:10:00	00:01:00
3	00:02:06	00:03:25	00:03:59	00:03:19	00:04:07	00:05:48	00:05:28	00:09:29	00:11:42	00:00:15		
4	00:02:28	00:03:12	00:04:14	00:02:33	00:03:46	00:06:05	00:04:44	00:07:15	00:12:07	00:00:22		
5	00:01:50	00:03:19	00:03:50	00:02:33	00:04:22	00:05:55	00:04:56	00:06:49	00:12:33	00:00:19		
6	00:01:33	00:03:25	00:04:30	00:03:13	00:03:44	00:05:52	00:04:47	00:07:55	00:12:12	00:00:11		
7	00:02:01	00:02:52	00:04:23	00:03:05	00:03:39	00:06:09	00:04:47	00:07:53	00:12:38	00:00:16		
8	00:01:38	00:02:32	00:04:24	00:02:53	00:04:02	00:06:00	00:04:34	00:06:16	00:13:15	00:00:18		
9	00:01:45	00:02:33	00:03:56	00:02:57	00:03:36	00:06:25	00:04:40	00:08:37	00:10:59	00:00:19		
10	00:01:49	00:02:56	00:03:31	00:02:33	00:04:17	00:06:15	00:04:42	00:09:24	00:11:58	00:00:20		

Despatching

#	T36	T37	T38	T39	T40
	Time variable				
1	00:00:50	00:01:49	00:04:10	estimate:	estimate:
2	00:00:02	00:01:33	00:03:56	00:01:00	00:10:00
3	00:00:29	00:01:16	00:03:41		
4	00:00:04	00:01:35	00:03:44		
5	00:00:31	00:01:23	00:03:50		
6	00:00:41	00:01:32	00:04:02		
7	00:00:43	00:01:44	00:03:35		
8	00:00:16	00:01:31	00:03:54		
9	00:00:12	00:01:11	00:03:47		
10	00:00:39	00:01:39	00:03:48		

Fig. 7.9: Activity time measurements.

Each time measurement is denoted by variable from $T1$ to $T40$. Values for variables $T12$, $T22$, $T23$, $T34$, $T35$, $T39$, and $T40$ were estimated by the management.

7.4.3 Time drivers

Time drivers were obtained through interviews with a warehouse management and an analysis of the warehouse activities (Section 7.3). There is some variation in the observed time drivers. Cardinaels and Labro (2008) point out that models with a relatively small number of drivers, such as those

Process	Time drivers
Receiving	Waiting time in case of discrepancy in documents Number of products in categories: small, medium, large Waiting time to create discrepancy report
Put-away	Number of products in categories: small, medium, large Number of products to put-away in distance travelled: close, middle, far Waiting time if discrepancy or problem occurs Time to update document
Storage	Time spent in storage
Order picking	Number of products in categories: small, medium, large Number of products at pick locations in distance travelled: close, middle, far Waiting time if discrepancy or problem occurs Time to update document
Despatching	Number of products in categories: small, medium, large Time to update document

Tab. 7.3: Time variations in warehouse processes.

based on simple activities at small companies, sufficiently explain variation in the processes. Time variations (time drivers) in each of the warehouse processes are presented in the Table 7.3.

7.4.4 Analysis of time measurements

Next building block implementing TDABC is analysis of the time measurements and assigning activity variables to time variables. Time measurements obtained by observation underwent analysis of median, mean, standard deviation (SD), standard error of the mean (SE), minimum and maximum values. Mean values are selected for building the time equations in the following subsection.

Receiving is presented in Figure 7.10, put-away in Figure 7.11, order picking in Figure 7.12, and lastly despatching in Figure 7.13. Storage is not taken into account as there is no significant activity while goods lay in storage.

Receiving											Selected for equation	
Time variable	Activity variable	Activity description	Num. of measure ments	Median	Mean	SD	SE	Min	Max	Minutes	Value
T1	X1	truck arrival, checking transport documents, X1=1	10	00:03:22	00:03:26	00:00:53	00:00:17	00:02:12	00:04:51	00:03:26	3.43
T2	X2	if investigation of transport documents required, X2= 0 or 1	10	00:14:03	00:12:51	00:03:37	00:01:08	00:07:11	00:18:02	00:12:51	12.85
T3	X3	unload, number of S	10	00:00:07	00:00:08	00:00:02	00:00:01	00:00:04	00:00:10	00:00:08	0.13
T4	X4	unload, number of M	10	00:00:16	00:00:16	00:00:01	00:00:00	00:00:14	00:00:18	00:00:16	0.27
T5	X5	unload, number of L	10	00:10:13	00:10:23	00:01:46	00:00:34	00:08:05	00:12:55	00:10:23	10.38
T6	X3	sort, number of S	10	00:00:07	00:00:07	00:00:01	00:00:00	00:00:05	00:00:08	00:00:07	0.12
T7	X4	sort, number of M	10	00:00:11	00:00:11	00:00:01	00:00:00	00:00:09	00:00:12	00:00:11	0.18
T8	X5	sort, number of L	10	00:05:42	00:05:56	00:01:20	00:00:25	00:04:04	00:07:47	00:05:56	5.93
T9	X3	check, number of S	10	00:00:04	00:00:04	00:00:00	00:00:00	00:00:03	00:00:04	00:00:04	0.07
T10	X4	check, number of M	10	00:00:05	00:00:04	00:00:01	00:00:00	00:00:03	00:00:05	00:00:04	0.07
T11	X5	check, number of L	10	00:01:54	00:02:02	00:00:31	00:00:10	00:01:14	00:02:55	00:02:02	2.03
T12	X6	if discrepancy report required, X6= 0 or 1	estimate							00:15:00	15

Fig. 7.10: Receiving - analysis of time measurements.

Put-away											Selected for equation	
Time variable	Activity variable	Activity description	Num. of measure ments	Median	Mean	SD	SE	Min	Max	Minutes	Value
T13	X7	put-away, number of S to close locaction	10	00:01:33	00:01:30	00:00:17	00:00:05	00:01:04	00:01:53	00:01:30	1.5
T14	X8	put-away, number of S to middle locaction	10	00:02:28	00:02:29	00:00:15	00:00:05	00:02:07	00:02:56	00:02:29	2.48
T15	X9	put-away, number of S to far locaction	10	00:03:38	00:03:35	00:00:12	00:00:04	00:03:12	00:03:57	00:03:35	3.58
T16	X10	put-away, number of M to close locaction	10	00:02:21	00:02:25	00:00:12	00:00:04	00:02:10	00:02:45	00:02:25	2.42
T17	X11	put-away, number of M to middle locaction	10	00:03:35	00:03:32	00:00:19	00:00:06	00:03:00	00:03:58	00:03:32	3.53
T18	X12	put-away, number of M to far locaction	10	00:05:42	00:05:38	00:00:14	00:00:05	00:05:11	00:05:55	00:05:38	5.63
T19	X13	put-away, number of L to close locaction	10	00:04:39	00:04:36	00:00:16	00:00:05	00:04:07	00:04:56	00:04:36	4.6
T20	X14	put-away, number of L to middle locaction	10	00:08:01	00:08:00	00:01:00	00:00:19	00:06:14	00:09:48	00:08:00	8
T21	X15	put-away, number of L to far locaction	10	00:11:06	00:10:58	00:01:05	00:00:21	00:09:24	00:12:45	00:10:58	10.97
T22	X16	storage location not empty, X16= 0 or 1	estimate							00:10:00	10
T23	X17	update document, X17=1	estimate							00:01:00	1

Fig. 7.11: Put-away - analysis of time measurements.

Order picking											Selected for equation	
Time variable	Activity variable	Activity description	Num. of measure ments	Median	Mean	SD	SE	Min	Max	Minutes	Value
T24	X18	pick, number of S from close locaction	10	00:01:50	00:01:54	00:00:17	00:00:05	00:01:33	00:02:28	00:01:54	1.9
T25	X19	pick, number of S from middle locaction	10	00:02:54	00:02:57	00:00:20	00:00:06	00:02:32	00:03:25	00:02:57	2.95
T26	X20	pick, number of S from far locaction	10	00:04:01	00:04:04	00:00:17	00:00:06	00:03:31	00:04:30	00:04:04	4.07
T27	X21	pick, number of M from close locaction	10	00:02:55	00:02:53	00:00:16	00:00:05	00:02:33	00:03:19	00:02:53	2.88
T28	X22	pick, number of M from middle locaction	10	00:03:45	00:03:53	00:00:17	00:00:05	00:03:31	00:04:22	00:03:53	3.88
T29	X23	pick, number of M from far locaction	10	00:06:04	00:06:04	00:00:10	00:00:03	00:05:48	00:06:25	00:06:04	6.07
T30	X24	pick, number of L from close locaction	10	00:04:45	00:04:52	00:00:19	00:00:06	00:04:34	00:05:29	00:04:52	4.87
T31	X25	pick, number of L from middle locaction	10	00:07:54	00:07:58	00:01:02	00:00:19	00:06:16	00:09:29	00:07:58	7.97
T32	X26	pick, number of L from far locaction	10	00:12:16	00:12:16	00:00:36	00:00:11	00:10:59	00:13:15	00:12:16	12.27
T33	X27	product identification, for each picked product	10	00:00:19	00:00:18	00:00:03	00:00:01	00:00:11	00:00:22	00:00:18	0.3
T34	X28	storage location empty, find new, X28= 0 or 1	estimate							00:10:00	10
T35	X29	update document, X29=1	estimate							00:01:00	1

Fig. 7.12: Order picking - analysis of time measurements.

Despatching											Selected for equation	
Time variable	Activity variable	Activity description	Num. of measurements	Median	Mean	SD	SE	Min	Max	Minutes	Value
T36	X30	checking, number of S	10	00:00:30	00:00:27	00:00:16	00:00:05	00:00:02	00:00:50	00:00:27	0.45
T37	X31	checking, number of M	10	00:01:32	00:01:31	00:00:11	00:00:04	00:01:11	00:01:49	00:01:31	1.52
T38	X32	checking, number of L	10	00:03:49	00:03:51	00:00:10	00:00:03	00:03:35	00:04:10	00:03:51	3.85
T39	X33	update document, X33=1	estimate							00:01:00	1
T40	X34	rectifying picking errors, X34=10	estimate							00:10:00	1

Fig. 7.13: Despatching - analysis of time measurements.

7.4.5 Constructing the time equations

Next step in the implementation TDABC is the construction of the time equations. Detailed background theory on creating time equations was presented in a Section 5.6.1. Time equations built for activities at Exquisite Bathrooms warehouse are presented below.

Receiving time equation is presented in Equation 7.1. Explanation of X_i variables is provided in Figure 7.10.

$$\begin{aligned} T_{receiving} &= 3.43X_1 + 12.85X_2 + 0.13X_3 + 0.27X_4 \\ &+ 10.38X_5 + 0.12X_3 + 0.18X_4 + 5.93X_5 \\ &+ 0.07X_3 + 0.07X_4 + 2.03X_5 + 15X_6 \end{aligned} \tag{7.1}$$

Put-away time equation is presented in Equation 7.2. Explanation of X_i variables is provided in Figure 7.11.

$$\begin{aligned} T_{putaway} &= 1.5X_7 + 2.48X_8 + 3.58X_9 + 2.42X_{10} \\ &+ 3.53X_{11} + 5.63X_{12} + 4.6X_{13} + 8X_{14} \\ &+ 10.97X_{15} + 10X_{16} + 1X_{17} \end{aligned} \tag{7.2}$$

Order picking time equation is presented in Equation 7.3. Explanation of X_i variables is provided in Figure 7.12. It should be noted that variable X_{27} is a count of all items to be picked, since 18 seconds (0.30) is spent on identification of each item.

$$T_{orderpicking} = 1.9X_{18} + 2.95X_{19} + 4.07X_{20} + 2.88X_{21} + 3.88X_{22} + 6.07X_{23} + 4.87X_{24} + 7.97X_{25} + 12.27X_{26} + 0.30X_{27} + 10X_{28} + 1X_{29} \quad (7.3)$$
$$X_{27} = count of all items to pick$$

Despatching time equation is presented in Equation 7.4. Explanation of X_i variables is provided in Figure 7.13.

$$T_{despatching} = 0.45X_{30} + 1.52X_{31} + 3.85X_{32} + 1X_{33} + 10X_{34} \quad (7.4)$$

The implementation of the TDABC costing at 'Exquisite Bathrooms' warehouse was a step towards implementation of RFID-TDABC at this warehouse, which will allow for activity improvements and a more detailed analysis of activity costs. The set up and investment required for RFID-TDABC implementation is presented in the next section.

