THALES

University of Twente
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Life Cycle Cost Optimisation

Integrating spare parts with level of repair analysis

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Preface

This report is the result of my master graduation project for my study Industrial Engineering and Management at the University of Twente. The project has been carried out at the Logisitic Engineering department of Thales Nederland.

I thank the employees of the Logistic Engineering department of Thales Nederland for their contribution to my project. My special thanks go out for my supervisor Cees Doets. I appreciate the way he provided me the time, space and freedom that I needed to successfully complete the project. I thank Charles Jongbloed for his technical assistance during the project. The rest of the LE group must be mentioned as well, as they were always prepared to invest time and effort in my project.

I also would like to thank my supervisors from the University of Twente. Rob Basten, Marco Schutten and Matthieu van der Heijden provided valuable criticism that resulted in a consistent report.

Finally I would like to thank my parents for the support and contribution they gave me during my study at the University of Twente.

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Management Summary

Research motive
Thales Nederland is a major developer and manufacturer of expensive defence related systems, such as radar equipment. Radar equipment requires maintenance and support in order to achieve sufficient operational system availability. In case of expensive technical systems, such as radar systems, the life cycle costs play an important role. The objective of the department Logistic Engineering (LE) is to provide customers with a maintenance plan such that the total life cycle cost are minimal. The current life cycle cost optimisation approach that Thales uses is not optimal.

Problem statement
Currently, Thales LE uses two optimisation techniques in order to minimise the total life cycle cost. First, they perform a level of repair analysis (LORA) to identify efficient repair policies and subsequently they use a spare part optimisation to optimise the spare part stock levels for the given LORA solution. LORA decides whether it is efficient to repair or discard a component upon failure. If a component is repaired, LORA also decides where it must be repaired in the repair network. The repair actions and locations of all components are used as input for the spare part optimisation. The spare part optimisation determines where spare parts must be stocked in the repair network such that the total spare part costs are minimal and the requested system availability is achieved. With this approach the requested system availability is achieved and for the given LORA solution the spare part costs are minimal. However, the total life cycle costs are not minimised because LORA does not take the costs of spare parts into consideration. Alternative solutions exist in which the costs for LORA are higher but the costs for spare parts are significantly lower. In this case, the total life cycle costs can be significantly lower. The current optimisation approach uses a simplified model for LORA, it requires a lot of time and concentration, it is sensitive to mistakes and errors, and the optimisation is not reproducible since it is no formalised method.

Approach
In the literature, no integrated model is available that minimises the costs for LORA and spare parts in one optimisation. Therefore we use an iterative optimisation approach where we use the spare part costs that come out of a METRIC optimisation as fixed costs in the LORA model of Basten et al. (2008-b). METRIC only calculates the spare part costs for the repair decisions that are part of the LORA solution. However, it does not calculate the spare part costs for the repair decisions that are not part of the LORA solution. After every iteration, we save the spare part costs that come out of the METRIC optimisation to a database. With this approach we build up a database that contains spare part costs for every efficient repair decision that is available for components in the system. At the end of the iteration process, the optimisation approach can make better decisions because the spare part costs are known for all efficient repair decisions. This approach however, has two drawbacks. It does not account for the component interaction effect of the spare part optimisation and the spare part costs in the database can be overestimated. We offer a solution for the last drawback. The optimisation approach has been tested on three cases. The first case reflects the actual situation of a customer of Thales. The other two cases further test the optimisation approach. The case study is based on the Variant

radar system and the logistical data that is used is based on existing project data. Thales LE provided solutions for the first two cases. We used the results from Thales LE as a benchmark for the optimisation approach.

Results
The test results of the case study show that a significant cost reduction can be achieved. For Case 1, a total cost reduction of € 16 million (17%) can be achieved compared to the solution of Thales LE. For Case 2, a cost reduction of €21.6 million (24%) can be achieved. The results of the optimisation approach show that more components are repaired downstream in the repair network. With downstream repair many repair locations need test equipment and therefore the total costs for test equipment are high. However, downstream repair results in a short repair cycle time (i.e. weeks instead of months) which requires significantly less stocks of expensive spare parts. The optimisation approach that is used in this report requires a fraction of the time for the analysis compared to the original approach of Thales LE (days instead of weeks. It requires less concentration and reduces the probability of errors and mistakes. A sensitivity analysis of the input parameters shows that the MTBF and the repair probability have a large influence on the total life cycle costs. The costs for tools and test equipment, the MTBF and the repair cycle time have a significant influence on the decisions that are made by the optimisation approach.

Conclusions
Conclusion 1: Current life cycle cost optimisation approach of Thales is not optimal.
Conclusion 2: No literature available that satisfies the requirements of Thales.
Conclusion 3: A cost reduction of 17% and 24% can be achieved for Case 1 and 2.
Conclusion 4: The optimisation approach gives good results but it is not very robust.
Conclusion 5: Overall, the MTBF is the most sensitive parameter.

Recommendations
Recommendation 1: Use simplified algorithms for LORA
The LORA model that is used in this report is very complex. A simplified algorithm that does not require a sophisticated solver would simplify the implementation process and increase the understanding of the employees at Thales LE. A simplified algorithm could be based on simple calculation rules that, for example, indicate per test equipment whether it is efficient to procure it or not.

Recommendation 2: Improve logistical data at Thales LE
The logistical data that are used at Thales LE holds a lot of uncertainty. The quality of the optimisation can be improved if the input parameters are more reliable. The sensitivity analysis shows that the MTBF is the most important parameter. The cost factor for tools and test equipment and the repair cycle times are also important.

Recommendation 3: Study the factors that influence the MTBF and repair probability
Both factors have a large influence on the life cycle costs. The life cycle costs can be reduced if these component characteristics can be improved.

Recommendation 4: Improve the robustness of the optimisation approach
The robustness of the optimisation approach can be improved by an alternative improvement technique that is discussed in the recommendations section of this report.

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1 Introduction

The subject of this graduation assignment is the development of optimal repair and stock policies for the corrective maintenance of naval radar systems[1]. Repair and stock policies are part of a maintenance plan that will support the customer in maintaining radar equipment during the entire life cycle. The project is conducted at Thales Hengelo. Section 1.1 contains a company introduction. Section 1.2 defines the actual problem. Research questions that emerge from this problem are the subject of Section 1.3. Section 1.4 gives an approach on how to answer the research questions. Boundaries of the project will be discussed in Section 1.5. Finally, Section 1.6 gives an overview of the report.

1.1 Company

This section gives an overview of Thales. Different company levels are discussed. The graduation assignment is conducted at the department Logistic Engineering, which is part of the business unit Industrial & Logistic Services at Thales Nederland. The Thales company information is subtracted from the Thales Introduction presentation and the business unit I&LS website. The historical description of Thales Nederland in Section 1.1.2 is subtracted from Florijn (2006).

1.1.1 Thales

Thales is a global corporation and market leader in mission critical information systems in the areas of aerospace, defence, and security with annual revenues of approximately 12.6 billion euros. Figure 1 shows Thales' core businesses. The Thales group is present in 50 countries and has a total of 68,000 employees.

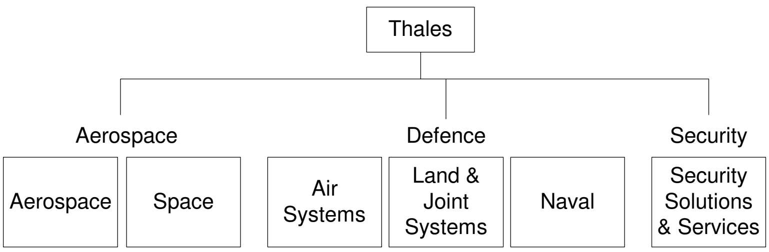

Figure 1: Three market-driven core businesses

1.1.2 Thales Nederland

Thales Nederland, formerly known as "Hazemeyer's Fabriek van Signaalapparaten", started in 1922 in Hengelo with the production of fire control equipment for two new ships of the Royal Netherlands Navy. The company grew rapidly and soon it served customers from all over Europe. In the Second World War, the invading German army captured the company's factory. After the Second World War, the Dutch government became aware of the importance of a well-organised defence industry and bought the factory. The company's name changed to "N.V. Hollandsche Signaalapparaten" also known as Signaal. In 1965, Philips became main shareholder of Signaal.

[1] This graduation assignment is related to the IOP-IPCR research project "life-cycle oriented design of capital goods", part of which is conducted at the OMPL department of the University of Twente.

At the end of the cold war, the Dutch government made budget cuts for defence activities and Signaal was forced to reorganize. At the same moment, Philips decided that defence was not a core business and sold Signaal to Thomson-CSF, a French electronics and defence company. In 2000, Thomson changed its name to Thales and Thomson-CSF Signaal became Thales Nederland.

Currently, there are three operational locations in the Netherlands with a total of 2,000 employees. Thales Hengelo is the head office, with approximately 1,700 employees. Today, Thales Nederland is the largest defence contractor in the Netherlands.

Thales Nederland is organised in four main business units (Figure 2). The goal of Operations & Purchasing (OPS) is to be the interface of Thales to supplier markets. Industrial & Logistic Services (ILS) supports customers to achieve operational availability of sold systems and products. Above Water systems (AWS) provides integrated combat systems and Surface Radar (SR) provides radar and optical solutions such as search radars, track radars, infrared sensors and TV sensors, for military and civil applications.

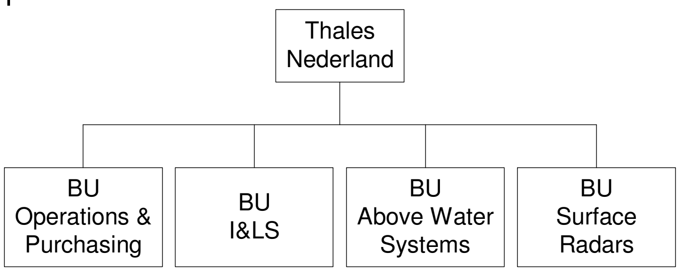

Figure 2: Four business units within Thales Nederland

1.1.3 Industrial & Logistic Services

The business unit I&LS is divided in two departments: Industrial Services (IS) and Customer Services & Support. Industrial Services deals with offset orders. It is a political agreement that, if the Dutch government buys products, such as fighter jets, from a foreign company, that foreign company also has to buy products from a company in the Netherlands.

Customer Services & Support (CSS) provides Integrated Logistic Support (ILS) for customers that bought Thales equipment. One of the responsibilities is providing spares in the after sales trajectory. Within the department Customer Services and Support there are several sub-departments such as Documentation & Training, Business Development, Material Handling and Logistical Engineering.

1.1.4 Logistic Engineering

Logistic Engineering (LE) is a sub-department of CSS. Logistic Engineering is responsible for the design of a logistically reliable system. Logistic Engineering gathers system data to support the development of technical documentation and training. It also supports the process of making a financial and logistical analysis. Customers' questions about life cycle costs and maintenance policies are answered in the procurement phase. If customers buy Thales equipment, LE supports the customer with maintenance policies to assure system availability. The actual logistics research is done at this department.

1.2 Research motive

If customers buy naval equipment from Thales Nederland, they expect Thales LE to provide them with a well-founded maintenance plan. A maintenance plan advises on the preventive and corrective maintenance tasks that have to be carried out to assure system availability during the system's life. It describes which tools and test equipment are required, which spare parts are needed throughout the repair network, and what kind of personnel is needed to perform the maintenance. A maintenance plan is proposed in order to achieve optimal operational system availability against a minimum of life cycle costs. Operational system availability is the percentage of time that a technical system is available for operation to a customer. Section 2.1 explains availability in more detail.

A level of repair analysis (LORA) is performed to identify the efficient repair actions and repair locations for components. A failing component can be repaired or discarded. If it is discarded, a new component is procured. LORA also indicates where to repair or discard the component in the repair network. If a repair action requires expensive tools or test equipment, it is efficient to repair the component upstream in the repair network. Upstream repair is repair at the top of the supply chain, such as repair at the contractor or repair at a central depot. In this case multiple technical systems from several operational locations can share the test equipment.

After LORA is performed a spare part optimisation is done. To assure system availability, spare part components are placed throughout the repair network. In case of a system failure, the faulty component is exchanged by a spare part. It is sent to a repair facility and after a successful repair action the component is placed back on stock in a ready-to-use state. For availability measures it is preferable that components are repaired downstream. Downstream repair results in a short repair cycle time which results in fewer inventories. Downstream repair is repair at the operational location or at a base nearby the operational location.

1.2.1 Problem statement

The Thales LE group expects that the procedure of generating stock and repair policies at Thales is not optimal. The current optimisation of repair and stock decisions consumes a significant amount of time. Employees indicated that the current LORA procedure is mainly based on intuition, supported by some rough calculations. In general, LORA does not consider system availability. The repair policies that result from LORA are input to an spare part optimisation. The inventory optimisation determines the most efficient stock locations for components to assure a given system availability. For efficiency, LORA favours upstream repair of components in the repair network. However, an inventory optimisation favours short repair cycle times and thus downstream repair. The optimal solution to the problem is a trade-off between minimal repair costs and minimal spare part costs.

The problem statement that results is:

Thales LE has no tool that helps in the evaluation and trade-off of alternative maintenance and repair concepts to determine the best balance between costs, schedule, performance, readiness, and supportability.

1.3 Research questions

The main research objective is formulated as:

"Develop a model that Thales can use to generate repair and stock policies, such that total life cycle costs are minimized for a given system availability"

Research questions that need to be answered are:

(1) How does Thales generate repair and stock policies in the current situation?
- (1.1) Which methods, processes and tools does Thales use in the generation process?
- (1.2) What are the difficulties that are encountered by Thales during the generation process?
- (1.3) How reliable is the information that Thales LE uses for logistical analysis?

(2) Which models exist in the literature for creating repair and stock policies?
- (2.1) Which models exist in the literature for LORA?
- (2.2) Which models exist in the literature for the allocation of inventory?
- (2.3) Which models exist in the literature that offer an integrated solution?

(3) How can we optimise the overall problem?
- (3.1) Which important aspects have to be modelled?
- (3.2) Which optimisation concept can be used to solve the problem?
- (3.3) What are the difficulties for the chosen optimisation concept?
- (3.4) What are possible solutions to overcome the difficulties?

(4) How can we set up a case study?
- (4.2) Which existing project data can we use for the case study?
- (4.3) How can we retrieve or calculate the input parameters for the case?

(5) What is the performance of the model?
- (5.1) What are the differences between the solutions created by Thales LE and the model?
- (5.2) What new insights result from the solution generated by the model?
- (5.3) How sensitive is the solution to a change of the parameters?

(6) How can the model be implemented at Thales LE?

1.4 Approach

The research is carried out in several steps. Each step refers to one research question.

(1) To understand why and when Thales generates repair and stock policies, employees will be interviewed. We use a case to determine, in depth, how Thales generates repair and stock policies in the current situation. The case reflects the situation of Thales and includes the relevant parameters.
(2) A literature review will be conducted for an identification of the available models in the literature. Starting point for this literature review is the paper of Basten et al. (2008-a).

(3) A model is introduced to optimise the overall problem. Difficulties of the concept of the model are discussed as well as improvements to the concept to overcome the difficulties.
(4) In cooperation with an Thales LE employee we set up a case that reflects the situation of a Thales customer.
(5) Thales LE employees will solve the case study with their original procedures. The solution will be compared to the model's solution. Starting conditions are varied, to indicate whether these will influence the outcome of the model.
(6) The case study will give insight and information on how the model can be implemented at Thales LE.

1.5 Demarcation

There is a difference between preventive maintenance and corrective maintenance. Preventive maintenance is scheduled and corrective maintenance needs to be carried out upon system failure. In general, preventive maintenance is done for wear-out components that are discarded upon exchange. Because preventive maintenance is not carried out during mission time it has no effect on the system availability. For these reasons preventive maintenance is excluded from this research.

We make a short evaluation to indicate how reliable the logistical input data is. Due to time restrictions, the evaluation is limited to a short description and does not contain a statistical analysis. The evaluation excludes a detailed study of how the reliability of input data can be improved.

An evaluation of existing software packages that can perform a life cycle cost optimisation is excluded from this research as directed by the Thales LE department.[2]

1.6 Report overview

The report has 8 chapters. Chapter 2 describes some basic terminology. It also describes why and how Thales generates repair and stock policies and it contains a small assessment of the reliability of the logistical information that is used during the generation process. Chapter 3 covers a literature review of LORA models, spare part inventory models, and models that integrate both optimisations. In Chapter 4 we propose an optimisation approach, explain the drawbacks of this approach, and formulate an algorithm. Chapter 5 describes a case study. We test the performance of the optimisation approach in Chapter 6. We compare the solutions that are generated with the optimisation approach with the solutions that are generated by the Thales LE department. We also test the sensitivity of the most important input parameters in Chapter 6. Chapter 7 explains how the optimisation approach can be implemented at Thales LE. The report ends with conclusions and recommendations in Chapter 8.

[2] Research in this context is already covered in the IOP-IPCR project.

2 Repair and Stock Policies at Thales

This chapter contains information about maintenance policies at Thales. Section 2.1 defines the concept of availability of the systems that are sold by Thales. Section 2.2 explains the multi-indenture system structure and Section 2.3 explains the concept of a multi-echelon repair network. Section 2.4 explains the need for repair and stock policies and at what moment in the process these are generated. Section 2.5 identifies the methods and procedures that are currently being used for generating repair and stock policies. Section 2.6 contains a small assessment of the reliability of the input parameters that are used in the process of generating repair and stock policies.

2.1 Availability

A radar system is available if all its critical components are functioning. The failure of one component will cause system failure. Availability is an important output parameter for stock policy models. Customers want certain system availability for minimum life cycle costs.

In the literature (Sherbrooke, 2004), three types of availability can be distinguished: inherent availability, achieved availability, and operational availability. It is important to know the differences between these types of availability.

Inherent availability: $$100 \cdot \frac{MTBF}{MTBF + MTTR} \tag{1}$$

with MTBF: Mean Time Between Failure
MTTR: Mean Time To Repair

Inherent availability is a measure of hardware reliability and maintainability where the downtime due to the shortage of spare parts is not included. It is assumed that spare parts are present when a component needs to be repaired.

Achieved availability: $$100 \cdot \frac{MTBM}{MTBM + MCMT + MPMT} \tag{2}$$

with MTBM: Mean Time Between Maintenance
MCMT: Mean Corrective Maintenance Time
MPMT: Mean Preventive Maintenance Time

The definition of achieved availability, also referred to as maintenance availability, is an improvement over inherent availability but it still does not account for downtime due to unavailability of spare parts. The last type, operational availability, does account for spare part shortage.

Operational availability: $$100 \cdot \frac{MTBM}{MTBM + MDT} \tag{3}$$

with MTBM: Mean Time Between Maintenance
MDT: Mean Downtime due to supply of parts and maintenance

Operational availability is also the availability that Sherbrooke (2004) uses throughout his book. A system is available if it is not down for maintenance or spare part delivery. The product of maintenance availability and supply availability is a good approximation for the operational availability if both availabilities are high (Adan et al., 1996).

Maintenance availability: $100 \cdot \dfrac{MTBM}{MTBM + MCMT + MPMT}$ (4)

Supply availability: $100 \cdot \dfrac{MTBM}{MTBM + MSD}$ (5)

with MSD: Mean Supply Delay

At Thales, in most cases the downtime due to preventive maintenance is not important because it will not affect mission availability. In general, for customers of Thales preventive maintenance is done when a ship is not on a mission. Therefore preventive maintenance will not affect the operational availability of a radar system. When leaving out the preventive maintenance time, the operational availability for Thales' radar equipment can be expressed by:

Operational availability Thales: $100 \cdot \dfrac{MTBM}{MTBM + MCMT + MSD}$ (6)

Exceptions to the above stated definition of availability occur. Some customers maintain their own definition of availability in which preventive maintenance is included. If customers demand maximum availability throughout the year, the preventive maintenance will affect availability. This research excludes preventive maintenance. Thus, whenever availability is mentioned in this report, it refers to the operational availability of Thales defined in (6).

2.2 Multi-indenture system

The term indenture is used for the different levels in a system breakdown. In general, capital goods contain multi-indenture levels. Figure 3 represents a multi-indenture system breakdown. The first indenture, level 0, is used for the system itself; in the case of Thales this could be a radar system. A radar system is built-up by subsystems such as a processing cabinet or an antenna director. A subsystem is built-up by line replaceable units (LRU). LRUs are built-up by shop replaceable units (SRU) and SRUs are built-up by parts. A component that contains one or more subcomponents is referred to as the parent of those subcomponents. In this case, the subcomponents that are located at the indenture level directly under the parent are referred to as its children. If a parent is located at indenture level *i* then the children of this parent are located at indenture level *i + 1*. In the example shown in Figure 3, the search processing cabinet is a child of the radar system. The radar system is in this case referred to as a parent.

Failure of a part will cause an SRU to fail. Failure of this SRU means LRU failure and thus subsystem and system failure. In principal, a system is repaired by replacing an defective LRU on-board. The defective LRU is then sent to a repair facility and is repaired by replacing or repairing underlying defective components. Appendix A shows pictures of components from different indenture levels.

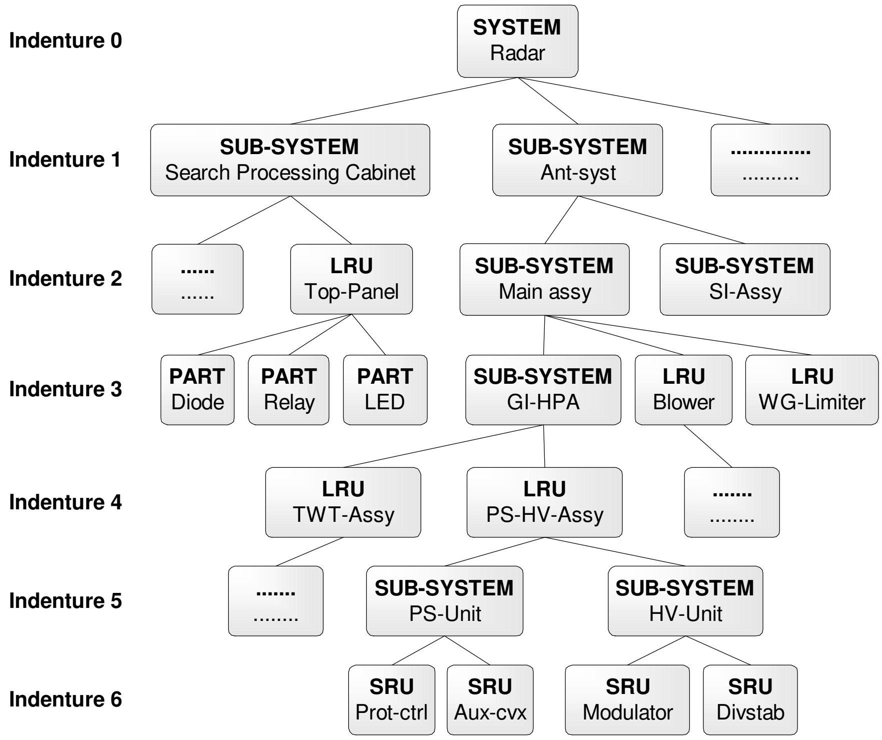

Figure 3: A multi-indenture system breakdown

2.3 Multi-echelon repair network

Upon failure, components can be repaired at different locations in the repair network. These locations are divided in levels, which are referred to as echelons. In most cases, if a component fails during a mission it can be exchanged on-board for a new one with a "repair by replacement" strategy. It is not predefined that the actual repair action of the components takes place on-board of the ship. Repair can be done at ship, at base, at depot or even at the contractor. Three levels of maintenance are commonly applicable for customers of Thales (LE Handbook, Chapter 2). Whenever maintenance cannot be performed at one of these levels the component is sent to the contractor. All levels of maintenance, as shown in Figure 4, are discussed in the upcoming four sections. Appendix B shows an example of a multi-echelon repair network for a customer of Thales. Repair at the top of the supply chain, such as contractor or depot repair, is called upstream repair. Repair at the bottom of the supply chain, such as repair at ship or at base, is called downstream repair.

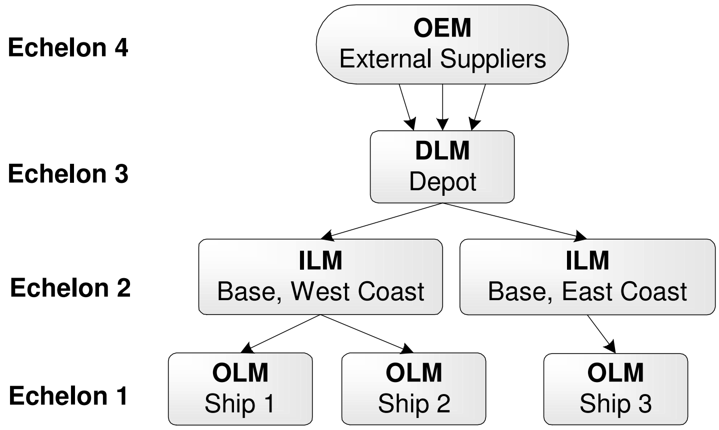

Figure 4: A multi-echelon repair network

2.3.1 Organisational Level Maintenance (OLM)

Organizational Level Maintenance (OLM), also referred to as On-board Level Maintenance, is performed at the ship. Repair actions include preventive as well as corrective maintenance. Thales employs a "repair by replacement" strategy of Line Replaceable Units (LRUs) using On-Board resources.

2.3.2 Intermediate Level Maintenance (ILM)

Intermediate Level Maintenance (ILM) is maintenance that is performed by a designated maintenance organisation using shore resources in addition to ship resources for direct and general support to the ship. Intermediate maintenance activities normally consist of calibration, repair or replacement of damaged or unserviceable parts, the emergency manufacture of non-available parts, and providing technical assistance to the ships crew.

2.3.3 Depot Level Maintenance (DLM)

Depot Level Maintenance (DLM) is maintenance performed at a remotely located facility. Depot level organisations enjoy the use of more extensive shop facilities, equipment and personnel of greater specialization than are available with OLM and ILM maintenance. DLM activities include: repair, modification, alteration, modernisation, overhaul, reclamation, or rebuild of parts, assemblies, sub-assemblies, components, and end items.

2.3.4 Original Equipment Manufacturer (OEM)

An Original Equipment Manufacturer (OEM) is the company that manufactures the original components. For customers, Thales can be an OEM. Thales however, does not manufacture all components that are part of a radar system. In this case a subcontractor of Thales can also be an OEM. Components are sent to the OEM when a component's repair action is too complex for the other maintenance levels. In case a component is not repairable a new one is procured from the OEM.

2.4 Thales and the need for maintenance policies

Thales serves approximately 85 individual customers in over 40 countries. Most customers are governments, rather than industrial parties. Organisational differences of these customers are responsible for the fact that no single product delivered by Thales is exactly the same. Important customers with a well-developed naval structure located in countries such as Canada, the United Kingdom, and the

Netherlands, demand detailed information concerning the maintenance of Thales equipment. They want to know exactly where to repair all the components that are subject to failure, where to hold spare parts in the repair network and what kind of equipment is needed to perform the repair actions. The MIL-STD-1388-1A is the general accepted standard of what has to be included in a maintenance concept.

If customers request maintenance information in the procurement phase, the department Logistic Engineering roughly indicates which repair activities and how many spare parts are needed. The indicated policies result in a maintenance budget that a customer can use to estimate the total life cycle costs of a system. A maintenance budget contains all the costs that are related to the upkeep of a system. Life cycle costs are incurred with the development, production, use, maintenance and disposal of a product. If customers decide to buy Thales radar equipment they can request a detailed maintenance analysis. Such an analysis consists of well-founded repair and stock allocation decisions. A detailed analysis is done at the Thales LE department by a logistic engineer and can take up to approximately 400 hours for a single system. The customer has to pay additionally for such a detailed analysis.

In general, customers carry out the maintenance that is needed to maintain the Thales radar equipment. Customers hold spare parts, procure test equipment, and open repair facilities in the repair network. More and more customers, such as the United Kingdom, request Thales to provide them with a service contract where Thales is responsible for the repair and the holding of spare parts. Denmark has contracted Thales for the delivery of spare parts within five days upon system failure. Thales expects that this trend will continue and considers the possibility of offering integrated service contracts in which Thales is responsible for the availability of the system that is sold to the customer. Since the selling of services is generally more profitable than the selling of products (Deloitte, 2006; Murthy et al., 2004; Olivia and Kallenberg, 2003), the generation of cost effective maintenance policies are, especially in this case, of great interest to Thales. Since not all customers require a LORA and the sale of capital goods is only limited to a few systems a year, a LORA is required only a limited number of times a year. The department LE is responsible for performing a LORA.

2.5 Current situation

The current optimisation process at Thales LE is not optimal. It is a complex process that requires a considerable amount of time and does not deliver a solution that has minimum life cycle costs. This section explains the current optimisation process and tools that Thales LE uses for the analysis.

2.5.1 Optimisation process

The objective of Thales LE is to provide customers with a maintenance plan that has minimum life cycle costs. In order to generate a maintenance plan that has minimum life cycle costs, two optimisation techniques are applied. First, a LORA is performed and subsequently a spare part optimisation is done. LORA minimises the costs that are related to maintenance, such as costs for repair and costs for test equipment. It evaluates for each component whether it is efficient to repair or discard the component. If it is efficient to repair a component then LORA determines where the component must be repaired in the repair network and which resources must be procured in the repair network in order to be able to perform the chosen repair action.

Spare part inventory is not considered in LORA. The costs of spare parts cannot be used as cost factor in the LORA model because a spare part optimisation uses a system approach. LORA cannot use a system approach for the spare part costs because it uses a linear approach. For this reason, LORA does not take the system availability into consideration. However, if the repair action (repair or discard) and the repair location are known for all components in the system then the spare part optimisation is able to provide optimal[3] stock levels such that the requested system availability is achieved.

With this approach, the requested system availability is achieved and for the given LORA solution the spare part costs are minimal. However, the total life cycle costs are not minimal. This approach results in a solution where many components are repaired upstream. LORA can save costs with upstream repair because components can share expensive resources such as test equipment at one central location. However, the lead time for upstream repair is much higher than for downstream repair. Therefore more expensive spare parts are needed to achieve the requested system availability. If the spare part costs are a fraction of the total life cycle costs, then this approach is appropriate. Since the spare part costs in the situation of Thales make up a very large part of the total life cycle costs this approach is not optimal.

In practice, Thales LE evaluates the outcome of this approach. If this approach provides a solution where the spare part costs for some components are extremely high then Thales LE tries alternative solutions. An alternative solution is, for example, to repair components with very high spare part costs at a lower echelon level in the repair network. For every alternative solution that is evaluated, the costs for LORA must be partly recalculated followed by a total recalculation of the spare part stock levels. Section 2.5.2 explains the current approach for LORA and Section 2.5.3 explains the current approach for the spare part optimisation.

2.5.2 Current approach LORA

Until a few years ago, Thales LE used the tool PRICE-HL (2007) to perform LORA and life cycle cost optimisation. In 2003, Thales performed a DLM Study (2003) with PRICE-HL for the Royal Netherlands Navy (RNLN). The purpose of this study was to evaluate whether Depot Level Maintenance (DLM) was economically feasible to the RNLN. During this study, many of the required input parameters of PRICE-HL were ignored or set to default because they were unavailable to Thales. PRICE-HL is capable of analysing 28 different maintenance concepts. Appendix C lists all possible maintenance concepts of which most were not applicable for the specific Thales situation. Only three maintenance concepts were applicable to the RNLN, since it was clear that, due to the low demand, the trade-off would be between depot and contractor repair. All scenarios exchanged components at organisational level. Scenario 1 discards faulty components, scenario 2 repairs faulty components at depot and scenario 3 repairs components at the contractor. For the analysis Thales LE divided components in so-called boxes or groups. Components that require the same test equipment for a repair action were grouped together in a box. For all boxes, Thales LE analysed if it was economically feasible for the RNLN to procure the aforementioned tools and test equipment at the depot. The output of PRICE-HL

[3] Stock levels are optimal when the total costs of spare parts are minimal.

showed the costs for each of the three maintenance scenarios, their relative cost effectiveness, and the achieved readiness of the components in the box (Figure 5).

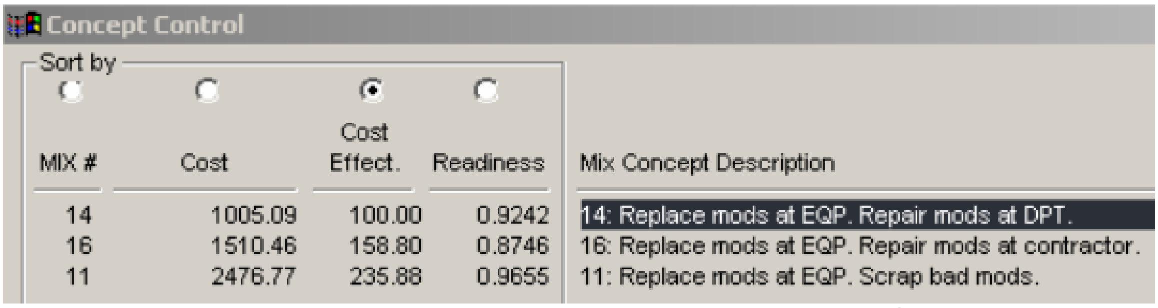

Figure 5: Results of a life cycle cost optimisation in PRICE-HL

Although PRICE-HL was capable of performing LORA, it did not meet all the overall requirements of Thales LE and they stopped using the package. Currently Thales LE uses no tool for LORA. In the case a LORA is requested by the customer, an employee of Thales LE calculates in Microsoft Excel whether it is efficient to procure one of the tools or test equipment. The trade-off is made between contractor repair and depot repair. In general, the ILM location, if there is more than one, is not considered as an efficient location for tools and test equipment. In this case every ILM location needs tools and test equipment. In case of contractor repair, no test equipment is needed. The variable repair costs of contractor repair however, are relative high. In case of depot repair, the variable repair costs are low, but the required tools and test equipment must be procured. Due to the high investment for tools and test equipment, only tools and test equipment that serve a relative high demand qualify for the trade-off analysis.

In order to perform a successful LORA a lot of data must be processed, converted, analysed and presented. Performing a LORA in Microsoft Excel requires a considerable amount of time and concentration. In Chapter 5 we discuss a case study. The Thales LE department also provided a solution for the case study. During this case study the disadvantages of doing a LORA in Microsoft Excel became apparent. The solution that has been provided for the case study by the Thales LE department is generated under time pressure because daily operational tasks had to be completed. In fact, whenever the Thales LE department performs a LORA for a customer this time pressure is also present. Due to the time pressure, Thales LE uses a simplified model for LORA where details are left out during the analysis such as disposal costs, transportation costs, maintenance costs for test equipment, and labour costs. It is very difficult for Thales LE to include the influence of spare parts in LORA. Therefore the costs of spare parts are not included in LORA. It is also very difficult for Thales LE to see the multi-indenture effect for components. In other words, it is difficult to see what happens to the children of a component if the repair decision changes for the parent of the children.

The major disadvantages of performing a LORA in Excel are:

- It is a time consuming process.
- It is a complex process where a lot of information is involved and the analysis requires a high level of concentration due to the lack of direct interaction between various cost drivers.

- The analysis is sensitive to errors.
- It is hard to include the influence of spare parts in LORA.
- The analysis uses a simplified model where not all cost drivers are included.
- It is difficult to see the multi-indenture effect of decisions.

2.5.3 Current approach spare part optimisation

Spare part optimisation is currently done with Inventri. The program Inventri has been developed by Districon and Ortec by order of Thales Nederland and has been based on the VARI-METRIC procedure of Sherbrooke (1992) and PhD research of Rustenburg (2000). The main reason for developing this tool was that, although initial inventory supply tools were widely available, resupply inventory could not be calculated with existing software packages. Resupply is not of interest for this research and thus not explained here. Inventri is currently being used in the support of service contracts and for the calculation of a Recommended Spare Parts List for customers. Since Rustenburg (2000) extensively covers the modelling techniques behind Inventri, these modelling techniques are not discussed in detail in this section. Chapter 3 covers a literature study. The major contributions of Rustenburg to the existing theory are summarized in that chapter.

The program Inventri uses system data, cost data and project data from the Logistic Support Analysis Records (LSAR) database. The LSAR database, also referred to as the SLIC/2B database, is mainly used by the LE department and holds information about current projects and projects from the past. Inventri uses this information to calculate a Recommended Spare Parts list, a required budget and the achieved system availability.

2.6 Input parameter reliability

Employees of Thales indicated that the logistical data that is used for analysis contains a high degree of uncertainty. According the employees the logistical data that contains the highest uncertainty is price and failure data. Internal research at Thales confirms that these parameters are not very reliable, see Appendix D. The usage of unreliable input parameters for a model will result in unreliable model outcomes, which is also known in popular speech as “garbage in, garbage out”. In Section 6.5 we perform a sensitivity analysis for the unreliable parameters in the case study.