7.5 Setting up RFID at Exquisite Bathrooms warehouse

Implementation of RFID-TDABC at Exquisite Bathrooms warehouse starts with setting up the RFID equipment and then costing a required investment.

7.5.1 RFID equipment set up

Implementing RFID-TDABC requires the installation of the RFID equipment throughout the warehouse. RFID equipment varies between activities, but in the case of Exquisite Bathrooms it may be shared between certain activities. This is due to a shared entry/exit and the small size of the company.

For receiving and despatching activities (entry, exit) an RFID portal is set up. An example of an RFID portal is presented in Figure 7.14. The RFID portal is located at the entrance/exit from the warehouse. RFID readers are installed on both sides of the portal and the top of the portal. Using three RFID readers increases the coverage of the entrance/exit area with radio-waves and ensures correct readings of every RFID tag passing through the entrance (Wang et al., 2007). RFID tags are attached to SKUs. Boxes are moved manually and the pallets are moved using a forklift truck through the RFID portal. Product identities are read from RFID tags and staff is given visual feedback by green and red lights. Green indicates correct readings and matching to the expected goods, red light indicates a discrepancy with the expected goods. It is more likely that a discrepancy will have something to do with mismatch of goods on delivery than incorrect readings, as nowadays RFID vendors guarantee reading accuracy close to 100% (Swedberg, 2009).

Staff working on put-away and order picking activities are equipped with handheld RFID readers and a portable small sized computer with a display. Figure 7.15 presents an example of such a device. Handheld RFID readers and a computer give worker flexibility to freely move around the warehouse and pick up or drop items. Workers may be given instructions on a device display. Furthermore, this device combines both barcode and RFID capabilities.

The storage area is covered with a number of RFID readers fixed to the shelving. Their coverage of the storage area gives information about the location of the stored items and updates the inventory records. An example of a fixed reader is shown in a Figure 7.16.

Fig. 7.14: Example of receiving RFID setup.

Fig. 7.15: Portable RFID reader with a hand-held computer (Intermec).

Fig. 7.16: Fixed RFID reader for storage area (Intermec).

RFID equipment set up also requires hardware for a wireless connectivity (Wi-Fi) as well as cables and wiring. In addition computers and servers with RFID related software are required. Lastly, the purchase of an RFID printer is suggested to print labels with embedded RFID tags.

7.5.2 RFID equipment investment

RFID equipment investment is presented in a Figure 7.17. Equipment is allocated to the relevant functional category (area). Prices for RFID equipment were obtained from the "UK's leading solutions provider" in RFID technology located online at http://www.thebarcodewarehouse.co.uk. Other costs such as consulting, installation, and training fees as well as cables and wiring were estimated. Estimates are based on informal conversations with professionals in the RFID field.

Once RFID is set up at the warehouse, the next step is to implement RFID-TDABC. Implementation is discussed in a next section.

Area	Item description	Quantity	Price/item	Total
Receiving &	Intermec IF61 Reader, fixed	3	£ 1,971.21	£ 5,913.63
Despatching	Intermec IP30 RFID Reader, portable	2	£ 772.91	£ 1,545.82
	Intermec CK70 RFID Computer, portable	2	£ 1,940.49	£ 3,880.98
	Frame and fixings*	1	£ 300.00	£ 300.00
Put-away &	Intermec IP30 RFID Reader, portable	6	£ 772.91	£ 4,637.46
Order picking	Intermec CK70 RFID Computer, portable	6	£ 1,940.49	£ 11,642.94
Storage	Intermec IF2 Network Reader, fixed	10	£ 576.34	£ 5,763.40
Connectivity	Zebra AP8232 Tri Radio WiFi	4	£ 629.99	£ 2,519.96
	Zebra RFS4000 Integrated Controller	2	£ 580.99	£ 1,161.98
	Cables & wiring (inc. installation)*	1	£ 1,000.00	£ 1,000.00
Soft/hard-ware	Software licenses*	1	£3,000	£ 3,000.00
	Hardware (computers, servers)*	4	£1,500	£ 6,000.00
Other	Zebra RZ600 RFID Label Printer & Encoder	1	£ 2,354.35	£ 2,354.35
	Printing materials, tags*	1	£ 700.00	£ 700.00
	Consulting*	1	£ 5,000.00	£ 5,000.00
	Installation costs*	1	£ 4,000.00	£ 4,000.00
	Training*	1	£ 10,000.00	£ 10,000.00
*Estimated cost			Total:	£ 69,420.52

Fig. 7.17: RFID equipment and associated costs

7.6 Implementing RFID-TDABC at Exquisite Bathrooms warehouse

In order to demonstrate the advantages of twinning RFID with TDABC (RFID-TDABC concept) in-depth analysis of the warehouse activities at the case study company was conducted. Firstly, the receiving activity is used as a model for implementing RFID-TDABC. Implementation steps include:

1. TDABC implementation, covered in a Section 7.4
    (a) Determine resources and practical capacity
    (b) Determine time estimates
    (c) Determine time drivers
    (d) Analyse time measurements to find values for time equations
    (e) Construct time equations
2. Data about activity (delivery schedule and orders)
3. Construct time equations based on RFID set up
4. Calculations, apply time equations to data on activity
5. Obtain results

The first step of the implementation of RFID-TDABC was discussed thoroughly in Section 7.4 and hence it will not be repeated here. Next, data about activities are collected from delivery schedules and orders (based on activity analysis). In the third step the time equations based on RFID set up are created (i.e. some activities such as checking may be omitted or significantly shortened). Lastly, calculations are made and results are obtained.

Subsequent activities: put-away, order picking, and despatching follow the same steps but only key details and final results are shown for presentation clarity. Omitted tables and figures are available in the Appendix 1. Analysis covers period of three months (January to March) and compares results obtained with TDABC and RFID-TDABC costings.

7.6.1 Receiving

Data about receiving activity

Data on the delivery schedule was collected over the course of three months, with ten 40'ft container arrivals during this time. There were four deliveries in January, two in February, and three deliveries in March. Containers were loaded with a variety of products, in three categories small, medium, large (pallets). There was one discrepancy in cargo documents (last delivery in March, denoted by 1) and one discrepancy report had to be created (second delivery in January, denoted by 1). Receiving details are presented in a Figure 7.18 and a Figure 7.19.

Construct time equations for receiving activity based on RFID set up

Next, the time equations were constructed for TDABC (Equation 7.5) and RFID-TDABC (Equation 7.6) respectively. Data for the TDABC equation was based on earlier analysis described in Section 7.4.5, specifically a Figure 7.10.

The variables used in equations for TDABC and RFID-TDABC are explained in Table 7.4. Activity descriptions for each equation are provided.

Regarding the RFID-TDABC equation (7.6) it should be noted that the use of RFID enables combination of sorting and checking into one almost instant activity, denoted as “sort&check”. The use of RFID allows for the

				Discrepancies	
Month	Small	Medium	Large	Cargo documents	Discrepancy report
Jan	47	34	20	0	0
Jan	59	17	20	0	1
Jan	53	34	11	0	0
Jan	66	33	10	0	0
Feb	70	30	20	0	0
Feb	41	13	15	0	0
Mar	52	26	14	0	0
Mar	49	35	15	0	0
Mar	68	10	18	0	0
Mar	47	10	18	1	0

Fig. 7.18: Receiving details between January and March 2014.

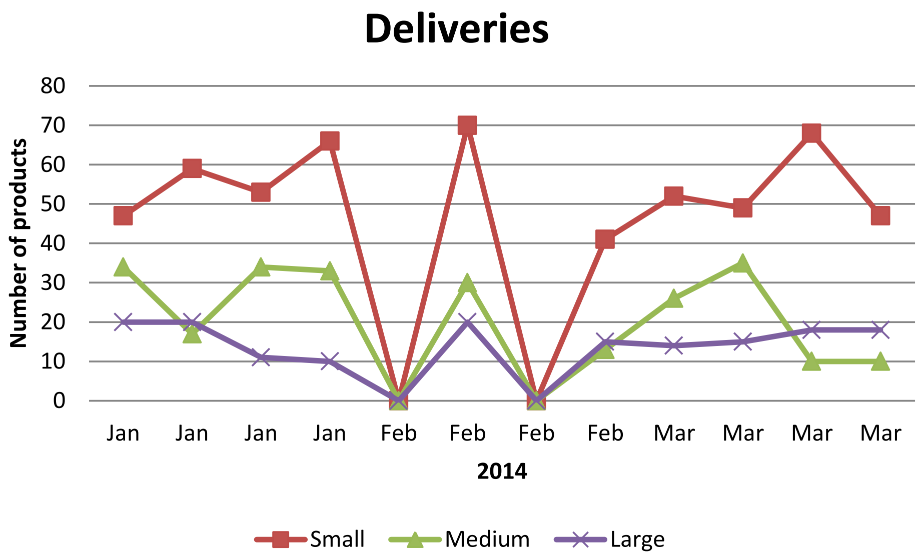

Fig. 7.19: Deliveries between January and March 2014, by product.

instant identification of products as soon as the item is recognised by the RFID reader. For the purpose of activity time calculation, it was decided to express this instant recognition as taking place within 1 second (expressed as 0.02 in the equation), which takes into account IT delays related to computer database readings and general performance issues.

$$\begin{aligned} T_{TDABC} = {} & 3.43X_1 + 12.85X_2 + 0.13X_3 + 0.27X_4 \\ & + 10.38X_5 + 0.12X_3 + 0.18X_4 + 5.93X_5 \\ & + 0.07X_3 + 0.07X_4 + 2.03X_5 + 15X_6 \end{aligned} \tag{7.5}$$

$$\begin{aligned} T_{RFID-TDABC} = {} & 3.43X_1 + 12.85X_2 + 0.13X_3 + 0.27X_4 \\ & + 10.38X_5 + 0.02X_3 + 0.02X_4 + 0.02X_5 \\ & + 15X_6 \end{aligned} \tag{7.6}$$

Equation	Receiving equation description
T_{TDABC}	X_1 - checking transport documents, $X_1 = 1$ X_2 - if investigation of transport documents required, $X_2 = 0 or 1$ X_3 - number items in small (S) category X_4 - number items in medium (M) category X_5 - number items in large (L) category X_6 - if discrepancy report required, $X_6 = 0 or 1$ check transport documents + investigation required? + unload S + unload M + unload L + sort S + sort M + sort L + check S + check M + check L + discrepancy report?
$T_{RFID-TDABC}$	X_1 - checking transport documents, $X_1 = 1$ X_2 - if investigation of transport documents required, $X_2 = 0 or 1$ X_3 - number items in small (S) category X_4 - number items in medium (M) category X_5 - number items in large (L) category X_6 - if discrepancy report required, $X_6 = 0 or 1$ check transport documents + investigation required? + unload S + unload M + unload L + sort&check S + sort&check M + sort&check L + discrepancy report?

Tab. 7.4: Receiving TDABC and RFID-TDABC time equations explained

Calculations on receiving activity

Next, the financial data about capacity cost rates for the calculation of activity cost was obtained from Figure 7.8, for both units involved in the activity: Warehousing, and Management/Admin. Rates for Warehousing Unit are: $£5.85/hour$ and $£0.10/minute$. Rates for Management/Admin Unit are $£22.26/hours$ and $£0.37/minute$. Rates were summarised since both units take part in the activities, and combined values are $£28.11/hour$ and $£0.47/minute$.

Receiving activities with TDABC only now could be calculated using equation 7.5 and the aforementioned cost rates. The results of calculation for ten deliveries between January and March with TDABC only are presented in Figure 7.20. Average time of receiving activity per container after delivery is 5 hours, 31 minutes, and 44 seconds, with an average cost of £155.92.