3 Literature Review

As stated in Chapter 1, the focus of the project lies on LORA and inventory allocation optimisation. The literature review has four sections. Section 3.1 discusses the concept of LORA and applicable models that are currently available in the literature. Section 3.2 discusses the concept of a spare part optimisation and applicable models that are available in the literature. Section 3.3 covers literature that addresses LORA and inventory allocation in an integrated fashion such that both are optimised simultaneously. Section 3.4 contains a discussion of the literature that is found in the first three sections of this chapter. In Section 3.5 we draw a conclusion of results of the literature study in this chapter. This section explains which models we will use. Basten et al. (2008-a) already reviewed important literature that is related to LORA. Therefore this paper is the starting point of the literature.

3.1 Level of repair analysis

The main purpose of LORA is to generate an efficient repair policy for the corrective maintenance of every component within a complex system structure. A non-economic LORA is performed prior to the economic LORA (MIL-STD-1390D). Component failure behaviour and variable and fixed costs are the basis for generating repair policies.

3.1.1 Non-economic LORA

Components within a system structure are evaluated to whether they are repairable or not. According to Florijn (2006), several questions have to be answered for a non-economic analysis, such as:

- Does the customer have a preferred maintenance policy for certain components? If so, then use this preferred maintenance policy and exclude the component from LORA. If not, do nothing.
- Is the component procurable? If yes then do nothing. If no then exclude discard as a repair option.
- Does the component have any handling constraints? If yes then exclude repair locations that are not capable of handling these constraints. If no then do nothing.
- Is the component hazardous? If yes then exclude repair locations that are not capable of handling hazardous components. If no then do nothing.
- Are resources available for component repair? If yes then do nothing. If no then use discard as repair option and exclude from LORA.
- Does the component contain any intellectual rights? If yes then forbid repair at locations that do not have the right to perform the repair. If no then do nothing. If no location has the right the repair the component then it must be discarded and excluded from LORA.
- Is the component technically and economically[4] repairable? If yes then do nothing. If no then use discard as repair option and exclude from LORA.

Bulk components for example, are economically not interesting for repair and are thus excluded from the economic LORA. For some components the actual repair

[4] Bulk items that are relatively cheap are considered as items that are economically not repairable.

action might be too complicated for onboard repair. The onboard repair option in this case will be excluded. The result of the non-economic LORA will be a list with relevant components and the possible repair and discard options for these components. This list will serve as input for the economic LORA.

3.1.2 Economic LORA

The process of finding the best corrective maintenance policies for components is called economic LORA. The outcome of the economic LORA is a decision for every component, whether they should be repaired or discarded, and where this action should be performed in the repair network (Basten et al., 2008-a). The objective of LORA is to minimize total costs for the corrective maintenance policies of all components.

A repair action for complex components may require expensive tools and test equipment. These tools are, for example, needed to locate the defective child that causes the component failure. Upon repair this defective child is replaced or, if possible and economically feasible, a defective child of the child is replaced. The actual trade-off in LORA consists of the economic decision whether to procure expensive tools and test equipment to be able to repair components in the customers repair network. If the procurement of certain tools and test equipment is not cost efficient, components can be repaired at the OEM or they can be discarded and replaced by new components. Repair at the OEM is in most cases, more efficient than discarding a component and procuring a new one. Repair at the contractor requires no procurement of tools and test equipment.

3.1.3 Level of repair analysis literature

The United States Department of Defence requires in its MIL-STD-1388A (1993) that acquisition programs have to emphasise the evaluation of alternative support concepts and techniques to minimize costs and support risks. The evaluation of alternative support concepts requires a LORA according to MIL-STD-1390D (1993). Although the first edition of this standard dates from 1974, there are only a limited number of papers dedicated to LORA in the literature. In contrary, there are several commercial software solutions that pretend to cover the problem, such as EDCAS, OPUS10, and PRICE-HL. However, it is not possible to clearly identify which models and techniques are used to solve the problem.

In general, the models found in the literature use a combinatorial approach and formulate a linear integer program that can be solved by a commercial solver, such as LINDO or CPLEX. The models minimize total variable and fixed cost by choosing an efficient repair policy. A repair policy indicates for each component whether it has to be repaired or discarded and where this action has to be performed in the repair network. If tools and test equipment are required to perform the action the models account for the procurement costs of these tools and test equipment.

Barros (1998) proposes an Integer Programming (IP) model for LORA. In her model she assumes that, for simplicity, the option of discard has zero fixed cost. However, in practice some components may contain hazardous materials that need special disposal equipment or facilities. In that case, the option of discard will incur certain fixed costs. Another assumption she makes is that if a repair facility is capable of repairing a component, it will also be capable of repairing all the other components at the same indenture level. In addition, Barros (1998) does not consider repair facility capacities. Barros (1998) solves the model with the use of an algorithm that relies on the basic premise that there are a relatively small number of indenture levels and maintenance echelons. Barros and Riley, (2001) solve the model using a branch and bound algorithm to reduce the computation time.

Saranga and Dinesh Kumar (2006) present a model that they solve with the use of genetic algorithms. The model is based on three echelons and three indentures. They allow for a discount factor by which they calculate the Net Present Value of maintenance throughout time. They give a detailed description of what is included in the variable and fixed costs. Tools and test equipment are assumed to be used by one type of component. In practice, tools and test equipment can be shared by more components instead of just one.

Brick and Uchoa (2007) propose a Mixed-Integer Programming (MIP) model that is more general than the models of Barros (1998) and Saranga and Dinesh Kumar (2006). The model includes the use of resource capacity and the use of multiple identical resources. This allows the model to choose a solution in which identical components that originate from the same operational location can be repaired at more than one repair location. This could suggest that the demand per component is very high in the problems for which they developed their model. They allow for different maintenance scenarios by changing some of the restrictions. To represent the situation where some decisions are not valid, such as where it is not possible to choose a certain repair action for a component at a specific location, it is necessary to force some decision variables to be zero. The model is not restricted to a predefined indenture structure. Transportation costs are included in the model as well as a discount factor. The demand per operational location is a function of several parameters. Brick and Uchoa (2007) mention in their paper that the development of models subject to spare part stock optimisation and availability restrictions in combination with LORA, may be considered as one of the greatest challenges for researchers in the forthcoming years.

Basten et al. (2008-a) developed a LORA model in cooperation with Thales LE. Their MIP model is also more general than the models of Barros (1998) and Saranga and Dinesh Kumar (2006). They show that different problem instances can be solved with their model in reasonable time with the use of a commercial solver. An improved model, with respect to calculation time, is presented in the same paper. Any number of echelons and indenture levels are allowed. Resources can be shared by components at every indenture level. Discard costs can be specified for all locations in the repair network per component. The model assumes infinity resource capacity and does not account for a discount factor. It assumes that the Net Present Value of money is always the same. Decision variables are binary (zero or one) and indicate the chosen option of discard, repair, or move for each component that needs a decision (variable becomes one, if an option is chosen). Since the move option is incorporated in the model, transport costs can be included. Either one of the three options can be chosen for each component. If the option “move to a higher echelon” is chosen for a component then the algorithms must also make a decision for that component on that echelon. Because the model aggregates data per echelon and does not consider individual locations, a symmetrical repair network is assumed. Overall, the model of Basten et al. (2008-a) reflects the basic requirements of Thales

LE very well. A major advantage compared with the models of Barros (1998) and Saranga and Dinesh Kumar (2006) is that any number of indentures and echelons are allowed. The use of less restricted tools and test equipment restrictions are also an advantage compared to the above-mentioned models. The practical situation of Thales LE favours both advantages.

Basten et al. (2008-b) introduce some improvements to the model of Basten et al. (2008-a). The structural change in the improved model is that it is formulated as a minimum cost flow problem. Failure modes are now included in the model to be able to model different type of failures for a single component. Two generalisations are made compared to the previous model. The repair network is now explicitly modelled and failure types are now modelled instead of components. Explicitly modelling all the repair locations allows for asymmetry in the repair network. Different failure types can now be distinguished in one component, which allows for different repair decisions per component depending on the type of failure.

The change in formulation allows for some interesting extensions to the previous model such as resource capacity and repair probability. Resource capacity takes the maximum capacity of the tools and test equipment into account. Repair probability is related to the problem that not all components can be successfully repaired upon failure. Some components are damaged beyond repair, which will result in an unsuccessful repair attempt. In this case there are two options: a second repair attempt could be made at a higher echelon or the component has to be discarded and a new one must be procured. The improved model also allows for no-fault-found. In general, faulty components are examined to identify the type and cause of failure. In some situations the engineer that examines the component cannot identify any fault. In this case it seems that the component is working and that it was not responsible for the system failure. The component is then returned to the system or placed on stock in an as-good-as-new state without being repaired. Although components are not repaired in this situation some costs are incurred. A minor change in the formulation of the resources adds the possibility of using the same resource for different actions, such as repair and discard for the same component. Basten et al. (2008-b) show that, compared to the first model, the new model formulation is more efficient with respect to calculation time.

3.2 Spare part allocation

Properly managing an expensive spare part inventory is a challenging problem for customers that procure repairable technical systems such as radar systems. As stated earlier, a radar system will fail at a certain moment and a spare part is needed immediately to limit the system's downtime. The question remains where to locate the spare part in the repair network. Obviously, locating the spare part at the system's operational site (OLM) will minimize the system's downtime. In this case all OLM sites would need a spare part. Locating the spare part at ILM or DLM instead of at OLM will cause a decrease in the system's availability. The transportation time, also referred to as lead-time, between ILM and OLM will cause the system to be unavailable during the moment of spare part transportation. However, the positive effect is that all OLM sites that are below the ILM or DLM can share the spare part inventory. In this case, less spare parts, and thus less investment costs, are needed to maintain the system.

The two main questions that have to be answered are: at which locations do we have to place spare parts in the repair network and how much spare parts are needed at these locations in order to assure the requested system availability[5].

3.2.1 Spare part allocation literature

A lot of inventory models have been developed; see for example the literature review by Guide and Srivastava (1997) and more recent, Kennedy et al. (2002). There are a lot of models with specific characteristics that apply for different practical situations. Guide and Srivastava (1997) state that most of the repairable inventory models are based on METRIC. The work of Sherbrooke (2004) and Muckstad (2004) explain the METRIC approach and its recent extensions in detail. The program Inventri however, is based on Rustenburg (2000). He studied the inventory allocation problem of complex technical systems at the Royal Netherlands Navy (RNLN). The RNLN is a customer of Thales. The research of Rustenburg (2000) reflects the conditions and environments of the customers of Thales very well. According to Rustenburg (2000), six modelling approaches are applicable for spare part inventory allocation management:

1. Statistical Inventory Control (SIC) models.
2. Material Requirements Planning (MRP) techniques.
3. Multi-Echelon Techniques for Recoverable Item Control (METRIC).
4. Capacitated closed queuing network based inventory models.
5. Capacitated open queuing network based inventory models.
6. 'Cohen' models.

For our research, only modelling approaches 1 and 3 are of interest. The upcoming section discusses both. See Rustenburg (2000) for a detailed description of the other models.

(1) Statistical Inventory Control (SIC) models

Silver, Pyke and Peterson (1998) extensively describe Statistical Inventory Control (SIC) models. In general most models are periodic or continuous review models and pure cost or cost/service models. Cost models only minimize for example order and holding costs. Cost/service models minimize the order and holding costs and satisfy a service level constraint. Multi-echelon characteristics are included in most of the models. Base stock models are an important sub-class of inventory allocation models. Base stock models use a replenishment strategy in which the stock levels are periodically returned to a pre-determined order-up-to level, which is in general equal to the initial supply amount. In the case of capital goods or complex technical systems, demands are relative low and demand is concerned with only one item, in which a so-called one-for-one replenishment policy is adopted. Complex technical systems fit these models since demand rates are generally low and component prices are high. However, performance of these models is measured by individual item performance that does not depend on other items. Thales is interested in the system availability. Therefore, items cannot be considered individually.

[5] Per component type, spare parts can be located at more than one location.

(3) Multi-Echelon Techniques for Recoverable Item Control (METRIC)
Sherbrooke (1968) developed an effective way to optimise stock levels for repairable inventory of complex technical systems in a multi-echelon environment. His procedure became known as the METRIC procedure and is currently widely adopted by companies in the field of repairable inventory control. The goal of METRIC is to calculate optimal base stock levels, which results in a budget, such that a given system availability is met. As an alternative a budget can be specified, which will result in an achieved availability. The METRIC procedure places spare part inventories at stock locations in an iterative way, such that the availability increases with each spare part that is added. This procedure is also referred to as marginal analysis. The original METRIC procedure uses a system approach and is suitable for single-indenture products and two-echelon repair networks. This procedure generates the well-known availability-cost curve (see Figure 6). The inverse of the slope of the availability-cost curve at any point shows the marginal costs of obtaining a higher availability. Any point below the curve is considered to be inefficient and any point above the curve is unobtainable.

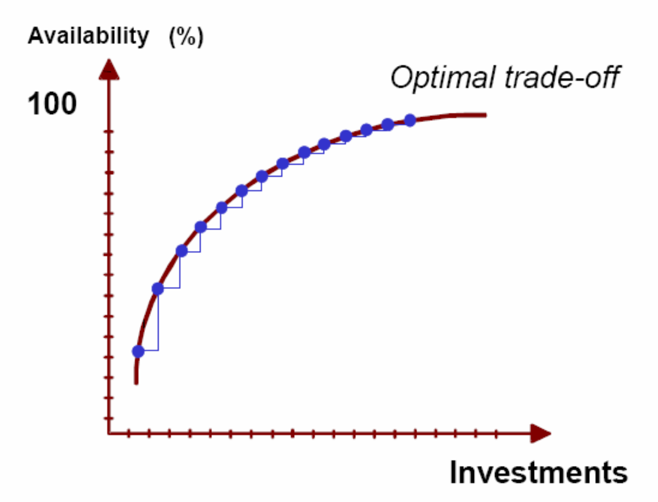

Figure 6: The availability-cost curve

A lot of extensions to the METRIC model have been developed, such as, MOD-METRIC and VARI-METRIC. Muckstadt (1973) extended the METRIC model to a two-echelon, two-indenture model, which is referred to as MOD-METRIC. Slay (1984) introduced VARI-METRIC, which accounts for the variance of the number of items in repair. The traditional METRIC only accounts for the average number of items in repair. Simulation studies show that results produced by VARI-METRIC are more accurate than the traditional METRIC procedure. Sherbrooke (1986) combined the MOD-METRIC and VARI-METRIC to a two-echelon and two-indenture version of VARI-METRIC. Lee (1987) provides a METRIC-based approach where lateral shipment is allowed. With the use of some simplifying assumptions, Sleptchenko et al. (2002) and Diaz and Fu (1997) address the influence of repair capacities on the repair cycle time. Many other extensions are available to METRIC, see Guide and Srivastava (1997). Appendix E shows possible improvements that might be of interest to Thales in the near future.

Rustenburg (2000) states that the presence of both consumable and repairable items and the objective of system availability are essential for a spare part inventory model.

He concludes that the METRIC model of Sherbrooke (1992) reflects the spare part inventory system very well. Rustenburg (2000) based his model on the VARI-METRIC model of Sherbrooke (1992) and added some extensions. The extensions are related to re-supply, condemnation, commonality, criticality on system level as well as on part level, a general demand process, redundancy and multiple failures. All the extensions are relevant to the RNLN as well as to the Thales LE department.

3.3 Integrated models

Few researchers studied the relation between LORA and inventory optimisation. Only Kaplan and Orr (1985) and Alfredsson (1997) address the simultaneous optimisation of repair policies of stock levels.

3.3.1 Literature integrated models

The first paper that addresses the problem is the one of Kaplan and Orr (1985). They propose a model that integrates inventory allocation optimisation and repair decision optimisation. It uses the so-called SESAME model of the United States Army to assess the inventory implications for the model. Inventory stock policies and costs are returned from the SESAME model and used in the model. They use a Lagrangian procedure to optimise the system availability for a chosen maintenance policy to a predefined target level. The paper was published in 1985 and the model uses looping procedures to interact on an iterative way with SESAME. It is not clear how the SESAME model works, since it is United States Army property. It is also strange to notice that, although the model is presented in 1985, only one paper (Alfredsson, 1997) addresses the integration of LORA and spare parts optimisation. However, the basic idea of connecting LORA to an inventory allocation optimisation in an iterative way might be quite useful.

Alfredsson (1997) developed an IP model that integrates LORA with the optimisation of inventory stock levels. He follows the METRIC procedure of Sherbrooke (1968) to calculate the total expected number of backorders of spare parts needed to restore the system to operational status. A backorder is an order that is not yet filled and still has to be delivered. Each backorder corresponds to one technical system being non-operational. He uses a complex model to calculate the total number of expected backorders. Fairly complicated algorithms are needed to solve the model. For the demand process at stock points and the arrival rate at repair locations he assumes Poisson processes. This enables him to use Palm's theorem (Palm, 1983) to determine the steady state distribution for the number of units in repair. The model of Alfredsson (1997) allows the use of a multi echelon repair network and capacitated test equipment, but does support multi indenture components. He also accounts for the fact that the usage rate of test equipment influences the repair cycle time. Repair level decisions are considered to be the same for all components that are assigned to the same resource, such as a tester. Test results showed that keeping track of the underlying information of efficient points, which must be generated to make the solution space convex, requires a lot of computer memory. In fact, in some situations, he had to store this information externally, due to the shortage of internal memory. One could imagine the difficulties that will be encountered when multi-indenture aspects are modelled. In the concluding remarks of the paper he states that it would be of interest to implement multi-indenture aspects to the model. Although the model is complex, it looks promising. It is quite remarkable to notice, that there are no succeeding papers that make use of the model or propose extensions to the model.

In fact, the paper is only cited a limited number of times by other researchers. At the time of publishing, Alfredsson was a member of the Royal Institute of Technology in Stockholm. Currently he works for Systecon in Sweden, which is the company that sells the logistical analysis software called OPUS10. This could explain why Alfredsson does not publish further model developments.

3.4 Discussion literature review

Thales LE as well as the University of Twente indicated that the most valuable contribution to the existing field of research is the integration of a level of repair analysis with a stock optimisation. The model of Alfredsson (1997) is the only model that satisfies this constraint. However, his model is already quite complicated and does not allow for multi-indenture systems. Adding multi-indenture aspects to the model would increase its complexity and this most probably results in a model that is not practical. Alfredsson (1997) made simplifying assumptions in order to use a METRIC-like optimisation procedure for the stock levels. It is not yet clear how accurate this METRIC-like optimisation procedure is, since there are no test results available that are related to the accuracy of the model. Due to the high model complexity we choose not to use the model of Alfredsson (1997).

Since there are no appropriate models that include both optimisations simultaneously we have to find an alternative to come to a solution. One alternative could be to extend an existing model to include a simultaneous optimisation of repair decisions and stock levels. There are a few problems when we would try to extend one of the models reviewed in Chapter 3. The LORA models in the literature review use a combinatorial approach that is solved with the use of linear programming, branch and bound or genetic algorithms. Spares optimisations like Sherbrooke (1986) are done with marginal analysis. Alfredsson (1997) already showed us that including METRIC-like spares optimisation result in non-linear restrictions. In order to solve the problems that arise from these non-linear restrictions, convexity issues must be solved that become very complicated and require that simplifying assumptions have to be made for the stock optimisation. The simplifying assumptions will have an undesirable effect on the accuracy of the results. Literature shows that METRIC and its extensions are currently one of the most accurate and well-accepted models in the field of repairable inventory (Guide and Srivastava, 1997). The METRIC procedure is subject to research and development for over forty years.

3.5 Conclusion literature review

Kaplan and Orr (1985) showed that the concept of models, which interact on an iterative basis, could be successful. The strength of using this approach is that it builds on the current literature and that it uses verified and accurate models. Using well-accepted models from the literature will result in a general approach. An additional effect is that linking two existing models limits the complexity of the model building to an acceptable level. The models of Basten et al. (2008-b) and Rustenburg (2000) are both accessible in the form of ready to use applications. The theory of Rustenburg (2000) is incorporated in the software program Inventri, which is currently being used at the Thales LE department. The literature review of Chapter 3 indicates that they are currently among the most well developed models in the literature and that they satisfactory reflect the situation of Thales LE. The focus of this research will be on linking the model of Basten et al. (2008-b) to the model of Rustenburg (2000).

4 Optimisation Concept

In Chapter 3 we chose for an optimisation approach where we use the LORA model of Basten et al. (2008-b) in combination with the model of Rustenburg (2000). In the optimisation approach we use the spare part costs that are calculated with a spare part optimisation in the LORA model. This chapter explains how we include the spare part costs in the LORA model. We explain the basic idea of the optimisation approach in Section 4.1. The optimisation approach uses an iterative process which we describe in Section 4.2. The optimisation approach has two drawbacks which are both described in Section 4.3. We tested three improvement techniques to overcome one of the drawbacks. The test results of the improvement techniques are discussed in Chapter 6. Section 4.4 contains the algorithm of the optimisation approach and Section 4.5 gives an example of the optimisation approach.

4.1 Optimisation approach

In order to optimise for minimal life cycle costs we must optimise the LORA and the inventory allocation problem simultaneously. In the current situation of Thales LE the problem is solved sequentially. First, some calculations are made to establish efficient repair locations (LORA) and then a spare part optimisation is done to minimise the costs of the spare parts for the given LORA solution. Decisions made in LORA can have a large impact on the number of spare parts that are needed to achieve the required system availability. For LORA it might be efficient to share expensive resources at a central location, such as a depot or a contractor. Repair at the depot or contractor however, results in a high repair cycle time. A high repair cycle time requires more spare parts in order to achieve the required system availability. In other words, an efficient LORA (excluding spare part costs) probably results in high inventories. The number of spare parts that are needed to achieve the required system availability depends on the choices made by the LORA. During the spare part optimisation, the quantity of spare parts is only calculated for the given LORA solution.

We optimise the overall problem by using an iterative approach. In the first iteration we start LORA without taking any spare part costs into consideration. The LORA model offers a minimum cost solution that is optimal with respect to the repair decisions if we ignore the system availability and the costs of spare parts. The LORA is followed by a spare part optimisation which results in a spare part list. The spare parts on the list are required to achieve the system availability for the given LORA solution. We now know costs of spare parts that belong to the repair decisions made in the calculated LORA solution. However, we do not know the costs of spare parts that belong to other repair decisions. We solve this problem by starting the first iteration with a database of spare parts costs that is filled with zeros for every possible repair decision and component in the system. The costs of spare parts that result from the first iteration are filled in the database and used as input for LORA in a second iteration. LORA will make different decisions for components during the second iteration because the spare part costs of the first LORA are included in the analysis. During the iteration process all appropriate repair options in the database will gradually be filled with spare part costs. Drawback of this approach is that it assumes that there is no relation between the spare part costs of different components in the system. The spare part optimisation approach however, uses a system approach that assumes there is a relation between the spare part costs of different components. This is a problem and we explain this drawback in detail in Section 4.3.

Suppose that the LORA model decides during the first iteration that it is efficient to repair a component at the contractor. Because the contractor repair cycle time is high, the spare part optimisation tool decides to place a considerable amount of spare parts for that component at various locations in the repair network to compensate for the high repair cycle time. During the second iteration, the sum of the costs of all spare parts for that component are now used as fixed costs in the LORA model for the option of contractor repair for that specific component. If the LORA model wants to choose the option of contractor repair for that component again, the fixed spare part costs must be paid. Probably LORA decides in the second iteration to repair at a different location due to the fixed spare part costs that must be paid for contractor repair. Suppose LORA decides to repair the component during the second iteration at the depot. Due to a lower repair cycle time, the spare part optimisation tool decides to place fewer spare parts in the repair network than with the option of contractor repair. However, the spare part costs incurred with depot repair is still significant. Suppose that, with the spare part costs for contractor and depot repair in stored in a database, the LORA model decides the third time to repair at base. Eventually all possible repair actions (repair/discard) and repair locations for a component will have related fixed spare part costs stored in the database.

4.2 The iteration process

Figure 7 shows the concept of the iteration process. We explain the iteration process step-by-step in this section. The iteration process stops when the solution that is found in the current iteration is the same as the solution that is found in the previous iteration.

Step 1
We start with a LORA optimisation. The costs of spare parts are not considered at this moment. The result of LORA is a repair action (repair or discard) and a repair location (OLM, ILM, DLM or OEM) for each component in the system.

Step 2
The repair location and repair action, which are the result of LORA, are used to calculate a repair cycle time for each component.

Step 3
The repair cycle times are used as input to the spare part optimisation. The spare part optimisation calculates a so-called spare part list, which lists all the spare parts that are needed to achieve the required system availability for the given LORA solution.

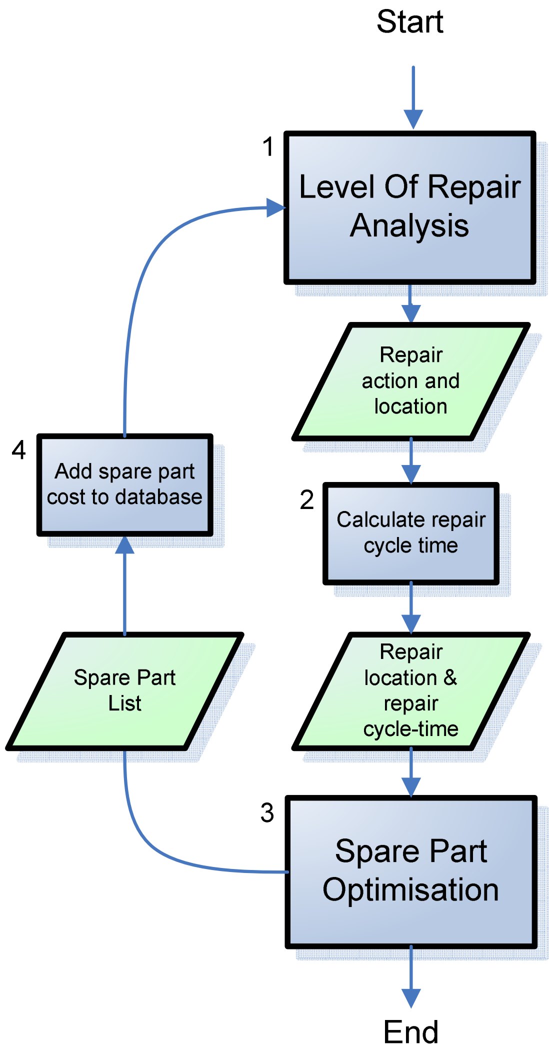

Figure 7: Optimisation concept flow-chart

Step 4
The result of LORA (Step 1) is a repair action and location for each component. If a component is on the spare part list (Step 3) then we add the costs of spare parts for this component to a database. This database holds entries for all possible LORA decisions for a component. For each component, the costs of spare parts are linked to the repair action (repair or discard) and location (OLM, ILM, DLM, or OEM) for that component in the database. Now the process starts again with a new LORA. The spare part costs in the database are used as fixed costs in the new LORA.

4.3 Drawbacks of the optimisation approach

There are two main drawbacks of the optimisation process, which are the consequence of this optimisation concept[6]. The drawbacks are related to the fact that during the iteration process, the inventory optimisation does only provide the spare part costs for a given LORA solution. Each time the LORA model provides a solution, the inventory optimisation model calculates the required number of spare parts that are needed to achieve the required system availability. However, the solution that an inventory optimisation model provides to the LORA model is specific for the choices made in the previous LORA. The information that the spare part optimisation provides to LORA is thus not complete. It does not contain spare part costs for all possible repair actions.

4.3.1 Component interaction

Every component that fails needs to be repaired or discarded. If we do not consider spare parts at this moment then a component, and thus the system, is unavailable during the repair. The time a component is away for repair, also known as the repair cycle time, depends on the repair location. If a component is discarded then the repair time depends on the procurement time for that component. In order to increase average availability of the system, the inventory optimisation model places spare parts of this component at various locations in the repair network. However, there always remains some average downtime that is caused by the failures of this component no matter how many spare parts are available. There is a probability that every available spare part at the system location that is installed in the system fails within a couple of days. There will be system downtime, if the last spare part that is installed in the system fails and all other spare part components are away for repair.

Consider the situation, where the LORA model has the choice for a component between depot repair with 5 spare parts on stock and contractor repair with 10 spare parts on stock. Suppose that the sum of the repair costs, the costs for test equipment and the spare part costs for both repair options is approximately the same. Although the total costs are the approximately same, the average yearly system downtime that is caused by both repair options can be different. For the first repair option it can be, for example, 2 days a year, but for the second repair option it can be 7 days a year. The second repair option causes thus more system downtime then the first repair option but both repair options have approximately the same costs. If the optimisation approach favours the second repair option due to a very slight cost advantage, then it chooses the repair option with the highest average component downtime. The 5 days

[6] There is another drawback that causes a technical modelling problem. Repair probabilities cannot be used with this optimisation approach. The last section of Appendix E (Problem 8) explains why repair probabilities cannot be used. That section also offers a solution for this problem.

extra downtime of the second repair option is probably compensated by placing other, less expensive, components on stock. The problem is that the optimisation approach does not include the average component downtime in the decision making process.

4.3.2 Overestimation of spare part costs

The costs of spare parts are calculated with a step-by-step procedure. Every LORA solution results in a different spare part list. It is possible that, although the decision for a component is identical in two different LORA solutions, the quantity of spare parts returned by the inventory optimisation model is different. The spare parts costs that are stored are a reflection for the spare part costs of the last LORA solution. These costs however, may be different for other LORA solutions. It can be the case that the inventory optimisation model decides that, for a specific LORA solution, many spare parts are needed for a component. Many spare parts will result in high spare part costs. If the costs for spare parts are too high, the LORA model will never choose the option with the high spare part costs again. This option however, might be part of the optimal solution.

4.4 Algorithm

This section describes step-by-step how the algorithm works. We start at Step 1. We end the algorithm after Step 5 when the last two solutions that are found are identical. This means that the algorithm cannot find a new solution that is better then the previous solutions. If the solutions are not identical after Step 5 we return to Step 2.

1. Create databases for spare part costs

1.1 Action: Create a spare part cost database for the action of repair.
1.2 Action: Create a spare part cost database for the action of discard.
1.3 Action: Per database list all locations of the repair network on the first row.
1.4 Action: Per database list all components of the system on the first column.
1.5 Action: Fill all database entries with zero.

Example: *See* Table 1 *and* Table 2 *for an example with 3 components and 2 locations.*

Repair database	ILM West	ILM East
Repair-Component A.1	0	0
Repair-Component B	0	0
Reapir-Component C	0	0

Table 1: Example of repair database

Discard database	ILM West	ILM East
Disacrd-Component A.1	0	0
Discard-Component B	0	0
Discard-Component C	0	0

Table 2: Example of discard database

2. Add spare part costs as fixed costs to the LORA input

2.1 Action: Link the spare part costs, which are in databases, as fixed costs to the components in the LORA model of Basten et al. (2008-b).

Example: *Make sure that for repair, component A.1 must use resource "Repair-Component A.1". For discard, component A must use resource "Discard-Component A.1". Do this for all components in the system. The fixed costs for using the resource are specified per location in the repair or discard database.*

3. Perform LORA

3.1 Action: Perform LORA with the model of Basten et al. (2008-b) with the spare part costs included as fixed costs. LORA will determine for each component an efficient repair action (repair or discard) and a location (Ship, Base, Depot, or Contractor).

4. Perform spare part optimisation

4.1 Action: Perform a spare part optimisation with METRIC. The result is a list with spare parts. This list contains quantities and spare part types that need to be procured in order to achieve the requested system availability.

5. Fill database

5.1 Action: Calculate the total spare part costs per spare part type that is on the spare part list.

Example: *Component A is listed 4 times on the spare part list and costs €500. Total spare part costs for this component type are €2000.*

5.2 Action: If identical components appear at more than one location in the system and these components are specified as separate components in the LORA input file then calculate the fraction that each component location is responsible for the total demand of this component type[7]. If a component appears only once in the system structure then the demand fraction is 100%.

Example: *See Table 3 for an example where component A appears at three locations in the system structure.*

	Location in system	Failures per year	Fraction
Component A.1	MS06AC	6	6/20
Component A.2	MS10AA12	3	3/20
Component A.3	MS22	11	11/20

Table 3: example of calculating the demand fraction

5.3 Action: Calculate for each echelon level the fraction of the demand that originates under each active location on that echelon level.

[7] Take into consideration that LORA can choose to repair the component that contains children at the contractor. In this case, no decision is made for the children that are contained in the parent. Because these children now disappear from the component list in METRIC the demand fraction of a component can change compared to the situation where all the children were repaired for example at the depot. Therefore it is necessary to calculate the demand fraction .

Example: *If there are 12 ships at OLM then each ship is responsible for 1/12 of the total demand. If there are two ILM locations (ILM West serves 7 ships and ILM East serves 5 ships) then West is responsible for 7/12 of the total demand and East is responsible for 5/12 of the total demand.*
If there is one depot then the demand fraction is 1/1. For the contractor the demand fraction is always 1/1.

5.4 Action: For all component types that are on the spare part list of METRIC:
- Go the appropriate database (repair or discard, this depends on choice of LORA).
- Find all entries in the database for this component type (i.e. Component A.1, A.2, and A.3).
- Go to the database entry that represents the correct echelon level (OLM, ILM, DLM, or OEM, this depends on the choice of LORA).
- Multiply the total spare part costs of Step 5.1 with the fraction that is calculated in Step 5.2 and the fraction that is calculated in step 5.3.
- Fill the costs in the appropriate database entries.

Example: If LORA decided that component A.1 is repaired at ILM then the spare part costs in the database for ILM West are €2000 * 6/20 * 7/12 = €350. Table 4 shows an example of the database spare part costs for repair of component A.1 at ILM. If the database entry already contains spare part costs from a previous iteration then overwrite it with the new spare part costs from the current iteration.

Repair database	ILM West	ILM East
Repair-Component A.1	**350**	**250**
Repair-Component B	0	0
Reapir-Component C	0	0

Table 4: Example of spare part costs in database

6. Check convergence

6.1 Action: If the last two solutions generated by the LORA model are identical then stop the algorithm at this point. If the last two solutions generated by the LORA model are not identical then return to Step 2.

4.5 Iteration example

We created the repair and discard databases in Microsoft Excel. Per database we listed all repair location at the first row and al the components in the first column. The iteration process starts with a database that is filled with zeros. Table 5 shows an example of the database for three components after the first LORA and Inventri iteration. In the example there are twelve ships, but only three are listed in the table. Suppose that, in the example, LORA decides, during the first iteration, that it is efficient to repair component A at the ships, component B at the contractor and component C at ILM. Suppose that, in the example described above, one spare is needed of component A (1x €3,000), three spares are needed of component B (6x € 2,000 = € 12,000) and three spare parts are needed of component C (3x €4,000 = €

12,000) to achieve the requested system availability. The “bold” values are filled after the first iteration.

Repair	Ship 1	Ship 2	Ship ….	ILM East	ILM West	Depot	Contractor
Component A	**250**	**250**	**250**	0	0	0	0
Component B	0	0	0	0	0	0	**12,000**
Component C	0	0	0	**7,000**	**5,000**	0	0

Table 5: Example of spare part costs after the first iteration

Because there are twelve ships, the total spare part costs of component A is divided by twelve (costs € 3,000 / 12 = € 250 per ship). For repair of component B at the contractor we take the total costs of six spare parts and assign these to the repair location “contractor” (€ 12,000). For repair of component C at ILM, we have to allocate the € 12,000 spare parts costs to ILM East and ILM West. We first calculate the percentage of the demand that originated under East and West. In this case there are seven ships under East and five ships under West. Thus 58% of the total spare part costs of component B is allocated to East (7/12 * € 12,000 = € 7,000) and 42% is allocated to West (5/12 * € 12,000 = € 5,000).

Due to the spare part costs calculated in the first iteration, the LORA model will make different decisions for most of the components in the second iteration. Suppose now LORA decides that it is efficient that component A is repaired at ILM, that component B is repaired at the depot and component C is also repaired at the depot. Suppose that, in this example, four spare parts are needed of component A (4x €3,000 = € 12,000), two spare parts are needed of component B (2x € 2,000 = € 4,000) and five spare parts are needed of component C (5x €4,000 = € 20,000) to achieve the required availability of the system. Table 6 shows an example of how the database will look after the second iteration. The “bold” values are filled after the second iteration.

Repair	Ship 1	Ship 2	Ship ….	ILM East	ILM West	Depot	Contractor
Component A	250	250	250	**7,000**	**5,000**	0	0
Component B	0	0	0	0	0	**4,000**	12,000
Component C	0	0	0	7,000	5,000	**20,000**	0

Table 6: Example of spare part costs after the second iteration

Suppose that, in the next iteration, LORA decides that component B is repaired at the depot. The database already has a value for depot repair of component B. In this case the value will be overwritten with the last value returned by the inventory optimisation model.