Next, calculations were made using the RFID-TDABC concept using

				Discrepancies				
Month	Small	Medium	Large	Cargo documents	Discrepancy report	Activity time (min)	Activity time (h)	Activity cost (£)
Jan	47	34	20	0	0	402.95	06:42:57	£ 189.39
Jan	59	17	20	0	1	412.95	06:52:57	£ 194.09
Jan	53	34	11	0	0	239.81	03:59:49	£ 112.71
Jan	66	33	10	0	0	225.11	03:45:07	£ 105.80
Feb	70	30	20	0	0	408.23	06:48:14	£ 191.87
Feb	41	13	15	0	0	298.41	04:58:25	£ 140.25
Mar	52	26	14	0	0	290.35	04:50:21	£ 136.46
Mar	49	35	15	0	0	312.41	05:12:25	£ 146.83
Mar	68	10	18	0	0	360.51	06:00:31	£ 169.44
Mar	47	10	18	1	0	366.64	06:06:38	£ 172.32
						Average:	05:31:44	£ 155.92

Fig. 7.20: Receiving activity calculations with TDABC only.

Month	Small	Medium	Large	Discrepancies: Cargo documents	Discrepancies: Discrepancy report	Activity time (min)	Activity time (h)	Activity cost (£)
Jan	47	34	20	0	0	228.00	03:48:00	£ 107.16
Jan	59	17	20	0	1	239.89	03:59:53	£ 112.75
Jan	53	34	11	0	0	135.31	02:15:19	£ 63.60
Jan	66	33	10	0	0	126.54	02:06:32	£ 59.47
Feb	70	30	20	0	0	230.23	03:50:14	£ 108.21
Feb	41	13	15	0	0	169.12	02:49:07	£ 79.49
Mar	52	26	14	0	0	164.06	02:44:04	£ 77.11
Mar	49	35	15	0	0	176.60	02:56:36	£ 83.00
Mar	68	10	18	0	0	203.41	03:23:25	£ 95.60
Mar	47	10	18	1	0	213.18	03:33:11	£ 100.19
						Average:	03:08:38	£ 88.66

Fig. 7.21: Receiving activity calculations with RFID-TDABC.

equation 7.6 and the aforementioned cost rates. The results of calculation for ten deliveries between January and March with RFID-TDABC are presented in Figure 7.21. Average time for receiving a container after delivery is 3 hours, 8 minutes, and 38 seconds, with an average cost of £88.66.

Following the calculation steps, the results of TDABC and RFID-TDABC calculations are visualised using bar charts in Figure 7.22 and Figure 7.23. Activity time utilizing with RFID-TDABC is significantly lower on each occasion, and on average is lower by 43%, giving an average saving of activity cost of £66.90 on each container receipt.

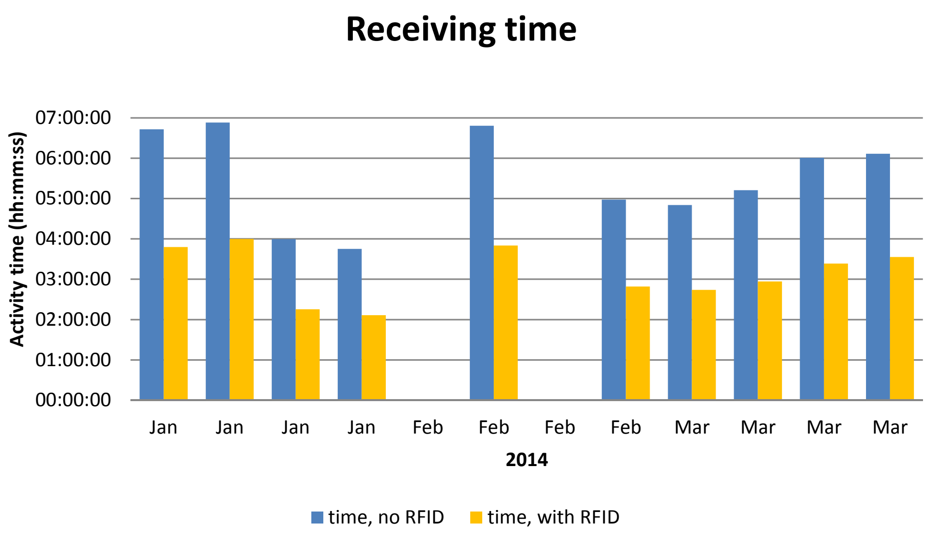

Fig. 7.22: Receiving activity, time analysis results.

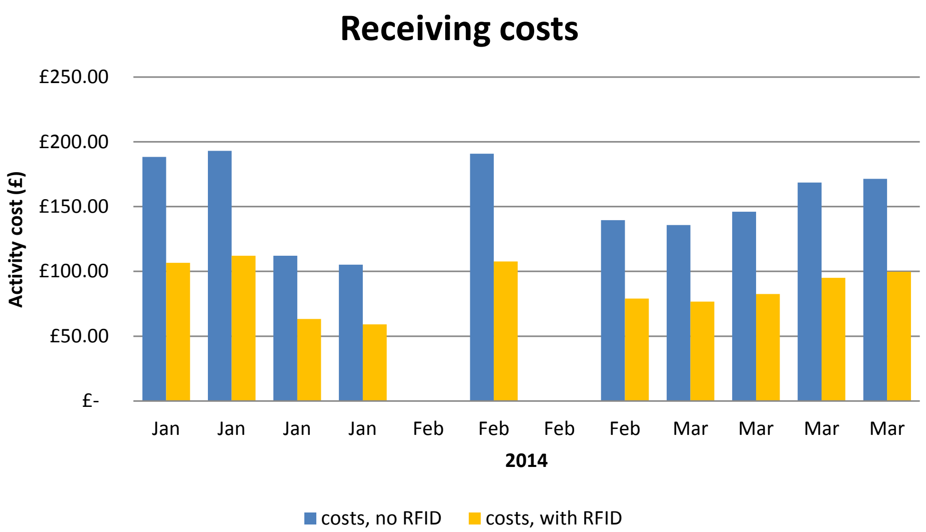

Fig. 7.23: Receiving activity, cost analysis results.

7.6.2 Put-away

Data about put-away activity

Put-away follows the receiving activity and is driven by it. Received goods are put into their locations. Figure 10.1 on page 224 shows the details of goods received each week and their put-away location in the warehouse. Locations in the warehouse are divided into three categories, depending on distance from the warehouse entry/exit. Location categories used in a put-away and also in an order picking) activity are:

- Close - high demand, usually small goods, close to entry/exit point
- Middle - medium demand, goods in all sizes, medium distance from entry/exit point
- Far - low demand, usually large goods, furthest from entry/exit point

Construct time equations for put-away activity based on RFID set up

Put-away time equations are constructed for TDABC (7.7) and RFID-TDABC (7.8). Equation details are explained in a Table 7.5.

$$\begin{aligned} T_{TDABC} = {} & 1.5X_7 + 2.48X_8 + 3.58X_9 + 2.42X_{10} \\ & + 3.53X_{11} + 5.63X_{12} + 4.6X_{13} + 8X_{14} \\ & + 10.97X_{15} + 10X_{16} + 1X_{17} \end{aligned} \tag{7.7}$$

$$\begin{aligned} T_{RFID-TDABC} = {} & 1.5X_7 + 2.48X_8 + 3.58X_9 + 2.42X_{10} \\ & + 3.53X_{11} + 5.63X_{12} + 4.6X_{13} + 8X_{14} \\ & + 10.97X_{15} + 10X_{16} + 1X_{17} \end{aligned} \tag{7.8}$$

Equation	Puta-away equation description
T_{TDABC}	X_7 - put-away, number of S to close location X_8 - put-away, number of S to middle location X_9 - put-away, number of S to far location X_{10} - put-away, number of M to close location X_{11} - put-away, number of M to middle location X_{12} - put-away, number of M to far location X_{13} - put-away, number of L to close location X_{14} - put-away, number of L to middle location X_{15} - put-away, number of L to far location X_{16} - storage location not empty, X16= 0 or 1, 5% error chance (est. by manager) X_{17} - update document, X17=1
$T_{RFID-TDABC}$	X_7 - put-away, number of S to close location X_8 - put-away, number of S to middle location X_9 - put-away, number of S to far location X_{10} - put-away, number of M to close location X_{11} - put-away, number of M to middle location X_{12} - put-away, number of M to far location X_{13} - put-away, number of L to close location X_{14} - put-away, number of L to middle location X_{15} - put-away, number of L to far location X_{16} - storage location not empty, X16= 0, no errors with RFID X_{17} - update document, X17=1

Tab. 7.5: Put-away TDABC and RFID-TDABC time equations explained

Calculations of put-away activity

Calculations of put-away activities are made by using time equations and applying them to put-away data. Figure 10.2 on page 225 presents calculations with TDABC. Figure 10.3 on page 226 presents calculations with RFID-TDABC.

Results of put-away time calculations with TDABC and RFID-TDABC are presented in Figure 7.24. Results of put-away cost calculations with TDABC and RFID-TDABC are presented in Figure 7.25.

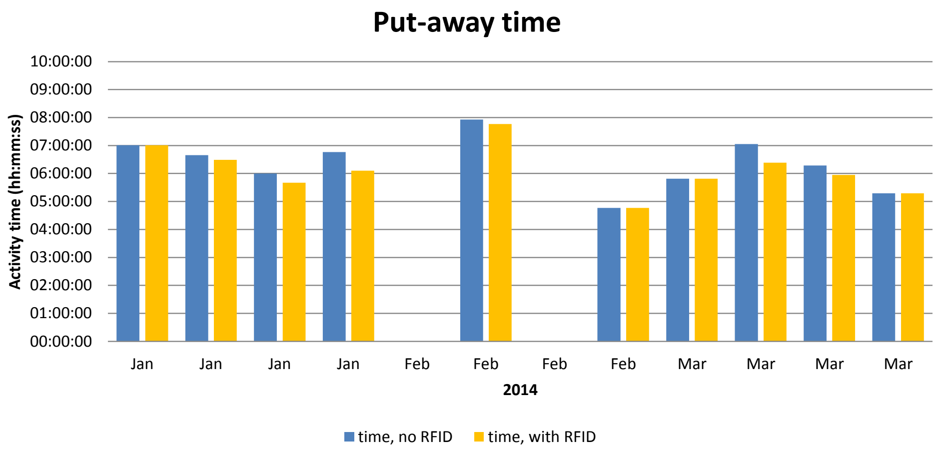

Fig. 7.24: Put-away activity, time analysis results.

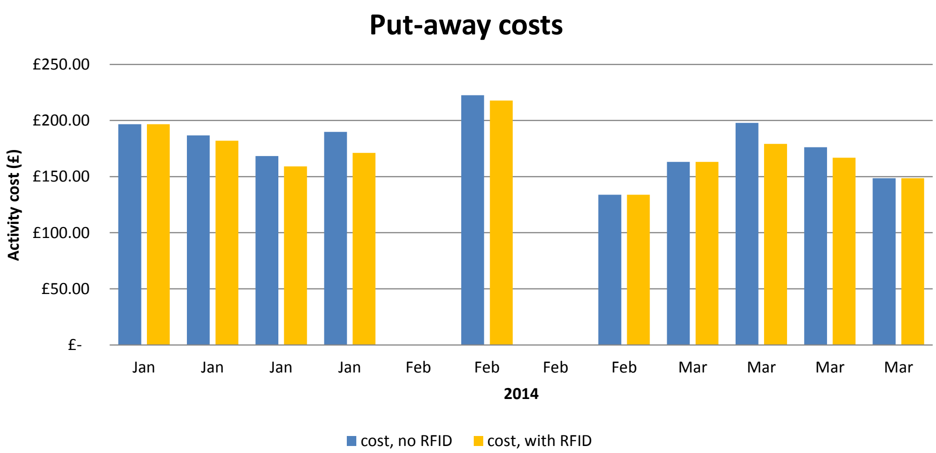

Fig. 7.25: Put-away activity, cost analysis results.

7.6.3 Order picking

Data about order picking activity

Order picking activity is driven by customer's orders. Goods ordered by customers are picked up from their respective warehouse locations. Figure 10.4 on page 227 shows the details of which goods were ordered each week and their storage location in the warehouse. Storage locations are categorised as: close, middle, and far.

Construct time equations for order picking activity based on RFID set up

Order picking time equations are constructed for TDABC (7.9) and RFID-TDABC (7.10). Equation details are explained in a Table 7.6.

$$\begin{aligned} T_{TDABC} = {} & 1.9X_{18} + 2.95X_{19} + 4.07X_{20} \\ & + 2.88X_{21} + 3.88X_{22} + 6.07X_{23} \\ & + 4.87X_{24} + 7.97X_{25} + 12.27X_{26} \\ & + 0.30X_{27} + 10X_{28} + 1X_{29} \end{aligned} \tag{7.9}$$

$$\begin{aligned} T_{RFID-TDABC} = {} & 1.9X_{18} + 2.95X_{19} + 4.07X_{20} \\ & + 2.88X_{21} + 3.88X_{22} + 6.07X_{23} \\ & + 4.87X_{24} + 7.97X_{25} + 12.27X_{26} \\ & + 0.02X_{27} + 10X_{28} + 0.02X_{29} \end{aligned} \tag{7.10}$$

Equation	**Order picking equation description**
T_{TDABC}	X_{18} - pick, number of S from close location X_{19} - pick, number of S from middle location X_{20} - pick, number of S from far location X_{21} - pick, number of M from close location X_{22} - pick, number of M from middle location X_{23} - pick, number of M from far location X_{24} - pick, number of L from close location X_{25} - pick, number of L from middle location X_{26} - pick, number of L from far location X_{27} - product identification is 18sec (18/60=0.30), X_{27}=SUM(all picked products) X_{28} - Error: storage location empty, find new, X28= 0 or 1, 10% chance (est. by manager) X_{29} - update document, 1 min, X_{29}=SUM(all picked products)
$T_{RFID-TDABC}$	X_{18} - pick, number of S from close location X_{19} - pick, number of S from middle location X_{20} - pick, number of S from far location X_{21} - pick, number of M from close location X_{22} - pick, number of M from middle location X_{23} - pick, number of M from far location X_{24} - pick, number of L from close location X_{25} - pick, number of L from middle location X_{26} - pick, number of L from far location X_{27} - product identification is 1sec (1/60=0.02), X_{27}=SUM(all picked products) X_{28} - Error: storage location empty, find new, X28=0 as no errors with RFID X_{29} - update document, 1sec (1/60=0.02) , X_{29}=SUM(all picked products)

Tab. 7.6: Order picking TDABC and RFID-TDABC time equations explained

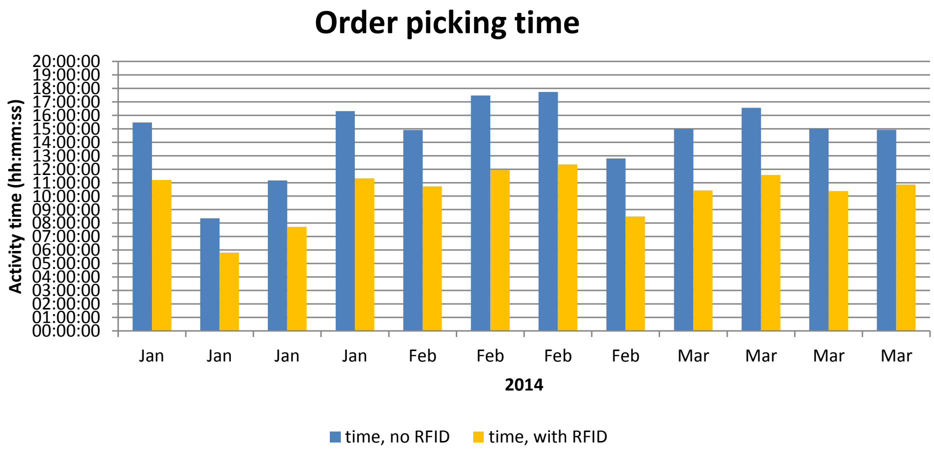

Fig. 7.26: Order picking activity, time analysis results.

Calculations on order picking activity

Calculations on an order picking activity are made by using time equations and applying them to order picking data. Figure 10.5 on page 228 presents calculations with TDABC. Figure 10.6 on page 229 presents calculations with RFID-TDABC.

Results of order picking time calculations with TDABC and RFID-TDABC are presented in Figure 7.26. Results of order picking cost calculations with TDABC and RFID-TDABC are presented in Figure 7.27.

7.6.4 Despatching

Data about despatching activity

Despatching is the last activity in the case study warehouse. Orders picked in a previous activity are checked and loaded onto delivery trucks. Figure 10.7 on page 230 shows the details of what goods were despatched each week.

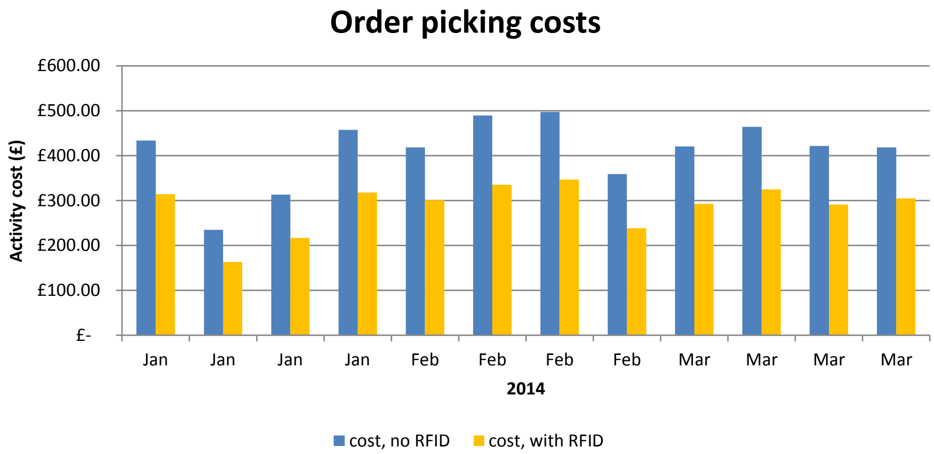

Fig. 7.27: Order picking activity, cost analysis results.

Construct time equations for despatching activity based on RFID set up

Despatching time equations are constructed for TDABC (7.11) and RFID-TDABC (7.12). Equation details are explained in a Table 7.7.

$$T_{TDABC} = 0.45X_{30} + 1.52X_{31} + 3.85X_{32} + 1X_{33} + 10X_{34} \tag{7.11}$$

$$T_{RFID-TDABC} = 0.4X_{30} + 1.2X_{31} + 3.1X_{32} + 0.02X_{33} \tag{7.12}$$

Calculations on despatching activity

Calculations on a despatching activity are made by using time equations and applying them to despatching data. Figure 10.8 on page 231 presents calculations with TDABC. Figure 10.9 on page 232 presents calculations with RFID-TDABC.

Equation	Despatching equation description
T_{TDABC}	X_{30} - checking & loading, number of S X_{31} - checking & loading, number of M X_{32} - checking & loading, number of L X_{33} - update document, X32=1, X_{34} - errors, estimated at 2% chance, 10min rectifying
$T_{RFID-TDABC}$	X_{30} - checking & loading, number of S X_{31} - checking & loading, number of M X_{32} - checking & loading, number of L X_{33} - update document, X32=1, 1sec (1/60=0.02) with RFID X_{34} - with RFID omitted, no errors

Tab. 7.7: Despatching TDABC and RFID-TDABC time equations explained

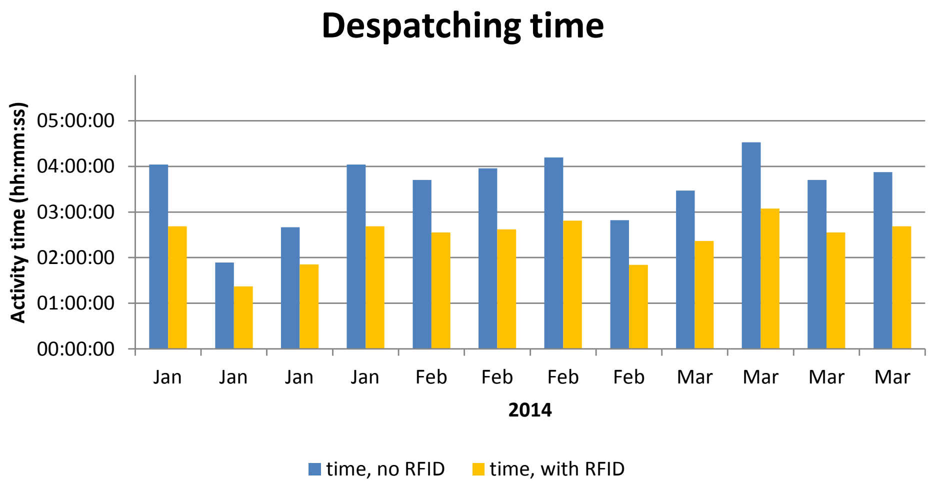

Fig. 7.28: Despatching activity, time analysis results.

Results of despatching time calculations with TDABC and RFID-TDABC are presented in Figure 7.28. Results of despatching cost calculations with TDABC and RFID-TDABC are presented in Figure 7.29.

7.7 Results overview

Lastly, comparisons can be made between *"as is"* warehouse activities (discussed in a Section 7.3) and *"to be"* warehouse with the implementation of RFID-TDABC.

Summary of results of *"as is"* warehouse state with TDABC used to

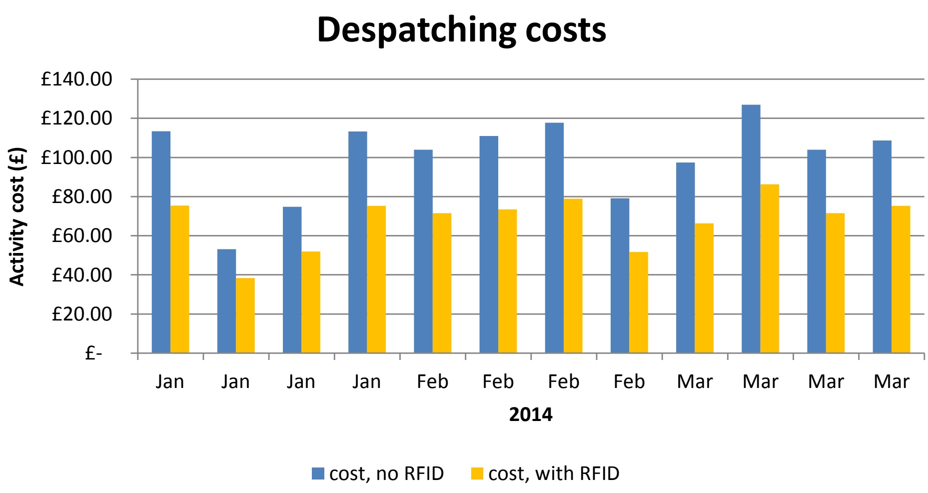

Fig. 7.29: Despatching activity, cost analysis results.

	Receiving		Put-away		Order picking		Despatching	
Month	**Time (h)**	**Cost (£)**	**Time (h)**	**Cost (£)**	**Time (h)**	**Cost (£)**	**Time (h)**	**Cost (£)**
Jan	06:42:57	£ 189.39	07:00:44	£ 196.70	15:27:41	£ 433.69	04:02:34	£ 113.40
Jan	06:52:57	£ 194.09	06:39:19	£ 186.68	08:21:53	£ 234.63	01:53:41	£ 53.15
Jan	03:59:49	£ 112.71	06:00:10	£ 168.38	11:10:09	£ 313.30	02:39:55	£ 74.76
Jan	03:45:07	£ 105.80	06:46:00	£ 189.81	16:18:16	£ 457.34	04:02:20	£ 113.29
Feb					14:54:40	£ 418.26	03:42:18	£ 103.93
Feb	06:48:14	£ 191.87	07:55:54	£ 222.48	17:27:43	£ 489.80	03:57:19	£ 110.95
Feb					17:44:06	£ 497.47	04:11:49	£ 117.73
Feb	04:58:25	£ 140.25	04:46:21	£ 133.87	12:47:42	£ 358.90	02:49:11	£ 79.10
Mar	04:50:21	£ 136.46	05:48:59	£ 163.15	15:00:13	£ 420.85	03:28:17	£ 97.38
Mar	05:12:25	£ 146.83	07:03:21	£ 197.92	16:32:56	£ 464.19	04:31:36	£ 126.97
Mar	06:00:31	£ 169.44	06:16:53	£ 176.19	15:01:53	£ 421.63	03:42:13	£ 103.89
Mar	06:06:38	£ 172.32	05:17:40	£ 148.51	14:55:02	£ 418.43	03:52:20	£ 108.62

Fig. 7.30: Summary of results without RFID, TDABC used

capture time and cost of activities is presented in a Figure 7.30.