5 Case Study

We test the optimisation approach of Chapter 4 with a case study. The case study is set up in cooperation with the Thales LE department. For the case study we used existing project data. In Section 5.1 we discuss the characteristics of the case study. Section 5.2 explains how the input parameters must be specified. We include cost factors in the case study, such as storage costs for inventory and storage costs for test equipment. All are discussed in this section.

5.1 Case study characteristics

The system that we use in the case study is based on the Variant radar system. We added some expensive multi-indenture components to this system in order to increase the complexity of the case. There are 376 components in the case study of which 230 components are discarded at forehand (non-economic LORA, see Section 3.1.1). The LORA model does not make a decision for these components. These components however, are included in the inventory optimisation. Only 146 components remain for which a repair decision can be made. Effectively, there are only two indenture levels for components in the case[8]. The procurement costs of repairable components in the case vary from approximately €500 to approximately €890.000.

The repair network of the case study consists of 12 operational locations (ships) that all have one system onboard. There are 2 bases (east coast and west coast), a central depot and a contractor. The lead-time for component transportation from the central depot to base is 2 days and the lead-time for component transportation from base to ship is 14 days.

There are 20 different tools and testers and 34 adaptors in the case that are required when components are repaired. Some components require an adaptor if they are used on a tester. The procurement price for tools and test equipment varies up to €3,500,000. We see a distinctive difference in the costs for tools and test equipment. From the 20 different tools and test equipment there are 9 tools that are relatively inexpensive (< €20,000) and 11 testers that are expensive (> €100,000). The inexpensive tools are only used to exchange the children of a component. The expensive test equipment is used for repair as well as exchange of components. The procurement price of an adaptor is €25,000.

For all experiments we use a target system availability of 95%. This is a commonly used availability measure at the Thales LE department. The project duration, or the service duration of the systems, is 15 years.

5.2 Specification of the input parameters

In this section we specify how the input parameters in model of Basten et al. (2008-b) are calculated. In the model we minimize the total life cycle costs of multiple systems during the system's service duration. The objective is to minimise the sum of the variable repair costs, the fixed repair costs and the spare part costs.

[8] We do not include structure parts when we look at the indenture depth because no decision can be made for structure parts.

5.2.1 Variable costs

In the model of Basten et al. (2008-b) a decision is made for each component whether it should be repaired, discarded or moved to a higher echelon. All actions incur variable costs. Some components have a repair probability that is lower than 100%. In this case not all components can be repaired successfully. In case of unsuccessful repair a component is discarded. In case a component has a repair probability of for example 95% the model accounts that 100% of the demand of the component must be repaired according (9) and 5% of the demand of component must be discarded.

5.2.1.1 Variable repair costs

The variable repair costs of spare part *s*, for a repair action in the customer's repair network, is calculated as

$$\text{Variable repair costs network (s)} = (HE_s + HR_s) \cdot LC + P_s \tag{9}$$

where HE_s is the time in hours that is needed to exchange component s, HR_s is the time in hours that is needed to repair component s, LC are the labour costs per hour and P_s are the costs of additional parts that are needed for repair of component s. Additional parts are general parts such as wires or screws[9]. In the case we use €75 per hour for the costs of labour. The exchange times, the repair times, and the costs of additional parts are specified per component by a Thales LE employee.

In case a component is repaired at the contractor, the contractor repair price is calculated as

$$\text{Variable repair costs OEM (s)} = (HE_s) \cdot LC + F_s \tag{10}$$

where F_s are the costs for contractor repair of component s. The costs for exchange are incorporated in the variable repair costs as well as in the discard costs. A component is either repaired or discarded. The exchange costs are important because the LORA model can decide to repair a parent directly at the contractor. In case of contractor repair the children of the component do not need to be exchanged. The Thales LE department provided the costs of F_s for all components. For most components the value of F_s is equal to 40% of the component procurement price. For some expensive components the Thales LE department provided a specific contractor repair price because 40% of the component procurement price is in this situation is not appropriate (Appendix F).

5.2.1.2 Discard Costs

The costs for discarding a component of type *s* is calculated as

$$\text{DiscardCosts (s)} = HE_s \cdot LC + V_s + G_s \cdot V_s \tag{11}$$

[9] Additional parts must not be confused with the parts that are part of the system structure which are mentioned in Section 2.2.

where the V_s is the procurement price of component s. The procurement prices of components are available in logistical database of Thales LE. Inventri uses the same procurement prices for a spare part optimisation. Together with the Thales LE department we decided to use 1% of the component procurement price to account for the disposal costs of a component $(G_s = 0.01, \forall s)$.

5.2.1.3 Transportation costs

We account transportation costs between base, depot and the contractor. We do not account for transportation costs between ship and base. According to the Thales LE department there is transportation between ship and base at regular time intervals. We assume that the transportation of components can be combined with these shipments and incur no costs. The costs of transportation are difficult to specify per component. The transportation costs depend on the country, distance, package weight and package volume. DHL Nederland charges shipping rates based on package weight or volume for a specific region (DHL website, 2008). Since it is difficult to specify the transportation costs for all the components in the case, we decided, in consultation with Thales LE, to take a small percentage of the procurement price to account for the transportation costs. The average procurement price of a component in the case study is approximately €28.000. Most of the components do not weigh more than 30 kilogram. If we look at the price specification sheet of DHL we see that the transportation costs of a package with a weight between 5 and 30 kilogram varies from €16 to €22. We take €19 for the transportation costs of an average component. If we express the costs of transportation as a percentage of the component procurement price, then approximately 0.1% of the procurement price covers the costs of transportation.

5.2.2 Spare part costs

If we look at the costs of a technical system it is important to consider the costs that are related to the life cycle of a system. According to Durlinger (1998), Visser and Van Goor (2004) and Silver et al. (1998) we have to account for several cost factors if we look at inventory management. It is important to notice that there is a difference between the traditional inventory management, which focuses on consumer items, and repairable spare part inventory management. Repairable spare part inventory management is related to slow moving items that are in general very expensive.

The costs for the initial supply of spare parts are based on the procurement costs of the component that is procured to assure the system availability. We denote the procurement price of spare part s with the symbol V_s. The costs of carrying inventory in traditional inventory management include the interest or opportunity costs for the money invested, the storage costs and the costs for risk. The carrying costs for one spare part are denoted by

$$\textit{Carrying costs per component (s) per year} = V_s \cdot \sum_{i=1}^{3} R_i \tag{12}$$

where the sum of R is the inventory carrying charge, which represents the costs in euro's of carrying one euro of inventory for one year. The carrying charge is made up by the sum of the interest rate $(i = 1)$, the rate for storage costs $(i = 2)$ and the rate for risk $(i = 3)$.

5.2.2.1 Capital ($R_1 = 12.5\%$)

The largest part of the inventory holding costs are made up by the interest or opportunity cost of capital. Visser and Van Goor (2004) state that it is realistic to use a short-term interest rate between 10% and 15%. According to Tanaydin (2007), Thales Naval used a percentage of only 4%, which is a legally established interest rate that is proposed by the government. He disagrees with the 4% that is being used by Thales Naval. To limit the increase in the interest rate he proposes to use 10%. Silver et al. (1998) however, state that it is not correct to use interest costs. Instead, opportunity costs should be used. The opportunity costs are defined as the return on investment that could be earned on the next most attractive business opportunity that cannot be taken advantage of due to the decision to invest the available funds in inventories. According to Durlinger (2005), companies use different interest rates. He gives an example where one company takes the standard interest rate from the bank plus a small percentage (8%). Another company looked at the return on investment (12%) and the last company in the example uses opportunity costing (18%). We take 12.5%, which is the average of the proposed interest rate by Visser and Van Goor (2004).

5.2.2.2 Storage ($R_2 = 0.2\%$)

The storage costs depend on the space that is needed to store items. Repairable spare parts are in general very expensive (up to €850.000 per component). We assume that, for the initial supply of spare parts, a bonded storage area is needed at every location in the supply network. We did a preliminary test run of the case study where the cost factors from this chapter were not included. The optimal solution showed that approximately €14 million is spent on the procurement of the initial supply of approximately 500 spare parts. The dimension of a component rarely exceeds 50 by 50 cm. If we account for an average storage space of 50 by 50 cm, then it is possible to store four components per m^2. Visser and Van Goor (2004) state that €200 per m^2 per year is a normal rate for warehouse space, which includes handling, heating and maintenance of the building. However, the price stated by Visser and Van Goor (2004) dates from 2004. We include €20 for an inflation of 2.5% over four years. If we account €220 per m^2 of storage area then on average only a rate of 0.2% is needed to account for storage costs. Due to a relative high procurement price of components, the storage costs of spare parts are limited to only a very small percentage.

5.2.2.3 Costs for risk ($R_3 = 0.5\%$)

According to Visser and Van Goor (2004) there are two risk factors. Preventive risk is related to the insurance against, for example, water damage, fire damage and theft. Corrective risk accounts for costs related to damage by wrong material handling and deterioration of stock. Warehouse managers at Thales Nederland use a rate of 3.5% for the risk of carrying inventory. They use 3% for the deterioration of products and 0.5% for accidental damage. In case of repairable spare parts, the storage area is bonded, which means that access is restricted to qualified personnel only. Repairable spare parts are slow moving products and we think the risk of damage is limited. However, we do want to include a small percentage for risk. Therefore we take a rate of 0.5% as the insurance for accidental damage.

5.2.2.4 *Residual value of spare parts*

In general, projects that are related to the management of repairable spare parts deal with multiple systems and a specific operational time horizon. Not every system is put into use at exactly the same moment. Systems are put into use gradually within a couple of years. The situation also occurs at the end of the service duration. Not all systems are taken out of operation at the same moment. From the moment the project starts the stock levels gradually increase with the number of systems that are in operation, see Figure 8.

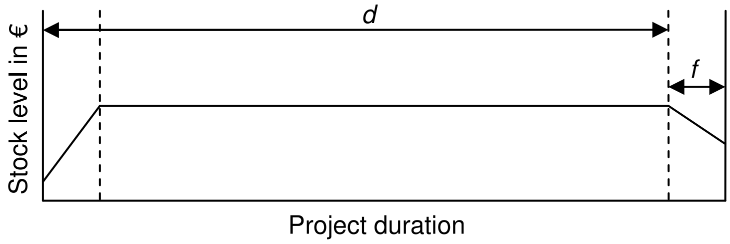

Figure 8: Amount of stock during the service duration

The symbol d represents the average service duration of one system in years. We denote the time between the moment the first system is taken out of order and the moment the last system is taken out of order with the symbol f. The Thales LE department agreed to use a period of 2 years for f. In practice, the customer chooses the duration of this period. During the service duration, the initial supply amount of spare parts must be maintained in order to maintain the system availability. Near the end of the project, when the number of operational systems gradually decreases, the stock levels are not maintained anymore. We assume that, from this moment, no additional spare parts are procured and the stock levels will gradually decrease. The costs of one spare part are then denoted with

Cost of one spare part over the life cycle: $$C_s = V_s \cdot d \cdot \sum_{i=1}^{3} R_i + V_s \cdot \left\lceil \frac{d}{K_s} \right\rceil \cdot \eta_s \qquad (13)$$

where the first part of the formula accounts for the costs that are related to storage of the component during the service duration and the second part of the formula accounts for the costs that are related to the number of components that are left at the end of the project. Symbol K_s in the formula represents the duration in years that spare part s can be stored before it becomes unusable and Symbol η_s represents the fraction of spare parts in stock of component s that are left at the end of the project.

It may be the case that some spare parts can only be stored for a limited period. In this case they need to be replaced at a specific moment during the service duration period. The components in the case study are not perishable. They will last during the entire service duration. In the case study we assume that the value of K_s is at least equal or larger than the value of d.

We calculated that, during a period of 2 years, a fraction of 92% of the costs of the initial spare parts is left at the end of the project[10]. The cost for one spare part that is stocked for the duration of 15 years is then denoted with

$$\textit{Cost of one spare part over the life cycle: } C_s = V_s \cdot 15 \cdot 0.132 + V_s \cdot \frac{15}{15} \cdot 0.92 = V_s \cdot 2.9 \quad (14)$$

It is hard to predict whether spare parts, which are left at the end of the project, have any economical value. Spare parts may be sold for a small fraction of the procurement price at the end of the project. In this case there must be another company that needs spare parts and uses a Thales system that contains the same components. The Thales LE department indicated that they were not sure whether spare parts can be sold to another company at the end of the project. To be sure, we assume in the case study that spare parts, which are left at the end of the project, do not represent any economical value.

5.2.2.5 Obsolescence

Obsolescence occurs when components, that have to be procured, are no longer available or components that are in inventory become obsolete. In the first case the stock level of a component is equal to zero and the component cannot be procured anymore. Additional costs must be paid to find a solution to the problem. In the second situation, the stock level of the component is larger then zero and components become obsolete due to a change made to the system. It is complex to calculate obsolescence costs since it is not always negatively (or positively) related to the component's stock level. Another aspect that complicates the calculation of obsolescence costs is that the possibility of obsolescence increases as the system gets older. In the situation of Thales it is very difficult to account for obsolescence because there is no empirical data available at Thales LE that indicates how many times obsolescence occurs and how much it will cost. We do not account for obsolescence in the case study because we do not have the appropriate information to include obsolescence costs in the optimisation.

5.2.3 Costs of tools and test equipment

Tools and test equipment require a relative high investment for which capital must be reserved. There are more relevant factors, which are all discussed in this section. We specify the yearly costs of holding tools and test equipment as

$$\textit{Holding costs for test equipment per year} = W_e \cdot \sum_{i=1}^{4} L_i = W_e \cdot 0.257 \quad (15)$$

where W_e are the procurement costs for tool or test equipment e and the sum of L_i is the yearly holding rate for tools and test equipment, which is made up by the summation of the rate for capital $(l=1)$, the rate for storage $(l=2)$, the rate for risk $(l=3)$, and the rate for tester maintenance $(l=4)$. The procurement costs for tools and test equipment have been specified by a Thales LE employee.

[10] We solved the case study for the situation where all the spare parts are left at the end of the project. For this situation we calculated that, on average, 8% of the cost of the initial spare parts is consumed in a time period of 2 years.

5.2.3.1 Costs of capital ($L_1 = 12.5\%$)

For the costs of capital for tools and test equipment, we use the same interest rate as for the investment that is related to spare parts (12.5%).

5.2.3.2 Costs for storage ($L_2 = 0.2\%$)

The tools and test equipment need an environment in which they can operate. The set of tools and test equipment in the case study is divided in common support equipment, such as screwdrivers or socket head wrenches, and expensive testers. For the storage costs it is sufficient to look at the expensive testers only. The average procurement price of a tester in the case study is approximately €850.000. The space required to operate a tester is estimated at 8 m². We use €200 per m² of storage space (Visser and Van Goor, 2004), and add €20 for inflation of (2.5% over 4 years). We add another €20 per m² to account for the power consumption of an average tester[11]. The total yearly rate for storage is then approximately 0.2%.

5.2.3.3 Costs for risk ($L_3 = 0.5\%$)

We assume that the risk factor for the tools and test equipment is the same as the risk factor used for spare part inventory. Both are subject to insurance against fire damage, water damage and theft. We use a yearly rate of 0.5% of the procurement price.

5.2.3.4 Maintenance costs of test equipment ($L_4 = 12.5\%$)

Tools and test equipment require personnel for operation and maintenance. The costs for personnel are already included in the LORA model as variable repair costs. The cost is calculated by multiplying the mean repair time of a component with the man-hour tariff. Maintenance cost of tools and test equipment are not included in the LORA model. Maintenance costs for tools and test equipment are divided in preventive and corrective maintenance. According to the Finance department of Thales Nederland, the maintenance costs for tools and test equipment are approximately 10-15% of the procurement price on a yearly basis. These costs include work and materials that are related to preventive maintenance and corrective maintenance of the tools and test equipment. We use the average of the suggested percentage by the Finance department (12.5%).

5.2.3.5 Depreciation of tools and test equipment

In the model of Basten et al. (2008-b) the costs for tester e are given by the symbol C_e. We solve the model of Basten et al. (2008-b) for the entire service duration. The costs of a tool or tester during the service duration are then denoted by

Costs for test equipment over the life cycle (e): $$C_e = W_e \cdot d \cdot \sum_{i=1}^{4} L_i + W_e \cdot \left\lceil \frac{d+f}{T_e} \right\rceil \qquad (16)$$

where d is the average service duration of a system in years, f is the number of years between the moment the first system is taken out of service and the moment

[11] We took a tester of 1000 Watt that is used for 200 day a year, 8 hours a day with an utilisation rate of approximately 70%. We used a price of €0.15 per kilowatt-hour.

the last system is taken out of service and T_e is the write-off period of tester e in years. We round up the number of testers that are needed because in the situation where 1.5 testers are needed we need at least 2 testers. According to the Finance department of Thales Nederland, test equipment is written-off over a period of seven years. In practice however, we see that test equipment is used beyond the write-off period. Employees of Thales LE indicated that, in practice, test equipment is rarely replaced during the service duration of the project. In case of the Thales case study we use a write-off period that equals the total project duration. The costs for test equipment are then denoted by

$$\text{Costs for test equipment over the life cycle (e): } C_e = W_e \cdot 15 \cdot 0.257 + W_e = W_e \cdot 4.855 \quad (17)$$

The Thales LE department indicated that it is hard to predict whether test equipment can be sold after the write-off period. For this reason we assume that the tools and test equipment do not represent any economical value after the write-off period.

5.2.4 Other parameters

5.2.4.1 Repair cycle time

The result of LORA is a repair action and location for each component. This information is used to calculate the repair cycle time of a component. Inventri uses the repair cycle time of a component to calculate the system's availability and the required number of spare parts. The repair cycle time, for a repair action in the customer's repair network, is calculated with

$$\textit{Repair cycle time(s,j)} = \left\lceil \frac{HE_s + HR_s}{8} + D_j \right\rceil \quad (18)$$

where HE_s is the time in hours that is needed to exchange component s, HR_s is the time in hours that is needed to repair component s, and D_j is the administrative delay time, in days, for repair at echelon j. The administrative delay time has been specified by an employee of the Thales LE department. The administrative delay time for repair at ship is 0.25 day, the administrative delay time for repair at base is 5 days, and the administrative delay time for repair at the depot is 42 days. The lead-times between echelons in the repair network are not included in the repair cycle time. Inventri uses the lead-time in its algorithms to account for the transportation delay between echelons. The contractor repair time was already available in the Inventri input data.

5.2.4.2 Demand

In the case we minimise the total life cycle costs during the entire service duration for multiple radar systems. The LORA model requires that the demand of a component is specified per ship. The demand of a component is calculated with

$$\textit{Demand (s)} = \frac{b \cdot d \cdot Q_s \cdot U_s}{MTBF_s} \quad (19)$$

where b is the total mission time per year per system, d is the service duration of a system in years, Q_s is the total quantity of components of type s in the system and U_s is the usage rate of component s. The usage rate of a component is the fraction of the time a component is being used during a mission. The $MTBF_s$ is the MTBF for component s. The Usage rate and the MTBF of a component are listed in the logistical database of Thales LE. The rest of the parameters and their values are project specific. These are taken from existing project data.

6 Results

In this chapter we test whether the optimisation approach works. We test the optimisation approach on three cases. The results show that an improvement of the optimisation approach is required in order to overcome convergence problems. We compare the results of the improved optimisation approach with the results that are provided by the Thales LE department. Section 6.5 shows how sensitive the outcome the model is to a change of certain input parameters. In Section 6.1 we describe the different cases for which we run experiments. Section 6.2 shows the results of the optimisation concept. Section 6.3 shows the test results of the improvement techniques. Section 6.4 discusses the differences between the solutions that are generated by the optimisation approach and the solutions that are generated by the Thales LE department. Section 6.5 contains a sensitivity analysis for the most unreliable parameters that are used in the optimisation approach.

6.1 Experiments

We test the optimisation concept on three different cases. The only differences between the three cases are the procurement costs for tools and test equipment.

In the first situation we look at the original Thales case, which accurately reflects the situation of a Thales customer. We refer to this case as Case 1. The results of this case show that, in the best solution that is found, only a few expensive testers are procured at ship, the base or the depot. The fact that only a few testers are bought in the customer's repair network is caused by a combination of high procurement costs for the tools and test equipment and a low component demand.

To test the optimisation concept in the situation where there are more trade-off situations, in which components are repaired more evenly distributed over the repair network, we decrease the procurement costs of the tools and test equipment. We decrease the costs of the tools or test equipment independently. With this procedure we aim to have an even distribution in the optimal solution between OLM repair, ILM repair, DLM repair and OEM repair. We refer to this case as Case 2. For Case 2 we decrease the total procurement costs of the tools and test equipment from Case 1 with approximately 66%.

During the set-up of Case 2 we did several test runs, where we tested the solution of the optimisation approach with different parameter settings for tools and test equipment costs. We found that, for one combination of tool and test equipment costs, the solution of the optimisation approach did not converge to a better solution. We included this case with adjusted tool and test equipment costs in the experiments to show that an improvement of the optimisation concept is needed, see Section 6.3. We refer to this case as Case 3. For Case 3, some of the procurement costs of tools and test equipment are decreased and some of the procurement costs of tools and test equipment are increased.

The Thales LE department provided their best[12] solution for the first two cases. The solutions that are generated by Thales LE are compared to the solutions that are generated by the optimisation approach. The differences between the solutions are discussed in detail in Section 6.4.

6.2 Results optimisation procedure

Figure 9 shows the results of the optimisation procedure for Case 1. In the first iteration the costs for LORA are minimal but the costs for spare parts are high. Eventually the model can make better decisions by avoiding high spare part costs. At iteration 11 a steady state is reached where the solution that is found at iteration 10 is identical to the solution found at iteration 11.

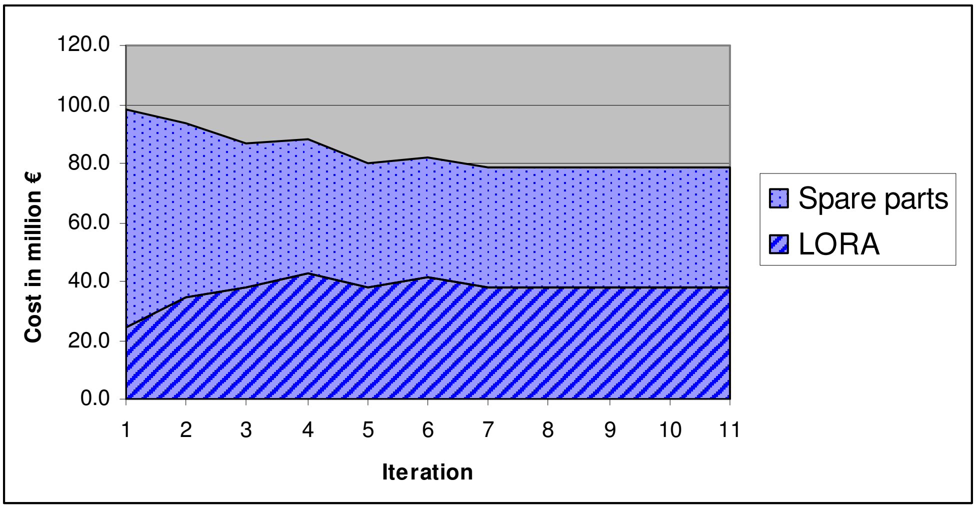

Figure 9: Optimisation process for Case 1

For Case 2, we see that the model is also able to reduce the total life cycle costs significantly compared to the start solution where the LORA is optimal (Figure 10). The steady state is reached at iteration 11.

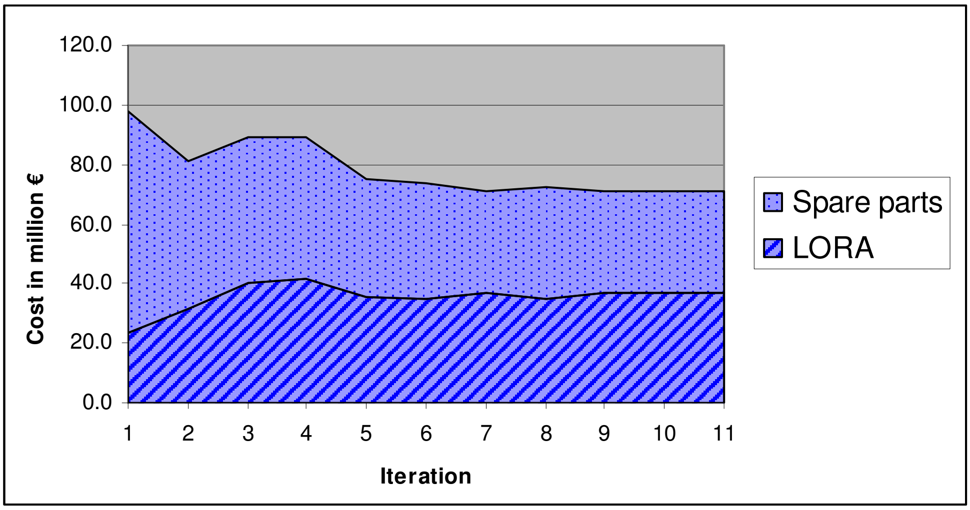

Figure 10: Optimisation process for Case 2

[12] Due to time constraints, Thales LE did not include details such as transportation cost, labour cost and disposal cost.

The results for Case 3 show that there are convergence problems with the optimisation procedure (Figure 11). The solution that is found at iteration 11 has approximately the same total life cycle costs as the start solution. The solutions that are found at iteration 2 and 5 however are better than the solution that is found at iteration 11. This is mainly caused by the effect of overestimation of the spare part costs in the database (see Section 4.3.2). In Section 6.3 we will test some improvement techniques to overcome the convergence problems that are caused by an overestimation of spare part costs in the database.

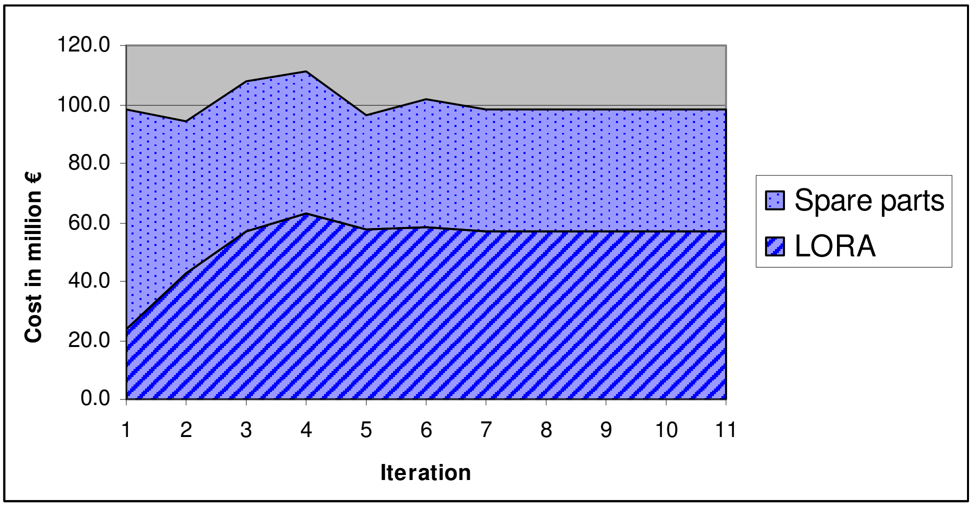

Figure 11: Optimisation process for Case 3

6.3 Improvement of the optimisation approach

One of the drawbacks of the optimisation approach is the overestimation of spare part costs in the database. Therefore we tested three improvement techniques that are able to reduce the effect of this drawback. We tested the improvement techniques on all three cases. We found that, especially for Case 3, better solutions can be generated if an improvement technique is applied. In this section we focus on the test results of Case 3 because the improvement techniques yield only very small improvements for Case 1 and Case 2 (see Appendix G).

6.3.1 Exponential smoothing

In statistics, exponential smoothing refers to a particular moving average technique applied to a time series. We use this procedure to calculate the spare part costs in the database. With this technique we gradually build up the costs in the database and therefore limit the overestimation effect. The calculated spare part costs are a weighted average of the spare part costs that are returned from the current inventory optimisation and the spare part cost that are in the database from the previous iteration. The spare part costs are calculated as

$$D_{s,t} = \alpha \cdot C_{s,t} + (1-\alpha) \cdot D_{s,t-1} \tag{20}$$

where $D_{s,t}$ are the spare part costs in the database for component s at iteration t, $C_{s,t}$ are the spare part costs that are returned by the inventory optimisation model for component s at iteration t and $D_{s,t-1}$ are the spare part costs in the database for component s at iteration $t-1$. The symbol α represents the smoothing factor. In order to prevent the effect of over estimation of costs in the database we start with $D_{s,0} = 0$.

We tested exponential smoothing with smoothing factors of 60%, 70%, 80%, 90% and 95%. The results for Case 3 show that exponential smoothing can yield a better solution, see Table 7. The last column shows the iteration at which the best solution is found. A smoothing factor below 60% results in a lot of iterations and thus a slow optimisation process. For this reason we did not test a smoothing factor below 60%.

Improvement method	Best solution	Improvement	# iterations
None	94,316,889	0.00%	2
Smooth factor 60%	89,253,112	5.37%	29
Smooth factor 70%	90,713,239	3.82%	20
Smooth factor 80%	94,316,889	0.00%	2
Smooth factor 90%	94,316,889	0.00%	2
Smooth factor 95%	94,316,889	0.00%	2

Table 7: Exponential smoothing for Case 3

A smoothing factor of 80% or above did not improve the optimisation process. A smoothing factor of 60% yields a solution that is 5.37% better than the solution found without exponential smoothing. We found that the best solutions are found with a smoothing factor of 70% or below. Exponential smoothing with a smoothing factor of 70% or below and a start value of $D_{s,0} = 0$ limits the probability of overestimation of spare part costs in the database for Case 3. However, exponential smoothing will only be successful if the smoothing factor can compensate the degree of overestimation. This is the reason why a smoothing factor of 80% or above for Case 3 does not improve the optimisation process. It is hard to predict beforehand how small the smoothing factor must be to achieve good results. For Case 3 a smoothing factor of 60% yields good results but for other cases 60% might not be low enough.

6.3.2 Estimation of initial spare part costs with a single item approach

In the original optimisation process we started with no spare part costs in the database ($D_{s,0} = 0$). With this approach, the solutions that are found during the first iterations are probably not very close to the optimal solution. The result of the first iteration is an optimal LORA solution that has very high spare part costs. In this case there is a probability that some spare part costs in the database are overestimated. We try to improve the optimisation process by starting with a database that is filled with estimated spare part costs. With this approach we try to avoid solutions that are very different from the optimal solution.

We estimate the spare part costs by calculating the quantity of components that are needed to cover for the time that a component is away for repair. The costs in the database are calculated as

$$D_{s,0} = C_s \cdot k \cdot \frac{\lambda_s \cdot \beta_s}{365} \tag{21}$$

where $D_{s,0}$ are the spare part costs before the first iteration for component s, C_s are the costs for one spare part of type s (see Section 5.2.2), k is a multiplier, λ_s is the yearly demand of component s and β_s is the repair cycle time in days for component s. We use the k factor to account for the variation in the demand of components. We tested the estimation of initial spare part costs with a k factor between 0.5 and 3.

Appendix G shows that slightly better solutions can be found for Case 1 and Case2 if we start with an estimation of spare part costs in the database. The results for Case 3 show that good solutions can be found within a small number of iterations (t<=8), see Table 8.

Improvement method	Best solution	Improvement	# iterations
None	94,316,889	0.00%	2
Spare estimates k = 0.5	92,744,089	1.67%	4
Spare estimates k = 1	92,348,934	2.09%	8
Spare estimates k = 1.5	90,657,900	3.88%	2
Spare estimates k = 2	90,472,558	4.08%	2
Spare estimates k = 2.5	90,472,558	4.08%	2
Spare estimates k = 3	90,000,878	4.58%	8

Table 8: Estimation of spare part costs for Case 3

A factor of k = 1.5 or above for Case 3 yields goods results. However, we see for Case 2 that the results become worse if the safety factor is larger than 2 (see Appendix G).

6.3.3 Decrease of costs in the database

From Section 6.2 we see that the optimisation process ends in a so-called steady state where each LORA and inventory optimisation yields the same result as in the iteration before. If this happens we decrease the costs in the database during the next iteration with a fixed percentage. The costs in the database are decreased just before the results of the inventory optimisation of the current iteration are written to the database. With this procedure only the costs in the database are lowered that are not part of the current solution. Any overestimated spare part costs will be lowered each time the optimisation process reaches the steady state.

The results show that this improvement technique is capable of finding better solutions for Case 3 (Table 9). In the tests with a decrease factor of 1% and 3% we stopped the optimisation process at iteration 40 because no improved solutions were found at that moment. With a decrease factor of 3% or below for Case 3 we estimate that approximately 100 iterations or more are needed to achieve good results. In this case the optimisation process will take quite long, for example, two days[13]. For this reason we stopped the iteration process after 50 iterations.

[13] The optimisation process is very slow due to inefficient programming of the algorithms. For testing we connected the LORA model (CPLEX), Inventri and Microsoft Excel. One iteration takes approximately 4 minutes. We estimate that, if programmed efficiently, one iteration will approximately take 20 seconds.

Improvement method	Best solution	Improvement	# iterations
None	94,316,889	0.00%	2
Decrease database 1%	94,316,889	0.00%	2
Decrease database 3%	94,316,889	0.00%	2
Decrease database 5%	89,505,531	5.10%	51
Decrease database 10%	89,618,159	4.98%	46

Table 9: Decrease of database costs for Case 3

6.3.4 Choice of optimisation improvement technique

The test results show that all the three improvement techniques lead to better solutions. However, we want to have a good solution that can be generated within only a limited number of iterations.

Exponential smoothing can prevent overestimation of the spare part costs in the database if the smoothing factor is small enough. The problem with exponential smoothing is that, at forehand, we do not know how small the smoothing factor must be. If we choose a smoothing factor that is too high we risk the chance of not finding better solutions if they do exist. On the other hand, a smoothing factor equal or below 60% slows down the optimisation process because a lot of iterations are needed. Therefore we think it is not appropriate to apply exponential smoothing.

Starting the optimisation process with a database that is filled with estimated spare part costs results in good solutions that can be found within a few iterations (t<8). We see, that this approach is less effective if a safety factor is chosen that is too small (k<1.5, Case 3, Table 8) or too large (k>2, Case 2, Appendix G). We also see that the other two improvement techniques find better solutions for Case 3 but need far more iterations.

The cost decrease approach yields good solutions, especially for Case 3. In order to achieve good results within reasonable time for Case 3 a large decrease factor must be chosen. If we choose a small decrease factor we need a lot of iterations, which results in a slow optimisation process. Even with a large decrease factor a lot of iterations are needed for Case 3.

We propose to use a combination of two improvement techniques. We use the spare part estimation technique with k=1.5 to find a good solution within a limited number of iterations. At the moment the optimisation process reaches a steady state we try to improve the solution by applying a decrease factor of 5%. For Case 1 and Case 2 we already find a very good solution if we only apply the spare part estimation technique. A decrease factor of 5% did not improve the solution for Case 1 and the solution for Case 2 improved with approximately €0.1 million (Table 10). However, for Case 3, the solution can be improved with approximately €1.2 million if we additionally apply a decrease factor of 5%. The solution is found after 19 iterations.

	Estimation spares (k=1.5)	Additional decrease (5%)	Iterations
Case 1	78,332,083	78,332,083	11
Case 2	70,062,761	69,948,295	14
Case 3	90,657,900	89,432,438	19

Table 10: Estimation of spares versus estimation of spare and decrease factor

6.4 Analysis of the results

The Thales LE department provided a solution for Case 1 and Case 2 that is generated with the help of Microsoft Excel spreadsheets. We use the results of Thales LE as a benchmark for the optimisation approach. We compare the solutions provided by Thales LE with the solutions generated with the optimisation approach. It must be mentioned that in practice, Thales LE will spent more time and effort in such an analysis. Now, an employee of Thales LE has spent approximately two weeks for the analysis. With more effort, Thales LE would be able to generate a better solution. However, Thales LE thinks that it practically not possible to find the same solutions as the model. First we discuss the results of the optimisation approach and then we discuss the results of Thales LE.

There are 376 components in the case study of which 230 components are discarded in advance (non-economic LORA). The LORA model does not make a decision for these components. These components however, are included in the inventory optimisation. Only 146 components remain for which a repair decision can be made.

6.4.1 Results optimisation approach

6.4.1.1 Results optimisation approach - Case 1

The best solution found by the optimisation approach for Case 1 has total costs of €78,332,038. Figure 9 shows how the costs are divided over the various expenses.