Summary of results of *"to be"* warehouse with RFID and RFID-TDABC implemented to bring about operational efficiencies and capture time and cost of activities is presented in a Figure 7.31.

Three months data about the cost of activities is combined and presented in a Figure 7.32. Column "No RFID" is a *"as is"* state of a warehouse with calculations made using TDABC and no changes in activities. Column "With RFID" indicates a *"to be"* state with RFID and RFID-TDABC

	Receiving		Put-away		Order picking		Despatching	
Month	Time (h)	Cost (£)	Time (h)	Cost (£)	Time (h)	Cost (£)	Time (h)	Cost (£)
Jan	03:48:00	£ 107.16	07:00:44	£ 196.70	11:11:49	£ 314.07	02:41:16	£ 75.39
Jan	03:59:53	£ 112.75	06:29:19	£ 182.01	05:49:01	£ 163.16	01:22:10	£ 38.41
Jan	02:15:19	£ 63.60	05:40:10	£ 159.03	07:43:57	£ 216.90	01:51:09	£ 51.96
Jan	02:06:32	£ 59.47	06:06:00	£ 171.11	11:19:44	£ 317.78	02:41:05	£ 75.31
Feb					10:44:08	£ 301.13	02:33:03	£ 71.55
Feb	03:50:14	£ 108.21	07:45:54	£ 217.81	11:57:47	£ 335.56	02:37:04	£ 73.43
Feb					12:21:38	£ 346.71	02:48:40	£ 78.85
Feb	02:49:07	£ 79.49	04:46:21	£ 133.87	08:29:58	£ 238.41	01:50:34	£ 51.69
Mar	02:44:04	£ 77.11	05:48:59	£ 163.15	10:25:53	£ 292.60	02:21:51	£ 66.31
Mar	02:56:36	£ 83.00	06:23:21	£ 179.22	11:34:24	£ 324.63	03:04:30	£ 86.25
Mar	03:23:25	£ 95.60	05:56:53	£ 166.84	10:22:45	£ 291.13	02:33:00	£ 71.52
Mar	03:33:11	£ 100.19	05:17:40	£ 148.51	10:51:50	£ 304.74	02:41:05	£ 75.31

Fig. 7.31: Summary of results with RFID, RFID-TDABC used

implemented.

The highest savings percentage of 43.14% is obtained on receiving activity and the lowest on a put-away activity 3.67%. Order picking and despatching have a similar saving percentage of 30.06% and 32.18% respectively.

The highest cost savings expressed in a monetary value (£) was obtained for the order picking activity: £1,481.66. This result corroborates with order picking being the most costly and laborious warehouse activity. The lowest cost savings was achieved in the put-away activity: £65.45. Savings on the receiving activity were at £672.58 and lower for the despatching at £387.14.

Relatively small savings on put-away activity are explained by the simplicity of this operation. Achieved savings on put-away are due to lack of errors when RFID is implemented.

In order to give an insight into what an average week may be like in terms of savings, relevant calculations were made (based on Figures 7.30 and 7.31) and their summary is presented in a Figure 7.33.

In an average week the case study company spends £845.25 on its warehouse activities, but if RFID technology was implemented this figure drops

Activity	No RFID	With RFID	Savings %	Savings £
Receiving	£ 1,559.16	£ 886.58	43.14%	£ 672.58
Put-away	£ 1,783.68	£ 1,718.23	3.67%	£ 65.45
Order picking	£ 4,928.49	£ 3,446.83	30.06%	£ 1,481.66
Despatching	£ 1,203.14	£ 816.00	32.18%	£ 387.14
Total:	**£ 9,474.48**	**£ 6,867.64**	**27.51%**	**£ 2,606.84**

Fig. 7.32: Activity costs and savings combined results

Activity	No RFID	With RFID	Savings %	Savings £
Receiving	£ 155.92	£ 88.66	43.14%	£ 67.26
Put-away	£ 178.37	£ 171.82	3.67%	£ 6.54
Order picking	£ 410.71	£ 287.24	30.06%	£ 123.47
Despatching	£ 100.26	£ 68.00	32.18%	£ 32.26
Total:	**£ 845.25**	**£ 615.72**	**27.16%**	**£ 229.54**

Fig. 7.33: Activity costs and savings in an average week without/with RFID

to £615.72, which gives savings of 27.16% and £229.54. Interestingly, savings made with RFID roughly equate to the weekly salary of a warehouse worker.

Figure 7.34 presents a bar chart representation of the activity costs in an average week between *"as is, without RFID"* and *"to be, with RFID"* scenarios.

The meaning and significance of these results from the case study are provided Chapter 8.

7.8 Summary

This chapter introduced the company Exquisite Bathrooms which was used as a case study for showcasing the implementation of RFID-TDABC in warehousing. Firstly data regarding the company and its activities was

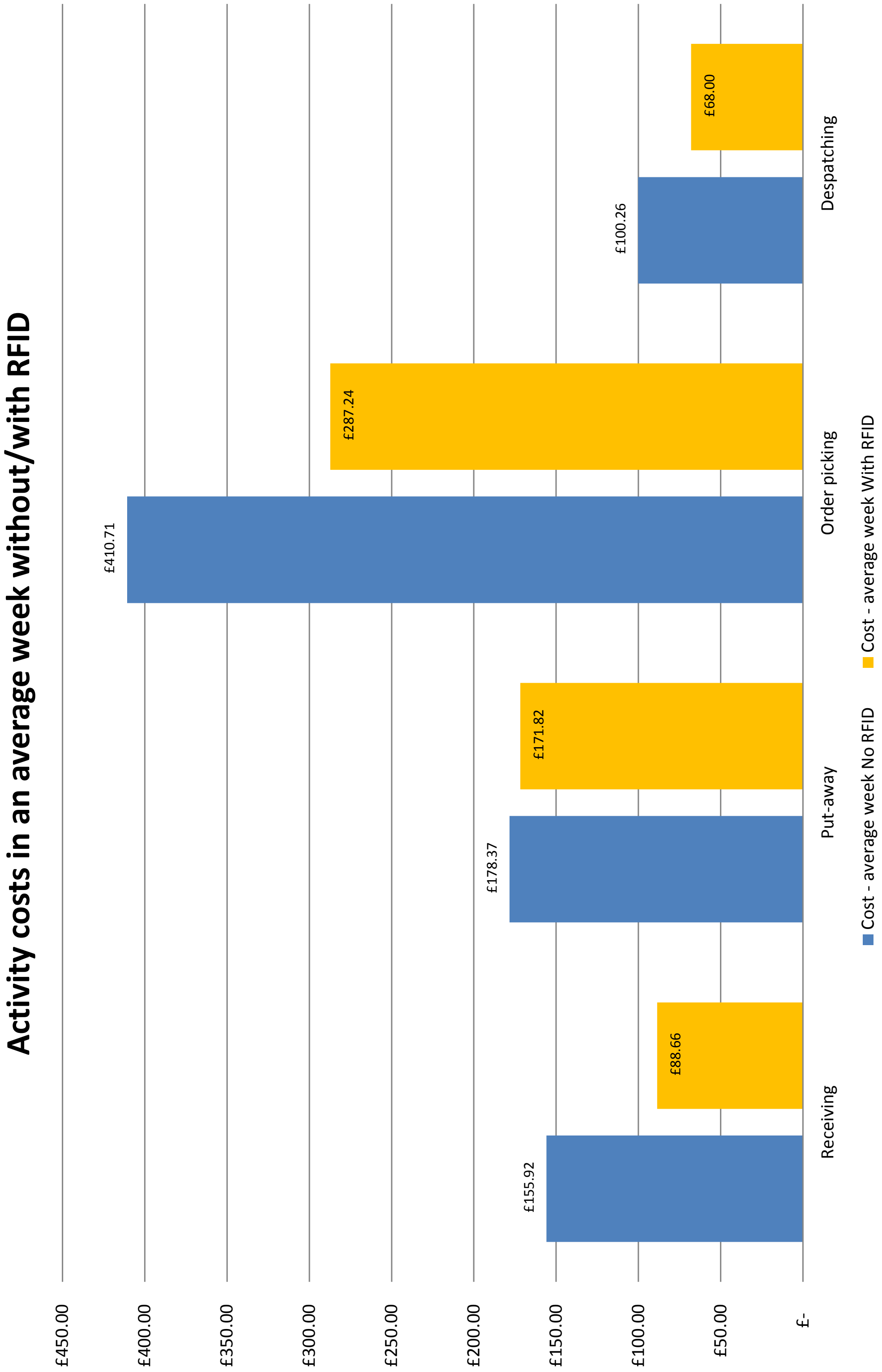

Fig. 7.34: Activity costs in an average week without/with RFID

collected and analysed. Then, TDABC was introduced and time equations and calculations were provided for activities of receiving, put-away, order picking, and despatching. Next, RFID-TDABC was implemented at these four activities and an overview of results was provided. The meaning and significance of the results of this case study are provided in the next chapter.

8. DISCUSSION OF FINDINGS

8.1 Introduction

This chapter presents a discussion of the findings obtained in the previous chapter. Firstly, the meaning and significance of the results is presented in Section 8.2. Section 8.3 compares costing methods: a traditional method, the TDABC method, and the RFID-TDABC method. Next, case study results are benchmarked with the literature in a Section 8.4. A business case for the implementation of RFID-TDABC is presented in Section 8.5, which includes calculating its ROI. The advantages of RFID-TDABC in the case environment are presented in Section 8.6 and practical applications for RFID-TDABC are outlined in Section 8.7. Lastly, Section 8.8 provides discussion of the findings with a reference to this thesis' research questions. Section 8.9 provides conclusions for this chapter.

8.2 Case study results: meaning and significance

8.2.1 Meaning and interpretation of the case study results

The combined results of a three month case study on warehouse activity times and costs without and with RFID are presented in a Figure 8.1.

There is a significant variation in results between activities. The most significant savings are achieved on order picking, which is the most costly activity in a warehouse. Operational changes due to implementation of RFID and capturing order picking costs with RFID-TDABC show significant savings of £1,481.66 (almost £500 a month). The least significant savings are achieved in put-away activity £65.45, as this activity benefits the least from RFID adoption. These findings corroborate with the analysis conducted by Lim et al. (2013) in which order picking is suggested as benefiting the most from RFID adoption and put-away the least. Both receiving and despatching activities have a similar level of savings. In the case study warehouse both activities shared the RFID infrastructure, however receiving was more labour intensive than despatching, which is reflected in the results.

Time savings of 92.81 hours of work time mean savings of almost 11.5 work days (8 hour/day). Achieved time savings are due to increased operational efficiencies such as: faster product identification, no need for manual counting, and automated paperwork. Interpretation of these results varies with the activity (order picking the most savings, put-away the least savings), but it may give an indication as to either the need to review warehouse staff requirements or look at other opportunities for increasing warehouse throughput and growing the business.

During the three month case study cost savings of £2,606.84 were achieved. Again, there is a variation between achieved level of savings (order picking the most savings, put-away the least savings).

Similarly, Figure 8.2 shows analysis of activity time and costs in an average week without and with RFID. The results are comparable in terms of variation between activities. The overall cost saving of £229.54 is significant because it roughly equals the weekly wage of a warehouse worker, thus indicating that adjustment of staff requirements may be in order.

	No RFID			With RFID			Savings		
Activity	Time (h)	Cost (£)		Time (h)	Cost (£)		Time (h)	Cost (£)	
Receiving	55.29	£	1,559.16	31.44	£	886.58	23.85	£	672.58
Put-away	63.59	£	1,783.68	61.26	£	1,718.23	2.33	£	65.45
Order picking	175.70	£	4,928.49	122.88	£	3,446.83	52.82	£	1,481.66
Despatching	42.89	£	1,203.14	29.09	£	816.00	13.80	£	387.14
Total:	**337.48**	**£**	**9,474.48**	**244.67**	**£**	**6,867.64**	**92.81**	**£**	**2,606.84**

Fig. 8.1: Combined results of activity time and cost without/with RFID

	No RFID			With RFID			Savings		
Activity	Time (h)	Cost (£)		Time (h)	Cost (£)		Time (h)	Cost (£)	
Receiving	4.61	£	155.92	2.62	£	88.66	1.99	£	67.26
Put-away	5.30	£	178.37	5.10	£	171.82	0.19	£	6.54
Order picking	10.97	£	410.71	10.24	£	287.24	0.73	£	123.47
Despatching	3.57	£	100.26	2.42	£	68.00	1.15	£	32.26
Total:	**24.45**	**£**	**845.25**	**20.39**	**£**	**615.72**	**4.06**	**£**	**229.54**

Fig. 8.2: Activity time and costs in an average week without/with RFID

8.2.2 Significance of the case study results

The case study results indicate considerable potential savings of both time and cost. Understanding the significance of these results for the business is very important as it may positively impact the future of the company.