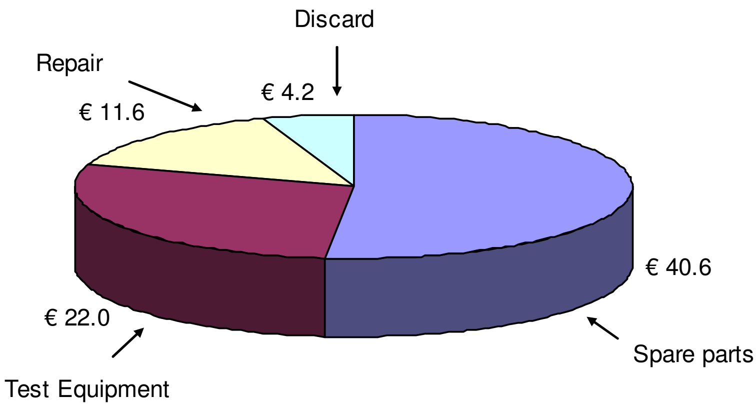

Figure 9: Results per cost driver in million € – Optimisation approach

By far most of the costs, approximately 51.8%, are made up by the spare parts that are required to achieve the system availability. The total costs for tools and test equipment, which are needed for exchange and repair of components at ship, base and depot, account for approximately 28.1% of the total costs. The actual repair costs account for only 14.8% of the total costs.

In Table 11 we see how the costs are divided over the repair network. Table 12 shows the costs in percentages where the rows in this table add up to 100%. Most of the costs are spent for spare parts that are located at ship.

There are 11 expensive testers in the case study that cost more than €100.000. One of these testers is used to exchange LRUs at ship. Inventri only allows LRU exchange at ship. Because LRUs are always exchanged at ship this tester is always procured. We kept this tester in the case study to get an idea of the total life cycle costs of the systems in the case. There are 10 expensive testers left for which a choice can be made. For Case 1 only 4 are procured in the repair network.

Cost in Million €	Total	Ship	Base	Depot	OEM
Spare Parts	€ 40.6	€ 20.2	€ 3.6	€ 16.8	-
Test Equipment	€ 22.0	€ 8.6	€ 10.2	€ 3.2	-
Repair	€ 11.6	€ 0.2	€ 7.5	€ 1.3	€ 2.5

Table 11: Results per location in million € - Optimisation approach

Cost in %	Total	Ship	Base	Depot	OEM
Spare Parts	100.0%	49.7%	8.8%	41.5%	-
Test Equipment	100.0%	39.0%	46.3%	14.7%	-
Repair	100.0%	2.0%	65.3%	10.9%	21.8%

Table 12: Results per location in % - Optimisation approach

All the costs for test equipment at ship, approximately €8.6 million, are reserved for equipment that is needed to exchange components. Most of these components are LRUs. Since LRUs can only be exchanged at ship these costs are fixed and cannot be avoided by the optimisation approach. At ship approximately €6.4 million is spent for support equipment that is needed to exchange the expensive camera unit from the system. The rest of the exchange equipment is less expensive. Almost all repair costs at ship are reserved for repair of the high voltage power supply.

At base, we see that a large amount of money is used for two CAM testers (approximately €8.6 million). Appendix H gives a description for all the test equipment that is mentioned in this report. The rest of the money for test equipment at base is spent on the GI-HPA tester. The repair costs at base are relatively high compared to the repair costs at other locations in the repair network. Almost all repair costs at base (approximately €7.5 million) are made up by the repair of the travelling wave tube. The reason why the repair costs are so high for the travelling wave tube is that it needs expensive additional parts for repair.

The PA tester and the OBJ tester are both procured at the depot. The PA tester is needed to repair the driver module and the power amplifier module. By far most of the repair costs at the depot, approximately €1.1 million, are used for unsuccessful repair of the power amplifier module. In case the power amplifier module cannot be repaired it must be procured at the contractor. The system in the case study contains 22 power amplifiers, which have a low MTBF and a high procurement price. Approximately 32% of the total system failures are caused by failure of the power amplifier.

Table 13 shows how the quantity of spare parts and the quantity of test equipment is divided over the repair network. The last row of this table shows where the 146 repairable components are repaired in the network. It does not show the actual number of times a repair action is performed. Table 14 shows the quantities as a percentage. Each row adds up to 100%. It is remarkable that from the 146 repairable components, most are repaired at the contractor (Table 14, 82.2%), while the costs for contractor repair are limited (Table 12, 21.8%). This is caused by the fact that there are many inexpensive components with a low demand in the case.

Quantity #	Total	Ship	Base	Depot	OEM
Spare Parts	1000	603	88	309	
Test Equipment	126	120	4	2	
Repair	146	15	7	4	120

Table 13: Quantities per location – Optimisation approach

Quantity in %	Total	Ship	Base	Depot	OEM
Spare Parts	100.0%	60.3%	8.8%	30.9%	-
Test Equipment	100.0%	95.2%	3.2%	1.6%	-
Repair	100.0%	10.3%	4.8%	2.7%	82.2%

Table 14: quantities per location in % - Optimisation approach

6.4.1.2 Results optimisation approach - Case 2

The best solution found by the optimisation approach for Case 2 has total costs of €69,988,029. Figure 10 shows how these costs are divided over the various expenses.

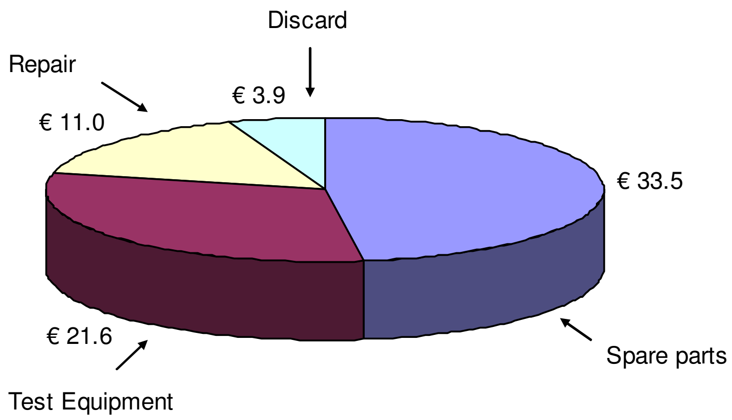

Figure 10: Results per cost driver in million € for Case 2 – Optimisation approach

We see that the optimisation approach now reduces the costs of spare parts with approximately €7.1 compared to the solution of the optimisation approach for Case 1. The costs for spare parts can be reduced because the procurement price for test equipment is lowered for Case 2.

Table 15 shows how the costs are divided over the repair network. Table 16 shows the cost in percentage where each row in this table adds up to 100%. If we compare these results with the solution found by the optimisation approach for Case 1 we see that the costs for contractor repair are approximately €1 million lower (Table 15) because less components are repaired at the contractor (Table 17).

Cost in Million €	Total	Ship	Base	Depot	OEM
Spare Parts	€ 33.5	€ 15.9	€ 3.2	€ 14.4	-
Test Equipment	€ 21.6	€ 10.9	€ 7.8	€ 2.9	-
Repair	€ 11.0	€ 0.3	€ 7.5	€ 1.6	€ 1.5

Table 15: Results per location in million € – Optimisation approach

Cost in %	Total	Ship	Base	Depot	OEM
Spare Parts	100.0%	47.5%	9.6%	42.9%	-
Test Equipment	100.0%	50.5%	36.0%	13.5%	-
Repair	100.0%	2.7%	68.7%	14.9%	13.7%

Table 16: Results per location in % – Optimisation approach

Compared to the solution of the optimisation approach for Case 1 some additional test equipment is procured in Case 2 because the costs for test equipment are lowered, see Table 17. At ship the IFF tester is procured and at the depot the RF tester and the MIC tester are procured. The RF tester and MIC tester are used for repair of various components. Table 17 and Table 18 show that more components are repaired at ship and at the depot and fewer components are repaired at the contractor compared to the solution found by the optimisation approach for Case 1.

Quantity #	Total	Ship	Base	Depot	OEM
Spare Parts	873	531	78	264	
Test Equipment	140	132	4	4	
Repair	140	27	5	16	92

Table 17: quantities per location – Optimisation approach

Quantity in %	Total	Ship	Base	Depot	OEM
Spare Parts	100.0%	60.8%	8.9%	30.2%	-
Test Equipment	100.0%	94.3%	2.9%	2.9%	-
Repair	100.0%	19.3%	3.6%	11.4%	65.7%

Table 18: quantities per location in % – Optimisation approach

6.4.2 Results Thales LE

6.4.2.1 Results Thales LE - Case 1

We compared the solution of the optimisation approach with the solution of Thales LE and we found that, due to the time pressure and the amount of data involved, errors and mistakes are easily made while doing a LORA in Microsoft Excel. The solution for Case 1 that was initially provided by the Thales LE department did not account for the fraction of the time that a component is being used during a mission. We also saw that some of the costs were differently allocated in the results. During the analysis, a repair decision for the camera unit changed from depot repair to contractor repair. In case of depot repair, the children are also repaired. In case of contractor repair only the camera unit itself is repaired. The person who did the analysis changed the repair decision for the camera to the contractor but did not delete the repair costs of the children at the depot.

The solution that has been provided by the Thales LE department for Case 1 has total life cycle costs of €94,329,382. The solution that is found by the optimisation approach has approximately 17% less total life cycle costs. Figure 11 shows how the costs are divided over the various expenses. We see that, compared to the solution of the optimisation approach, much more money is invested for spare parts and less money is invested in test equipment.

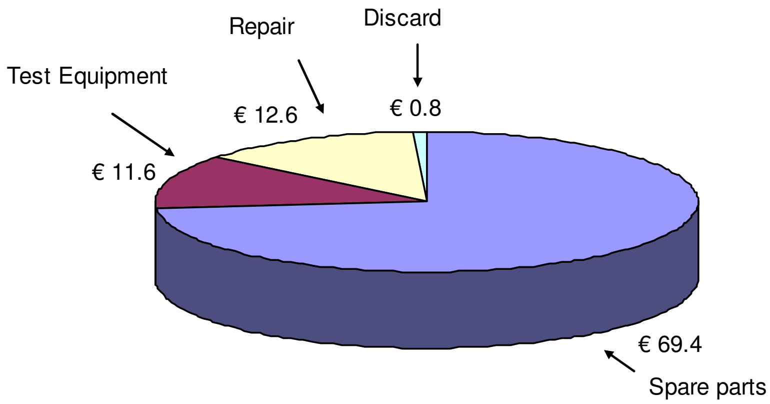

Figure 11: Results Thales LE for Case 1 – Costs in million €

In Table 19 we see that no test equipment is procured at base. Table 20 shows the costs as percentages. At the depot only €3.0 is invested for test equipment. The main difference compared to the solution found by the optimisation approach is that the cam tester is not procured. In the solution provided by Thales LE the camera unit is repaired at the contractor. Contractor repair however, requires that expensive camera units are put in inventory to increase the system availability. Because the camera unit is repaired at the contractor, the OBJ tester is not procured. The OBJ tester is used to repair a child from the camera unit. The GI-HPA tester is procured at depot instead of the base. This explains why the repair costs shift from base to the depot. The repair costs at ship are almost zero because the high voltage power supply is now repaired at the depot.

Cost in Million €	Total	Ship	Base	Depot	OEM
Spare Parts	€ 69.4	€ 23.9	€ 2.7	€ 42.9	-
Test Equipment	€ 11.6	€ 8.6	€ 0.0	€ 3.0	-
Repair	€ 12.6	€ 0.0	€ 0.0	€ 9.0	€ 3.5

Table 19: Results per location in million €

Cost in %	Total	Ship	Base	Depot	OEM
Spare Parts	100.0%	34.4%	3.9%	61.7%	-
Test Equipment	100.0%	74.2%	0.0%	25.8%	-
Repair	100.0%	0.1%	0.0%	71.7%	28.2%

Table 20: Results per location in %

6.4.2.2 Results Thales LE - Case 2

The solution that has been provided by the Thales LE department for Case 2 has total life cycle costs of €91,560,371. The solution that is generated by the optimisation approach has approximately 24% less life cycle costs. Figure 12 shows how the costs are divided over the various expenses. The costs for spare parts alone, approximately €67.8 million, almost equals the total costs of the solution of the optimisation approach for Case 2 (approximately €70 million).

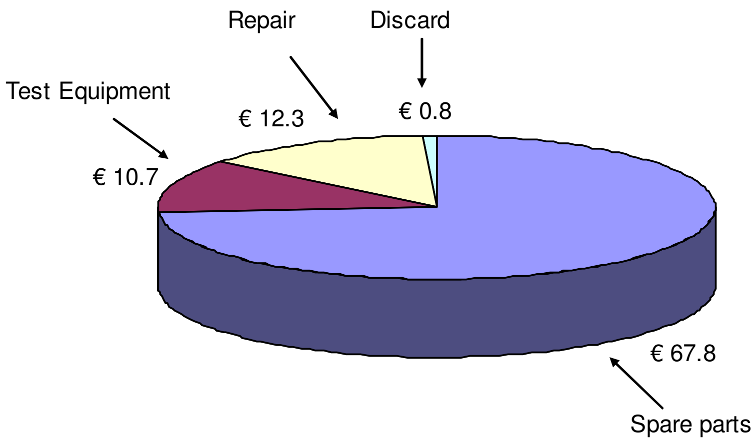

Figure 12: Results Thales LE for Case 2 – Costs in million €

Table 21 and Table 22 show how the costs are divided over the various cost drivers. We see that the investment for tools and test equipment at ship, base and the depot is less than in the solution of the optimisation approach. We also see that the costs for contractor repair are higher than in the solution of the optimisation approach.

Cost in Million €	Total	Ship	Base	Depot	OEM
Spare Parts	€ 67.8	€ 23.2	€ 2.7	€ 41.9	-
Test Equipment	€ 10.7	€ 8.6	€ 0.0	€ 2.1	-
Repair	€ 12.3	€ 0.0	€ 0.0	€ 9.1	€ 3.2

Table 21: Results per location in million €

Cost in %	Total	Ship	Base	Depot	OEM
Spare Parts	100.0%	34.3%	3.9%	61.8%	-
Test Equipment	100.0%	80.1%	0.0%	19.9%	-
Repair	100.0%	0.1%	0.0%	73.7%	26.3%

Table 22: Results per location in %

Table 23 and Table 24 show where the spare parts and test equipment are located and where the repair actions are performed. We see that in the solution of Thales LE less test equipment is procured at ship, at base and at the depot. We also see that fewer components are repaired at these locations and more components are repaired at the contractor compared to the solution of the optimisation approach.

Quantity #	Total	Ship	Base	Depot	OEM
Spare Parts	923	576	69	278	
Test Equipment	123	120	0	3	
Repair	130	15	0	14	101

Table 23: quantities per location

Quantity in %	Total	Ship	Base	Depot	OEM
Spare Parts	100.0%	62.4%	7.5%	30.1%	-
Test Equipment	100.0%	97.6%	0.0%	2.4%	-
Repair	100.0%	11.5%	0.0%	10.8%	77.7%

Table 24: quantities per location in %

6.4.3 Differences between the optimisation approach and Thales LE

6.4.3.1 Differences for Case 1

We see two major differences in costs and decisions between the solution of the optimisation approach and the solution of Thales LE. The differences are caused by three very expensive components. These are the travelling wave tube, the high voltage power supply and the camera unit.

In the solution of the optimisation approach the travelling wave tube and the high voltage power supply are repaired at base. In the solution of Thales LE the travelling wave tube and the high voltage power supply are repaired at the depot. For repair a GI-HPA tester is required that costs approximately €0.7 million. In the solution of the optimisation approach two testers are procured at base and in the solution of Thales LE only one tester is procured at the depot. In the solution of the optimisation approach the costs for repair and test equipment for the travelling wave tube and the high voltage power supply are approximately €9.3 million. The costs for repair and test equipment in the solution of Thales LE are approximately €8.5 million. However, the costs for spare parts in the solution of the optimisation approach are approximately €6.3 million and the costs for spare parts in the solution of Thales LE are approximately €11.6 million. There seems to be a large difference in spare part costs for both repair policies. We have to keep in mind however, that Inventri uses a system approach to determine the optimal quantity of spare parts in the repair network. Inventri can reduce the downtime of the system, which is partly caused by failure of the travelling wave tube and the high voltage power supply, by placing other components in stock.

We see the same effect for the camera unit. In the solution of the optimisation approach the camera unit is repaired at base. The costs for tools and test equipment and repair for the camera unit and its children are approximately €19.8 million. For base repair, Inventri decides that approximately €7.9 million of spare parts are needed for the camera unit. In the solution of Thales LE the camera unit is repaired at the contractor. For contractor repair approximately €7.6 million is required for repair and test equipment (tools are required at ship to exchange the camera unit). Because the camera unit is repaired at the contractor, the children of the camera unit cannot be placed in inventory. For contractor repair, Inventri decides that approximately €30.6 million is of spare parts are needed for the camera unit.

Overall we see that, for very expensive components, it is efficient to repair them downstream in the repair network if we include the costs of spare parts in the optimisation approach. Downstream repair results in a low repair cycle time. A low repair cycle time results in less system downtime and thus fewer spare parts are required to achieve the requested system availability.

6.4.3.2 Differences for Case 2

For Case 2 there are more differences in the repair decision for components than there are for Case 1. Therefore we discuss the differences per test equipment. Table 25 shows the test equipment and the location of the test equipment in the repair network for the solution of the optimisation approach. Table 26 shows the test equipment and the location of the test equipment in the repair network for the solution of Thales LE. Per tester we summarised the costs of all components that are repaired on that tester. We did this for the repair costs (including the costs for test equipment) and the spare part costs. Some components that are repaired on a tester also require exchange equipment. In this case, the costs of the exchange equipment are included in the column of the repair and tester costs (column 3).

Solution model	Location	Repair & tester	Spare parts	Total
RF tester	Depot	€ 2,325,395	€ 1,694,382	€ 4,019,776
MIC tester	Depot	€ 1,753,947	€ 2,348,199	€ 4,102,146
GI-HPA tester	Base	€ 9,745,481	€ 6,268,673	€ 16,014,153
IFF tester	Ship	€ 2,440,727	€ 523,088	€ 2,963,814
CAM tester	Base	€ 16,177,886	€ 5,016,290	€ 21,194,176
PA tester *	Contractor	€ 214,350	€ 2,205,276	€ 2,419,626

Table 25: Costs overview - solution optimisation approach*

Solution Thales LE	Location	Repair & tester	Spare parts	Total
RF tester	Contractor	€ 1,848,113	€ 2,660,027	€ 4,508,140
MIC tester	Contractor	€ 1,002,621	€ 3,153,935	€ 4,156,556
GI-HPA tester	Depot	€ 8,788,917	€ 11,554,805	€ 20,343,721
IFF tester	Depot	€ 305,263	€ 3,443,547	€ 3,748,810
CAM tester	Contractor	€ 7,591,970	€ 30,575,106	€ 38,167,076
PA tester	Depot	€ 429,719	€ 2,278,576	€ 2,708,296

Table 26: Costs overview - solution Thales LE

For the first five testers, the repair costs (including the costs for exchange and test equipment) in the solution of the optimisation approach are higher than the repair costs in the solution of Thales LE. However, the spare part costs are less in the solution of the optimisation approach. For every tester we see that the total costs are lower in the solution of the optimisation approach than in the solution of Thales LE. The OBJ tester is also procured in the solution of the optimisation approach. The costs are included in the costs for the CAM tester because children of the camera unit are not repaired in the solution of Thales LE.