The implementation of RFID-TDABC raises questions about the value of the "minute savings" for the business.

There are several reasons why "minute savings" are important. Firstly, there is a compounded effect of workers saving time in doing activities, as they can move to the next tasks increasing the daily warehouse throughput. Secondly, management may come to the conclusion that achieved time savings may indicate that current staffing levels may be adjusted, work hours reduced, or some staff moved to temporary contracts – which gives the business owner additional cost reductions and flexibility. Thirdly, as tasks are executed at higher speeds, it indicates a spare working capacity, which may prompt management to find additional warehousing contracts.

Area	**Traditional**	**TDABC**	**RFID-TDABC**
Implementation costs	low	medium	very high
Implementation difficulty	low	medium	very high
Information visibility (granularity)	very low	medium (activity level)	very detailed (item level)
Data capturing	manual	manual	automated
Data precision	low	medium	very high
ROI period	short	medium	long

Tab. 8.1: Costing methods comparison

The significance of cost savings is more straightforward and focuses on issues like: debt repayment, investing in the business (i.e. new technologies, equipment), expanding its activities etc.

8.3 *Costing methods comparison*

The case study at the Exquisite Bathrooms also gives an opportunity to compare three costing methods: traditional accounting, TDABC, and RFID-TDABC. Traditional accounting is used by the case study company, but as stated by the manager it gives a "very poor insight" about the activity costs. During the case study the TDABC and RFID-TDABC were implemented. As discussed in a previous section, case study results showed significant savings when RFID-TDABC is used. Experience of the three accounting methods during the case study gave insights to enable the creation the comparison Table 8.1.

Implementation costs and complexity — this is lowest for traditional costing methods utilizing simple spreadsheets and propitiatory software. Implementation costs and difficulty increase for the TDABC method, as it requires an in-depth study of activities and measuring their duration, but it is a manageable task even for a small-medium enterprise, for example Bruggeman et al. (2005) and Diaconeasa et al. (2010) both used small companies in their studies. Costs and difficulty are the highest for the RFID-TDABC implementation.

Information visibility (granularity) — this is lowest for a traditional accounting method as it only provides overall details about business costs. Insight increases with the TDABC and granularity at activity level. Very detailed information visibility is achievable with the RFID-TDABC as it provides activity cost details at the item level.

Data capturing and precision — this is lowest for a traditional accounting because it relies on manual data entry. The TDABC also relies on manual data entry but precision increases due to greater data granularity. The RFID-TDABC method relies on automated and precise data capturing, and as such eliminates the need for manual data entry and its associated errors and inaccuracies.

ROI — This is very short for a traditional costing method and medium for the TDABC (as it is more laborious). The ROI period for implementation of RFID-TDABC is long. The ROI for a case study is calculated in Section 8.5.1.

8.4 Benchmarking with the literature

The purpose of benchmarking is to compare results against a wider standard. Benchmarking results against the literature and analysing them using literature lenses aims to evaluate the case study results. To this end the benchmarking list based on recent literature on the implementation of RFID in warehousing was created. Table 8.2 presents an article reference, brief description, and results described in the paper. Level of detail about reported results varied between authors and included numerical (i.e. increase of 10%) and/or verbal descriptions (i.e. significant increase). It should be noted that authors used diverse range of companies hence results may not be directly comparable.

The case study results in an average week with RFID-TDABC include:

- receiving activity time decreased by 43.14%, activity cost lower by £67.26
- put-away activity time decreased by 3.67%, activity cost insignificantly lower by £6.54
- eliminating storage issues: location empty, misplaced items, etc.
- 100% stock/storage visibility (or nearly 100%)
- order picking activity time decreased by 30.06%, activity cost lower by £123.47
- despatching activity time decreased by 32.18%, activity cost lower by £32.26
- manual update of documentation eliminated
- item level insight into cost of activities

Referring these results back to the literature presented in the Table 8.2 it can be seen that reductions on activity time are similar to those achieved by Lao et al. (2012), Chen et al. (2013), and Vlachos (2014). The increase in stock visibility to 100% corroborates with the findings by Yang et al. (2011). Lastly, overall improvements and shorter activity times are confirmed by a similar decrease in the work of Wamba and Chatfield (2011).

Reference	Brief description	Results
Wamba and Chatfield (2011)	Case study and simulation modelling analysis of a third-party logistics supply chain.	17% annual time savings on activities
Poon et al. (2011)	Minimize the waiting time of production workstations and reduce stochastic production material problems in a warehouse. RFID technology is adopted to visualize the actual status of operations in production and warehouse environments.	For the small size orders, the improvement of total makespan is from 17.89% to 51.72% in the heavy production scenario. In the normal production scenario, there is similar improvement of total makespan, from 14.35% to 43.75%.
Yang et al. (2011)	Design a hybrid system architecture at the network level for a resource information management system in humanitarian logistics centres.	Increase the visibility of resource and improve the performance of the site in supply chain.
Chen et al. (2011)	A RFID-based method is proposed for resource localization and dual-command generation in unit-load warehouse environment	Compared with the manual data collection, resource data could be collected automatically as well as workloads and errors could be reduced. Also the average travelling distance could be reduced about 40%.
de Freitas Dias et al. (2012)	This work aims to analyse the effect caused by the implementation of logistics automation project (RFID) in the process of separation uniform refundable in Supply Sub Directorate.	The result showed that the automation project has increased the logistics performance of separation of uniforms from 69% to 100%.
Lao et al. (2012)	This paper is propose a real-time food receiving operations management system, focusing on demonstrating the use of a case-based reasoning and RFID technology in managing the complex food receiving activities in distribution centres.	Improve order fulfilment in 20.8%; Work station idle time 32.9%; Decision process time 70%; Inventory notification 96.7%; Customer complaints 66.7%; Defective inventory 33.3%.
Chen et al. (2013)	Integration of lean production and RFID to improve the efficiency and effectiveness of warehouse management	Improve Receiving time in 81.3%, Storage in 95.6%, Packaging time in 60.0%, Shipping time in 99.8%.
Li et al. (2013)	This study tests two calibration methods, namely the offset vector method (OVM) and convergence method (CM), to mitigate multipath and fading effects in indoor environments to support in-building asset management using RFID.	Overall accuracy by 5.1% for the warehouse
Tsai et al. (2013)	This research focused on cassette management in semiconductor industry. Based on RFID technology, label information where located on each cassette will be passed to the backend database system.	Warehouse keeper daily deliveries for the average operating time cut by about 50%. Production line of the machine could reduce the average time of 90%.
Vlachos (2014)	The primary purpose of this study was to evaluate the impact of radio frequency identification (RFID) practices on supply chain performance.	Performance of distribution system is improved by 33.8% and stock availability by 45.6%.

Tab. 8.2: RFID benchmarking

8.5 Business case for RFID-TDBAC

Case study results also gave an insight to building a business case for RFID-TDABC implementation. With RFID-TDABC significant time and cost savings, and operational efficiencies were achieved. However from the company perspective the return on investment (ROI) is a crucial criteria for any company to consider adoption of a new technology (Collins, 2004). Literature indicated significant doubts about ROI viability of the RFID technology (Attaran, 2007; Lim et al., 2013; O'Connor, 2005; Vijayaraman and Osyk, 2006; White et al., 2008). In order to strengthen the business case for the adoption of RFID-TDABC the ROI based on the case study results is calculated below.

8.5.1 ROI

The formula for calculating the ROI is widely discussed in the finance literature, for example Phillips and Phillips (2006) provide a helpful overview. The ROI formula is presented in Equation 8.1:

$$ROI = \frac{InvestmentGain - InvestmentCost}{InvestmentCost} * 100\% \tag{8.1}$$

In the case study the $InvestmentGain$ equals the savings made from introducing RFID-TDABC, and $InvestmentCost$ is the total cost of the investment in RFID technology. Hence:

- $InvestmentGain$ = £229.54 / week, taken from a Figure 8.2
- $InvestmentCost$ = £69,420.52, taken from a Figure 7.17

Now, ROI is calculated for the first year (52 weeks) of using the RFID-TDABC technology, as shown in Equation 8.2:

Year	ROI
1	-83%
2	-66%
3	-48%
4	-31%
5	-14%
6	3%
7	20%
8	38%
9	55%
10	72%

Fig. 8.3: Case study ROI

$$ROI_{1year} = \frac{£229.54 * 52weeks - £69,420.52}{£69,420.52} * 100\% = -83\% \tag{8.2}$$

Similarly, calculations are made for a 10 year period, as shown in a Figure 8.3. Calculations exclude amortization of equipment and ongoing costs such as label printing. Calculated ROI indicates that the RFID-TDABC implementation would turn profitable in year 6. This is a very long time span and it is not considered feasible for a small company (Busato et al., 2013). This result indicated that unless the costs of RFID hardware and installation don't decrease significantly, RFID technology will remain beyond the reach for small and medium enterprises.

8.6 Advantages of RFID-TDABC in the case environment

Despite the ROI drawback there were numerous other advantages of using RFID-TDABC in the case environment, such as:

- receiving activity time decreased

- receiving activity cost lowered
- put-away activity time decreased
- eliminating storage issues: location empty, misplaced items, etc.
- 100% stock/storage visibility (or nearly 100%)
- order picking activity time decreased
- order picking activity cost lowered
- despatching activity time decreased
- despatching activity cost lowered
- manual update of documentation eliminated
- item level insight into cost of activities

8.7 Practical applications for RFID-TDABC

There are numerous practical applications for RFID-TDABC, such as:

- automating the data collection for costing of activities,
- increasing data precision for accounting purposes,
- very detailed, item level visibility of activities and associated costs,
- calculations of time and cost of movements of goods and people in a warehouse or other environment such as manufacturing or retail,
- providing data for further operational improvements in activities of a warehouse, or manufacturing and retail facilities

- greater insight into the cost incurred (to item level), which gives an advantage in price setting, winning tenders, and setting up promotions for customers.

8.8 Research questions: integrated discussion

This section discusses the findings obtained during the case study with a specific reference to the research questions set out initially in Section 1.3. This discussion does not purport to answer each question in a definite manner but rather provides some insights into the issues based on the results of the case-study.

8.8.1 RQ1: Can RFID provide "automatic accounting of the future"?

The case study showed how RFID system can be set up in a conjunction with the TDABC to provide automated accounting of warehouse activities (RFID-TDABC). RFID provided a time measurement element to the TDABC accounting method thus removing a need for manual time measurements and automating the accounting process. It remains to be seen if RFID-TDABC gains recognition among practitioners in the future, but this thesis showed that RFID can provide data for accounting purposes and as such positively answered the RQ1.

8.8.2 RQ2: Can RFID be used in conjunction with a TDABC costing model? How can RFID benefit a TDABC costing model?

The findings from the case study show that RFID can be used successfully with a TDABC costing model. The RFID-TDABC being a combination of the RFID and the TDABC links advantages and robustness of both techniques and provides numerous benefits.

Firstly, an intelligent use of the RFID data to track time and feed it to the TDABC model alleviates problems with accuracy of the TDABC time estimates. Organization benefits from easier and faster accounting model building with the RFID-TDABC, its scalability and meaningful results.

Additionally, merging of operational and financial data provided by the RFID-TDABC gives management a better understanding of incurred costs. Added robustness of the RFID time measurements model of the TDABC gains more confidence not only of managers, but also it becomes easier to accept by staff as RFID based time measurements are objective.

Moreover, it is possible to constantly review the costs, as the the RFID data is continuously being collected during activities. Findings from the case study show that RFID-TDABC may bring significant savings of operational time and money.

Summing up, the RQ2 can be answered positively as the RFID-TDABC solution benefits a TDABC costing model.

8.8.3 RQ3: What is the impact of measuring time with RFID on a TDABC cost model?

Discussion on the impact of RFID on a TDABC cost model was presented in detail in Chapter 6. The case study confirmed that there is a positive impact of using RFID with the TDABC model, as creating cost equations is simplified, the RFID data collection is automated and without a human intervention. RFID-TDABC provides the potential benefits of increased time measurement accuracy as well as a chance for operational improvements. Hence, the RQ3 can also be answered positively.

8.9 Summary

This chapter discussed the results of a case study at the Exquisite Bathrooms warehouse. The meaning and significance of the results was presented. Then a comparison was made between costing methods: traditional, TD-ABC, and RFID-TDABC. Case study results were further scrutinized and benchmarked against the literature. A business case for the adoption of RFID-TDABC was outlined alongside the ROI calculations. Although in a small enterprise the ROI is not favourable there are numerous other advantages of RFID-TDABC and practical applications for this idea. Lastly, this thesis' research questions were positively answered in reference to the findings from the case study. The next chapter offers some final conclusions regarding RFID-TDABC and its implementation.

9. CONCLUSIONS

9.1 Introduction

The last chapter of this thesis summarises its contribution to the body of knowledge in Section 9.2. Then sets out the research implications for academics and practitioners in Section 9.3. Lastly, Section 9.4 presents the thesis limitations which lead to suggestions of further work that could be done in this area.

9.2 Contribution of the research

The thesis explored the use of RFID in warehousing, and proposed using it in conjunction with TDABC costing methodology - referred to here as RFID-TDABC model - in order to provide additional benefits beyond typical identification of items. The RFID-TDABC costing model is the original contribution of this thesis.

The research started with identifying gaps in the body of knowledge, firstly by noting the diminishing interest in the warehousing applications of RFID among academics and practitioners (Lim et al., 2013). This state may be attributed to limited understanding of the potential benefits of RFID and applying them only to the remit of identification, hence leading to seeing RFID as a replacement for bar-coding, and not as a comprehensive tool to improve and revolutionise warehousing operations. This was covered in Chapter 3.

Chapter 4 provides background information on warehouse classification, warehousing functions and roles, operations, and operational challenges. Operational challenges in the warehouse can be addressed by implementing RFID technology, and adding RFID-TDABC as proposed in this thesis, to achieve the benefits outlined.

Chapter 5 evaluates several approaches to costing in warehouses and proposes a combined perspective on warehouse costs. The traditional costing method and the alternatives (such as EVA, SCOR, balanced scorecard, ABC, TDABC) are then discussed. Evaluation of TDABC leads to enumerating several weaknesses of the TDABC model that are addressed by the adoption of RFID-TDABC.

The time element of the RFID data was identified as a complementary component of the TDABC costing methodology, which is usually weakened by inaccuracies of its time estimates. Providing time measurements with RFID data is addressed by the proposition of an RFID-TDABC model. This was covered in Chapter 6.

The RFID-TDABC model was implemented at the case study warehouse, which was described in Chapter 7. Results are evaluated and interpreted in a Chapter 8. Successful implementation suggests that RFID-TDABC can be applied in a warehouse to provide tracking of activity costs, thus leading to further optimisation of warehousing activities, increased understanding of operational costs, and expanding benefits offered by the RFID beyond product identification.

9.3 Implications

There are several implications of findings provided by this thesis for both academics and warehousing practitioners.

Firstly, the identified gap in RFID research indicates that more work should be done to explore the question of the benefits of technology beyond identification. An implication for academics is that there are still unexplored benefits to RFID technology in its applications in warehousing and the wider supply chain. Practitioners, especially decision makers at warehouses or technology consultants, may also look to see how RFID can alleviate bottlenecks in warehousing operations.

Secondly, a multi-disciplinary research approach should be taken to combining RFID technology and TDABC accounting method in order to gain the most benefit. Combining methods and theories from different fields with RFID, may lead researchers to develop new techniques such as RFID-TDABC presented in this thesis. The implication for practitioners is that there may be a range of new methods to increase the benefits of the RFID within warehousing.

The next implication for academics is in making use of RFID-TDABC as proposed in this thesis within their own research. Practitioners may look into ways that the RFID-TDABC method could be implemented at their warehouse, especially if the warehouse is already equipped with RFID systems. The WMS software vendors may incorporate RFID-TDABC in their software in order to provide it as a new feature.

9.4 Limitations and further work

There are several limitations of this work highlighted in this section. The discussion of limitations leads to a recognition of potential research avenues for further work.

1. The case study implementation is focused on a warehouse in an SME company, Exquisite Bathrooms, that handles limited number of deliv-

eries and orders per week, in addition to storing rather small number of SKUs. It would be interesting to explore how the RFID-TDABC method can be applied at larger companies. Further work includes the application of RFID-TDABC to medium and large companies. Additionally, further work could be done comparing the implementation of RFID-TDABC at company's own private warehouses with implementation done at warehouses belonging to the 3PL.

2. Due to a lack of companies interested in implementing RFID, as it is perceived as costly and not providing enough benefits beyond identification, research was carried out at a business that had not currently invested in the RFID technology. Further work could be focused on gaining interest from other industrial business parters that already use RFID in their operations. The use of actual RFID data to analyse activities and further create RFID-TDABC time equations could be a very rewarding avenue to pursue.

3. The case study company used a simple, traditional cost accounting method. Further work could be done to find industrial partners that uses the TDABC as their accounting method already and compare how implementation of RFID-TDABC changes the cost accounting, time equations etc.

4. Lastly, this thesis was concerned with the application of RFID-TDABC in the warehousing environment. Further work could apply the concept of RFID-TDABC to other areas such as manufacturing, retail, hospitals, libraries, tourism and hospitality, etc.

This thesis proposed the RFID-TDABC methodology, which merges RFID data with Time-Driven Activity Based Costing and implemented it in a warehouse environment. It is the author's hope that concepts and findings presented in this thesis will prompt academics and practitioners to implement them in their own work. Thus further expanding the range of benefits provided by the RFID technology.

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10. APPENDIX 1: ADDITIONAL DATA

Data tables for the Exquisite Bathrooms case study are presented below.

	Product deliveries			Distribution to locations								
				Small products			Medium products			Large products		
Month	Small	Medium	Large	Close	Middle	Far	Close	Middle	Far	Close	Middle	Far
Jan	47	34	20	32	7	8	6	18	10	3	3	14
Jan	59	17	20	39	7	13	4	7	6	2	3	15
Jan	53	34	11	37	8	8	9	17	8	1	2	8
Jan	66	33	10	41	9	16	8	16	9	1	2	7
Feb	0	0	0	0	0	0	0	0	0	0	0	0
Feb	70	30	20	42	8	20	9	13	8	2	3	15
Feb	0	0	0	0	0	0	0	0	0	0	0	0
Feb	41	13	15	27	5	9	3	6	4	1	3	11
Mar	52	26	14	36	5	11	5	14	7	1	2	11
Mar	49	35	15	29	14	6	7	18	10	2	2	11
Mar	68	10	18	41	12	15	2	4	4	3	3	12
Mar	47	10	18	31	4	12	2	4	4	2	3	13

Fig. 10.1: Put-away details between January and March 2014

	Product deliveries			Distribution to locations												
				Small products			Medium products			Large products			Loc. not	Activity time	Activity time	Activity time
Month	Small	Medium	Large	Close	Middle	Far	Close	Middle	Far	Close	Middle	Far	empty	(min)	(h)	(£)
Jan	47	34	20	32	7	8	6	18	10	3	3	14	0	420.74	07:00:44	£ 196.70
Jan	59	17	20	39	7	13	4	7	6	2	3	15	1	399.32	06:39:19	£ 186.68
Jan	53	34	11	37	8	8	9	17	8	1	2	8	2	360.17	06:00:10	£ 168.38
Jan	66	33	10	41	9	16	8	16	9	1	2	7	4	406.00	06:46:00	£ 189.81
Feb	0	0	0	0	0	0	0	0	0	0	0	0	0			
Feb	70	30	20	42	8	20	9	13	8	2	3	15	1	475.90	07:55:54	£ 222.48
Feb	0	0	0	0	0	0	0	0	0	0	0	0	0			
Feb	41	13	15	27	5	9	3	6	4	1	3	11	0	286.35	04:46:21	£ 133.87
Mar	52	26	14	36	5	11	5	14	7	1	2	11	0	348.98	05:48:59	£ 163.15
Mar	49	35	15	29	14	6	7	18	10	2	2	11	4	423.35	07:03:21	£ 197.92
Mar	68	10	18	41	12	15	2	4	4	3	3	12	2	376.88	06:16:53	£ 176.19
Mar	47	10	18	31	4	12	2	4	4	2	3	13	0	317.67	05:17:40	£ 148.51
													Average:	**381.54**	**06:21:32**	**£ 178.37**

Fig. 10.2: Put-away activity calculations with TDABC

	Product deliveries			Distribution to locations												
				Small products			Medium products			Large products			Loc. not	Activity time	Activity time	Activity time
Month	Small	Medium	Large	Close	Middle	Far	Close	Middle	Far	Close	Middle	Far	empty	(min)	(h)	(£)
Jan	47	34	20	32	7	8	6	18	10	3	3	14	0	420.74	07:00:44	£ 196.70
Jan	59	17	20	39	7	13	4	7	6	2	3	15	0	389.32	06:29:19	£ 182.01
Jan	53	34	11	37	8	8	9	17	8	1	2	8	0	340.17	05:40:10	£ 159.03
Jan	66	33	10	41	9	16	8	16	9	1	2	7	0	366.00	06:06:00	£ 171.11
Feb	0	0	0	0	0	0	0	0	0	0	0	0	0			
Feb	70	30	20	42	8	20	9	13	8	2	3	15	0	465.90	07:45:54	£ 217.81
Feb	0	0	0	0	0	0	0	0	0	0	0	0	0			
Feb	41	13	15	27	5	9	3	6	4	1	3	11	0	286.35	04:46:21	£ 133.87
Mar	52	26	14	36	5	11	5	14	7	1	2	11	0	348.98	05:48:59	£ 163.15
Mar	49	35	15	29	14	6	7	18	10	2	2	11	0	383.35	06:23:21	£ 179.22
Mar	68	10	18	41	12	15	2	4	4	3	3	12	0	356.88	05:56:53	£ 166.84
Mar	47	10	18	31	4	12	2	4	4	2	3	13	0	317.67	05:17:40	£ 148.51
													Average:	**367.54**	**06:07:32**	**£ 171.82**

Fig. 10.3: Put-away activity calculations with RFID-TDABC

	Orders for products			Picking locations								
				Small products			Medium products			Large products		
Month	Small	Medium	Large	Close	Middle	Far	Close	Middle	Far	Close	Middle	Far
Jan	116	78	8	63	48	5	25	36	17	4	0	4
Jan	44	52	1	21	15	8	20	16	16	0	0	1
Jan	79	68	0	42	34	3	19	39	10	0	0	0
Jan	113	99	0	58	41	14	39	42	18	0	0	0
Feb	95	80	7	47	36	12	29	35	16	0	2	5
Feb	137	81	3	70	55	12	22	42	17	0	0	3
Feb	135	81	7	69	45	21	44	18	19	0	3	4
Feb	106	57	1	54	47	5	19	25	13	0	0	1
Mar	108	72	5	57	48	3	34	8	30	2	0	3
Mar	90	120	2	43	40	7	60	40	20	2	0	0
Mar	91	71	11	43	42	6	21	41	9	3	0	8
Mar	102	82	8	50	32	20	37	37	8	3	0	5

Fig. 10.4: Order picking details between January and March 2014

	Orders for products			Picking locations									Storage			
				Small products			Medium products			Large products			location	Activity time	Activity time	Activity time
Month	Small	Medium	Large	Close	Middle	Far	Close	Middle	Far	Close	Middle	Far	empty	(min)	(h)	(£)
Jan	116	78	8	63	48	5	25	36	17	4	0	4	0	927.68	15:27:41	£ 433.69
Jan	44	52	1	21	15	8	20	16	16	0	0	1	3	501.88	08:21:53	£ 234.63
Jan	79	68	0	42	34	3	19	39	10	0	0	0	2	670.15	11:10:09	£ 313.30
Jan	113	99	0	58	41	14	39	42	18	0	0	0	3	978.27	16:18:16	£ 457.34
Feb	95	80	7	47	36	12	29	35	16	0	2	5	2	894.67	14:54:40	£ 418.26
Feb	137	81	3	70	55	12	22	42	17	0	0	3	5	1047.71	17:27:43	£ 489.80
Feb	135	81	7	69	45	21	44	18	19	0	3	4	4	1064.10	17:44:06	£ 497.47
Feb	106	57	1	54	47	5	19	25	13	0	0	1	5	767.70	12:47:42	£ 358.90
Mar	108	72	5	57	48	3	34	8	30	2	0	3	4	900.22	15:00:13	£ 420.85
Mar	90	120	2	43	40	7	60	40	20	2	0	0	3	992.93	16:32:56	£ 464.19
Mar	91	71	11	43	42	6	21	41	9	3	0	8	6	901.88	15:01:53	£ 421.63
Mar	102	82	8	50	32	20	37	37	8	3	0	5	0	895.04	14:55:02	£ 418.43
													Average:	**878.52**	**14:38:31**	**£ 410.71**

Fig. 10.5: Order picking activity calculations with TDABC

	Orders for products			Picking locations									Storage			
				Small products			Medium products			Large products			location	Activity time	Activity time	Activity time
Month	Small	Medium	Large	Close	Middle	Far	Close	Middle	Far	Close	Middle	Far	empty	(min)	(h)	(£)
Jan	116	78	8	63	48	5	25	36	17	4	0	4	0	671.81	11:11:49	£ 314.07
Jan	44	52	1	21	15	8	20	16	16	0	0	1	0	349.01	05:49:01	£ 163.16
Jan	79	68	0	42	34	3	19	39	10	0	0	0	0	463.95	07:43:57	£ 216.90
Jan	113	99	0	58	41	14	39	42	18	0	0	0	0	679.74	11:19:44	£ 317.78
Feb	95	80	7	47	36	12	29	35	16	0	2	5	0	644.14	10:44:08	£ 301.13
Feb	137	81	3	70	55	12	22	42	17	0	0	3	0	717.78	11:57:47	£ 335.56
Feb	135	81	7	69	45	21	44	18	19	0	3	4	0	741.63	12:21:38	£ 346.71
Feb	106	57	1	54	47	5	19	25	13	0	0	1	0	509.97	08:29:58	£ 238.41
Mar	108	72	5	57	48	3	34	8	30	2	0	3	0	625.89	10:25:53	£ 292.60
Mar	90	120	2	43	40	7	60	40	20	2	0	0	0	694.40	11:34:24	£ 324.63
Mar	91	71	11	43	42	6	21	41	9	3	0	8	0	622.75	10:22:45	£ 291.13
Mar	102	82	8	50	32	20	37	37	8	3	0	5	0	651.84	10:51:50	£ 304.74
													Average:	**614.41**	**10:14:24**	**£ 287.24**

Fig. 10.6: Order picking activity calculations with RFID-TDABC

	Despatching			
Month	Small	Medium	Large	Rectifying error
Jan	116	78	8	4
Jan	44	52	1	1
Jan	79	68	0	2
Jan	113	99	0	4
Feb	95	80	7	3
Feb	137	81	3	4
Feb	135	81	7	4
Feb	106	57	1	3
Mar	108	72	5	3
Mar	90	120	2	4
Mar	91	71	11	3
Mar	102	82	8	3

Fig. 10.7: Despatching details between January and March 2014

Month	Despatching			Rectifying error	Activity time (min)	Activity time (h)	Activity time (£)
	Small	Medium	Large				
Jan	116	78	8	4	242.56	04:02:34	£ 113.40
Jan	44	52	1	1	113.69	01:53:41	£ 53.15
Jan	79	68	0	2	159.91	02:39:55	£ 74.76
Jan	113	99	0	4	242.33	04:02:20	£ 113.29
Feb	95	80	7	3	222.3	03:42:18	£ 103.93
Feb	137	81	3	4	237.32	03:57:19	£ 110.95
Feb	135	81	7	4	251.82	04:11:49	£ 117.73
Feb	106	57	1	3	169.19	02:49:11	£ 79.10
Mar	108	72	5	3	208.29	03:28:17	£ 97.38
Mar	90	120	2	4	271.6	04:31:36	£ 126.97
Mar	91	71	11	3	222.22	03:42:13	£ 103.89
Mar	102	82	8	3	232.34	03:52:20	£ 108.62
				Average:	**214.46**	**03:34:28**	**£ 100.26**

Fig. 10.8: Despatching activity calculations with TDABC

Month	Despatching			Rectifying error	Activity time (min)	Activity time (h)	Activity time (£)
	Small	Medium	Large				
Jan	116	78	8	0	161.26	02:41:16	£ 75.39
Jan	44	52	1	0	82.17	01:22:10	£ 38.41
Jan	79	68	0	0	111.14	01:51:09	£ 51.96
Jan	113	99	0	0	161.08	02:41:05	£ 75.31
Feb	95	80	7	0	153.06	02:33:03	£ 71.55
Feb	137	81	3	0	157.07	02:37:04	£ 73.43
Feb	135	81	7	0	168.67	02:48:40	£ 78.85
Feb	106	57	1	0	110.57	01:50:34	£ 51.69
Mar	108	72	5	0	141.85	02:21:51	£ 66.31
Mar	90	120	2	0	184.50	03:04:30	£ 86.25
Mar	91	71	11	0	152.99	02:33:00	£ 71.52
Mar	102	82	8	0	161.09	02:41:05	£ 75.31
				Average:	**145.45**	**02:25:27**	**£ 68.00**

Fig. 10.9: Despatching activity calculations with RFID-TDABC

11. APPENDIX 2: COMMENTS ON POST-VIVA FEEDBACK

The thesis concerns the study of RFID in warehousing and proposes and explores the integration of RFID with time-driven activity-based costing (TDABC) in warehousing environments. This is a new area of work that is worthy of PhD study but the research falls short of satisfying the requirements for a PhD.

Author's comments: I would like to thank the reviewers prof. Andrew Lyons and dr. Aris Matopoulos for their helpful comments and suggested improvements to this thesis. Comments below indicate changes to the thesis.

The following changes and additions are necessary in order for the work to be considered for a PhD:

The research question and the aims and objectives need to be clearly stated in Chapter 1.

Chapter 1 was revised. Research questions, aims and objectives are clearly stated in Section 1.3 (page 20).

The value and novelty of the research are intuitively apparent but the justification of the research is insufficiently detailed within the thesis. The review of the literature needs augmenting to include a review of relevant work in order to justify the research value of RFID and TDABC integration. This will necessarily require a deep review of the problems associated with the adoption of TDABC and the potential for RFID to make TDABC adoption

more feasible.

Deep review of the problems associated with the adoption of the TDABC is found in a Section 5.6.5 (page 122). Research value of the RFID and the TDABC integration is explained in Section 6.4 (page 127). Potential of the RFID to make the TDABC adoption more feasible is found in Section 6.4 (page 127) and Section 6.6 (page 131).

The thesis demonstrates the candidates knowledge and critical appreciation of relevant subject matter including RFID, warehousing, multi-agent systems and activity-based costing but the presentation of the reviews of these topics has been done discretely and sequentially, and lacks adequate integration. The revised thesis should address this weakness.

Literature review sections were revised. Integration and a logical flow of the literature review is addressed by introducing a framework in a Section 2.3 (page 25).

There is limited attention paid to approaches to 1) costing in warehouses, and 2) alternative approaches to costing in the review of the literature. A basic review of warehousing costs is included in Chapter 4 but it is descriptive rather than evaluative and lacks focus on problems. These omissions need to be addressed in the revised thesis.

Costing in the warehouses is covered in the Chapter 5 (page 90). This chapter evaluates several approaches to costing in warehouses. Firstly warehouse cost frameworks are discussed in a Section 5.2 (page 90). Their evaluation leads to proposing the combined perspective on warehouse costs in a Section 5.3 (page 99). The traditional costing method and the alternatives (EVA, SCOR, balanced scorecard, ABC, TDABC) are discussed in a

Section 5.4 (page 100). Section 5.5 (page 103) presents the activity-based costing (ABC) and contrasts the benefits and advantages of the ABC model with the problems, focusing on the logistics industry. Time-driven activity-based costing (TDABC) is a further development of the ABC model and the TDABC benefits and advantages are evaluated and compared with the ABC model in Section 5.6 (page 112).

There is no Methodology chapter within the thesis although a half-page description of the research methodology is provided in Chapter 1 (Introduction). This is inadequate. A Methodology chapter should be included in the revised thesis. The chapter should include an evaluation of alternative methodological approaches to satisfying the research aims and a thorough description of the research methodology.

Methodology chapter was included (page 25). Evaluation of methodologies is conducted in a Section 2.5 (page 27). Description of the research methodology and design is provided in a Section 2.6 (page 30).

In the methodology chapter you also need to explain very clearly and in a convincing way the following: a. what makes the selection of this company so suitable for your research problem (e.g. justify the decision to go with this company) b. why you have decided to focus on the receiving process and not for example on order picking (which is a more costly process).

Point (a) is addressed in a Section 2.6.1 (page 30). Point (b) was addressed by extending focus to four warehouse activities.

The MAS architecture presented in Chapter 5 fits uncomfortably with the rest of the thesis. If this topic is to remain within the research and the thesis then its inclusion needs to be clearly

justified and its outputs clearly connected to other components of the research.

Following the reviewers' comments section on MAS was removed.

Some sections of the Simulation and Results chapter (Chapter 6) pertaining to integration of RFID, MAS and TDABC are unclear. The case study needs to demonstrate the advantages of twinning RFID with TDABC. This will require an analysis and evaluation of the effectiveness of TDABC in the case environment. In addition, a comparison of traditional costing, TD-ABC and RFID-TDABC across a significant area of the case environment would greatly aid the process of answering the fundamental research question concerning the value of RFID-TDABC, and, consequently, support the justification of the contribution to knowledge. In addition, the capacity cost rates and the application of the time equations needs to be unambiguously explained.

Chapter 7 (page 134) - previously called "Simulation and results" - was thoroughly revised and extended. The case study company is introduced in a Section 7.2 (page 134). Case study warehouse activities are analysed in a Section 7.3 (page 137). Analysis of warehouse activities leads to implementation of the TDABC throughout all warehouse activities in a Section 7.4 (page 142). The RFID equipment and associated investment costs are presented in Section 7.5 (page 154). Following from the TDABC and the RFID implementations, Section 7.6 (page 160) describes use of the RFID-TDABC in the four warehouse activities: receiving, put-away, order picking, and despatching. Results overview is provided in a Section 7.7 (page 175).

There is no Discussion chapter within the thesis although a brief discussion of results is provided as part of Chapter 6 (Sim-

ulation & Results). Consequently, the meaning and significance of the results have not been subjected to sufficient scrutiny and interpretation. A Discussion chapter needs to be included in the revised thesis.

Discussion chapter is now included, please see Chapter 8 (page 181). Meaning and significance of the results is presented in Section 8.2 (page 181). Section 8.3 (page 184) compares costing methods: a traditional, the TDABC, and the RFID-TDABC. Case study results are benchmarked with the literature (literature lens) in a Section 8.4 (page 185). Business case and the ROI are presented in Section 8.5 (page 188). Advantages of the RFID-TDABC in a case environment are presented in Section 8.6 (page 189) and practical applications for the RFID-TDABC are outlined in Section 8.7 (page 190). Section 8.8 (page 191) provides discussion of the findings with a reference to this thesis' research questions.

In the discussion chapter, but possibly also in other sections (e.g the RFID lit.review section or in the simulation chapter) there is a need to consider the economic/cost implications related to the required RFID investment. In other worlds there is a need to explain in a more detailed way the business case. This may also help you to discuss later on the practical applications.

Investment required by the RFID-TDABC is discussed in a Section 7.5 (page 154). Business case for the RFID-TDABC along with the ROI calculation is provided in a Section 8.5 (page 188). Practical applications are outlined in a Section 8.7 (page 190).

The Conclusions chapter will need to be re-written to take account of thesis changes.

Concluding chapter was revised.

Sentence construction and grammar need improving throughout the thesis.

Sentences and grammar were corrected throughout the thesis.

The Bibliography should be re-named References.

Bibliography re-named to References.