Overall we see that the major difference in costs is caused by the repair decisions for the expensive components. Expensive components are the travelling wave tube, the high voltage power supply and the camera unit. The first two components are repaired at the GI-HPA tester and the last component is repaired at the CAM tester.

Table 27 shows an overview of the differences in total costs for Case 1 and Case 2 for the solution of the optimisation approach and the solution of Thales LE. We see that in both solutions of Thales LE the amount of money spent for test equipment is less and the amount of money spent for spare parts is larger than in the solutions of the optimisation approach.

Case	Approach	Total	Savings	Spare Parts	Test equipment	Repair	Discard
Case 1	Model	€ 78.3	17%	€ 40.6	€ 22.0	€ 11.6	€ 4.2
Case 1	Thales LE	€ 94.3		€ 69.4	€ 11.6	€ 12.6	€ 0.8
Case 2	Model	€ 70.0	24%	€ 33.5	€ 21.6	€ 11.0	€ 3.9
Case 2	Thales LE	€ 91.6		€ 67.8	€ 10.7	€ 12.3	€ 0.8

Table 27: Overview of costs model/Thales LE – Case 1/Case2

* The driver module and the power amplifier module both require the PA tester for repair. In the solution of the model the PA tester is located at the depot as well as at the contractor. Even though the PA tester is located at the depot it is still more efficient to repair the driver module at the contractor. This is caused by a high repair price at the depot for the power amplifier module

6.5 Sensitivity analysis

The logistical data that is used at Thales LE holds a lot uncertainty. Together with the University of Twente and the Thales LE department we decided to do a sensitivity analysis for the parameters that are listed in Table 28. Our goal is to identify the impact of each parameter on the total life cycle costs and the impact of each parameter on the decisions that are made in the solution that is found. Especially the impact on the decision making process is of interest to Thales LE. Parameters that have a large influence on the decisions that are made need to be studied further in order to reduce their uncertainty. Parameters with less uncertainty increase the quality of the solution that is found by the optimisation approach.

We deviate the values of the parameters according to the degree of deviation that is shown in Table 28. The degree of deviation is determined in cooperation with the Thales LE department and is based on the estimated uncertainty that a parameter holds. For the sensitivity analysis, the parameters that are listed in Table 28 can either have a low value or a high value. For example, a low value for the MTBF (25%) means that we multiply the MTBF value of all components of Case 1 with 0.25.

		Low value	High value	
TTE	Cost factor tools and test equipment	50%	150%	compared to the value of Case 1
RCT	Repair cycle time	50%	200%	compared to the value of Case 1
MTBF	Mean time between failure	25%	200%	compared to the value of Case 1
OEM	OEM repair cost	50%	150%	compared to the value of Case 1
RP	Repair probability	80%	100%	

Table 28: Parameters for sensitivity analysis

TTE is the cost factor that is used to calculate the life cycle costs of tools and test equipment. We calculated the value of this parameter in Section 5.2.3. Because this factor is based on many assumptions it holds a certain degree of uncertainty. The repair cycle time[14] is the time that a component is away for repair (see Section 5.2.4.1).

The repair cycle time that is used for the original case is based on estimations made by the Thales LE department. We included the MTBF of a component because it holds a lot of uncertainty, see appendix D.

The OEM repair costs for the original case are calculated as 40% of the component procurement price. Because this calculation is in fact a rough estimation of the OEM repair cost, we included the OEM repair cost in the sensitivity analysis.

The repair probability can have significant impact on the results because new components need to be ordered in case of unsuccessful repair. New components that need to be ordered are expensive and have a high order-lead-time (compared to the repair cycle time). In the original case the repair probability of components is

[14] For the repair cycle time we included the repair time in the customer's network (OLM, ILM, DLM), the repair time at the contractor (OEM) and the component procurement time. Inventri uses maximum of 729 days for the procurement time of components. Inventri used 729 days in case the calculated procurement time exceeded 729 days.

either 95% or 100%. Components with a repair probability of 100% are by definition always repairable. Therefore we only change the repair probability of components that have a repair probability of 95% in the original case.

We apply multiple linear regression with a confidence interval of 95% in order to draw conclusions from the sensitivity analysis. We created dummy variables for the independent variables (parameter settings). If a parameter has a low value the dummy variable becomes 0 and if a parameter has a high value the dummy variable becomes 1.

6.5.1 Parameter impact on costs

Appendix I shows an overview of the impact of the parameters on the costs. Here we see the parameter settings and the effect on the total life cycle cost as well as the effect on each cost driver. Appendix J shows the test results for each cost driver per location in the repair network. Table 29 shows the results of regression analysis were we use the total life cycle costs as a dependant variable. The columns with the headings “Low” and “High” show the deviated values of the parameters compared to their original value. The column with the heading “Interval” shows the range of deviation. The parameters with a high interval are expected to have a high degree of uncertainty. The column with the heading “Coefficients” shows the coefficients for each parameter. These coefficients show the average difference in total costs between a low parameter setting and a high parameter setting.

	Low	*High*	*Interval*	*Coefficients*	*Coefficient/Interval*	*Significant?*
TTE	50%	150%	100%	€ 39,374,950	€ 393,750	Yes
RCT	50%	200%	150%	€ 26,522,867	€ 176,819	Yes
MTBF	25%	200%	175%	-€ 165,636,525	-€ 946,494	Yes
OEM	50%	150%	100%	€ 6,150,010	€ 61,500	
RP	80%	100%	20%	-€ 26,643,601	-€ 1,332,180	Yes

Table 29: Effect on the total life cycle costs

The MTBF parameter has the largest coefficient and is thus a very important parameter that influences the total life cycle costs. However, we see that the interval in which we deviate the MTBF parameter (175%) is larger than the deviation that we apply for the other parameters. We corrected the coefficients by dividing the coefficient value with the parameter interval (column “Coefficient/Interval”). This column shows the deviation in total life cycle costs if we change a parameter with only 1%. This enables us to compare the sensitiveness of the 5 parameters. Now we see that the repair probability parameter is the most sensitive parameter with respect to total life cycle costs. The MTBF is also a sensitive parameter. The sensitivity of the contractor repair costs (OEM) are statistically not significant. We assume statistical significance if the p-value for the coefficient of a parameter is smaller than 0.05. The most sensitive parameters are the component MTBF and the repair probability.

We apply regression analysis for each cost driver to find out which parameter influences which cost driver. Per cost driver we do a regression analysis for each location in the repair network. In other words, as the dependant variable we take for example the amount of money spent for spare parts in total as well as the amount of money spent for spare parts at ship, base or depot. Table 30, Table 31 and Table 32 show the value of the coefficients for the parameters that are significant.

	Total	Ship	ILM	DLM
TTE	€ 35,509,863	€ 24,015,015	€ 5,699,117	€ 5,795,731
RCT	€ 17,201,844			€ 14,939,541
MTBF	-€ 88,585,085	-€ 57,308,572	-€ 11,077,408	-€ 20,199,104
OEM				
RP				-€ 6,455,617

Table 30: Effect on spare part costs

	Total	Ship	ILM	DLM
TTE			€ 9,043,833	
RCT	€ 6,318,481		€ 5,630,405	
MTBF	-€ 19,558,979	-€ 13,016,741	-€ 4,301,348	-€ 1,832,386
OEM				
RP				

Table 31: Effect on tools and test equipment costs

	Total	Ship	ILM	DLM	OEM
TTE		-€ 785,625			
RCT			€ 12,816,526		-€ 6,714,592
MTBF	-€ 43,118,098	-€ 1,079,776	-€ 25,421,702		-€ 12,822,043
OEM	€ 7,115,234				
RP	-€ 17,314,324	-€ 1,233,831		-€ 6,670,832	-€ 4,195,192

Table 32: Effect on repair costs

We see that the MTBF has largest impact on all cost drivers. It influences the amount of money spent for spare parts, the amount of money spent for tools and test equipment and the amount of money spent for repair. We also see that the cost factor for tools and test equipment (TTE) has a large impact on the total costs spent for spare parts.

Overall we see that the MTBF is very important because the value of the MTBF is highly uncertain. The repair probability however, is the most sensitive parameter when we compared it to the other parameters (Table 29, coefficient/interval).

6.5.2 Parameter impact on decisions

The differences in decisions can be best identified by differences in the procurement of tools and test equipment and differences in the repair locations for components. The difference in quantity of spare parts is not very useful for explaining the differences in the repair decisions for components. For example, a change of the repair cycle time or a change of the component MTBF can result in different quantities of spare parts but the repair decision for a component might not change. Table 33 shows the difference in test equipment quantities at each location between a low and high parameter setting.

	Low	*High*	*Total*	*Ship*	*Base*	*Depot*
TTE	50%	150%	-19.37	-13.50		-6.87
RCT	50%	200%	7.75		1.50	
MTBF	25%	200%	-9.63		-2.50	-6.38
OEM	50%	150%				
RP	80%	100%				

Table 33: Quantity of tools and test equipment

The LORA model makes a repair decision for 146 components. Table 34 shows how the repair decisions change for the 146 repairable components when a parameter value changes from low to high. We see for example that 13.19 more components are repaired at the contractor in the case we use a high parameter value for the cost factor of tools and test equipment (TTE). Appendix K shows an overview of the impact of the parameters on the quantities.

	Low	*High*	*Total*	*Ship*	*Base*	*Depot*	*Contractor*
TTE	50%	150%		-2.81		-13.31	13.19
RCT	50%	200%			2.75		
MTBF	25%	200%			-2.38	-12.56	
OEM	50%	150%					
RP	80%	100%		0.94			

Table 34: Quantity of components that shift repair location

We see from Table 33 and Table 34 that the cost factor for tools and test equipment, the repair cycle time and the MTBF have a significant influence on the decisions that are made. The cost factor for tools and test equipment seems to have the greatest impact. It must be said however, that there is a large difference between the costs of inexpensive test equipment and expensive test equipment. Therefore we do not exactly know if there are many expensive testers involved in the differences.

Another possibility to identify any differences in the decisions that are made is to look at the amount of money spent for test equipment (Table 31). The cost factor for tools and test equipment has a direct influence on the quantity of testers that are procured. In this situation it is possible that more test equipment is procured but the total amount of money that is spent for test equipment stays the same because the procurement price of test equipment is lower. This might explain why we see no statistical significant coefficients in the first row of Table 31 (except for the ILM location). We see in the table that the repair cycle time and the MTBF have a large impact on the quantity of test equipment that is procured.

Overall we conclude that the cost factor for tools and test equipment, the repair cycle time, and the MTBF influence the decisions that are made. This can be confirmed by Appendix K. We see in this appendix that a combination of a low cost factor for tools and test equipment, a high repair cycle time and a low MTBF causes a noticeable shift in the decision making process (see row 11, 12, 13 and 14). In this case significantly fewer components are repaired at the contractor and more tools and test equipment are procured in the repair network. The cost factor for tools and test equipment seems to have the largest influence on the decisions that are made.

7 Implementation and use

This chapter explains how the optimisation approach can be implemented at Thales LE. Section 7.1 shows which tools are required for the optimisation process. Section 7.2 recommends on the implementation approach. Section 7.3 explains who should use the optimisation approach. Section 7.4 shows that additional logistical data is required for the optimisation process. This data is currently not available in the logistical databases at Thales LE. Appendix L gives detailed instructions on how to use the LORA model of Basten et al. (2008-b).

7.1 Required models and tools

The optimisation process requires two models. It requires the model of Basten et al. (2008-b) to solve the LORA problem and it requires the METRIC algorithm to do the spare part optimisation. In order to solve the model of Basten et al. (2008-b) a solver is required.

7.2 Recommended implementation approach

In the case study we used CPLEX as a solver for LORA and the program Inventri for the METRIC algorithm. Inventri is currently being used at the Thales LE department. Inventri is developed by Ortec. During the case study we connected the LORA model and Inventri with the help of Microsoft Visual Basic in Excel. This approach is not appropriate if Thales LE wishes to adopt the optimisation approach, because it has no user friendly interface. If Thales LE wishes to use the optimisation approach then it is wise to contact a software development company. The best approach would be to develop a program that is able to solve the model of Basten et al. (2008-b) and add this program to the already existing software of Inventri. The optimisation approach itself is explained in this report.

7.3 Use of the optimisation approach

The optimisation approach should be used by logistical engineers at Thales LE that are familiar with concepts of LORA and METRIC. It is important that they understand how the optimisation approach works and that the parameters that are used in the model hold a high degree of uncertainty.

7.4 Additional data that needs to be acquired

The optimisation approach requires logistical data in order to perform a successful logistical analysis. Although most of the logistical data is readily available at Thales LE, some additional logistical information is required that is not already available in an existing database. We divided the data that needs to be acquired in project data and in system and cost data. Project data must be specified once while the system and cost data must be specified per component. Most of the data are customer dependent.

7.4.1 Project data

Administrative delay time

This is the time that a general component has to wait at a repair facility before it can be repaired. The administrative delay time must be specified per echelon.

Labour costs
Are the costs of one man working one hour.

Cost factor for holding inventory
This is the cost factor for holding inventory in the support network. See Section 5.2.2 for how this factor can be calculated. In practice this factor depends on the situation of the customer.

Cost factor for holding tools and test equipment
This is the cost factor for holding test equipment in the repair network. See Section 5.2.3 for how this factor can be calculated. In practice this factor depends on the situation of the customer.

7.4.2 System and cost data

Transportation costs
The transportation costs must be specified per component. In the case study we specified the transportation costs as 0.1% of the procurement price of a component (Section 5.2.1.3). Because the transportation costs are very low in practice, we advise to use this factor.

Disposal costs
The costs for the disposal of a component.

Minimum exchange location
Some components, for example, cannot be exchanged at ship. This parameters specifies the minimum exchange location. Components cannot be exchanged at an echelon that is lower than the minimum exchange location.

Minimum repair location
Some components for example, cannot be repaired at ship or base due to a non-economical LORA. This is the minimum repair location. Components cannot be repaired at an echelon that is lower than the minimum repair location.

Exchange time
This is the time that is needed to exchange a component from its parent.

Repair time
The time in hours that it takes to repair a component

Exchange tool
This is the name of the tool that is required to take components out of their parent.

Repair tool
The name of the tool or tester that is required to repair a component.

Adaptor
The name of the adaptor that is needed to repair a component on a tester.

Tool costs
Per exchange tool, repair tool, or adaptor the costs must be specified.

Costs for additional parts
The costs for additional parts that are required to repair a component. Additional parts for example, can be wires or screws.

Contractor repair costs
The costs that must be paid when a component is repaired at the contractor.

8 Conclusions and recommendations

The objective of this study is to identify and improve the current process of level of repair analysis at Thales LE. We conclude that the current process of level of repair analysis can be improved significantly by incorporating spare part costs. Section 8.1 contains the most important conclusions of this study and Section 8.2 gives recommendations that are derived from the conclusions. This chapter gives an answer to the research questions that are listed in Section 1.3.

8.1 Conclusions

Current life cycle cost optimisation not optimal

The current life cycle optimisation process is not optimal. The LORA optimisation is done with the help of Microsoft Excel. The outcome of the LORA optimisation serves as an input for the spare part optimisation that is done with METRIC. This optimisation approach has several drawbacks. It is a time consuming process, it requires a high level of concentration and understanding, it is sensitive to errors, it uses a simplified model for LORA where not all cost drivers are included and there is no interaction between the LORA decisions and the spare part optimisation. The result is that the spare part costs are only optimised for the given LORA solution. The total life cycle costs are therefore not minimal because solutions may exist that have lower total life cycle costs at the expense of worse LORA solutions. The current optimisation approach of Thales LE is also difficult to reproduce since it is not formalised.

No literature available that satisfies the need of Thales LE

Thales LE indicated that there is a need for an integral approach that minimises the total life cycle costs. They expect that an integral approach can reduce the total life cycle costs of a radar system significantly. In general, the literature discusses the LORA optimisation and the spare part optimisation as two separate subjects. Currently there are two LORA models in the literature (Basten et al., 2008-b and Brick and Uchoa, 2007) that meet the requirements of Thales LE. Both models however, do not include a spare part optimisation. A spare part optimisation is crucial since the spare part costs make up a large part of the total life cycle costs. Alfredsson (1997) offers a model that integrates the LORA and spare part optimisation. The major drawback of this model is that it is fairly complicated and it does not support multi indenture components.

A life cycle cost reduction of 17% and 24% can be achieved for Case 1 and 2

We had to improvise on an optimisation approach that minimises the total life cycle costs. We use an iterative optimisation approach where we include the spare part costs that are provided by Inventri in the LORA model of Basten et al. (2008-b).We tested this optimisation approach on three different cases. The cases are based on the variant radar system. We added some expensive components to the cases to increase its complexity. The optimisation process yields good results for Case 1 and Case 2. The solution for Case 1 has 20% less life cycle costs compared to a solution where only the LORA is optimal. For Case 2 the optimisation approach is able to find a solution that has approximately 27% less life cycle costs. For Case 3 however, we see that the optimisation approach does not converge to a better solution. This is at least partly caused by the spare part overestimation drawback. We tested three improvement techniques that are capable of solving this drawback. Test results show that a combination of two improvement techniques yield the best result with respect to calculation time and total costs. With the first technique we aim to generate a good solution within short time and the second technique is used to improve this solution.

Compared to the solutions that are provided by the Thales LE department for Case 1 and Case 2 the optimisation approach offers solutions that have approximately 17% and 24% less life cycle costs. Overall we see that the optimisation approach finds a solution where more components are repaired downstream in the repair network. Downstream repair results in a shorter repair cycle time and thus less system downtime due to component failure. Due to the short repair cycle time less spare parts are needed in the repair network to achieve the required system availability. The optimisation approach is able to significantly reduce the costs of spare parts at the expense of procuring more expensive test equipment. Overall, we conclude that the costs of spare parts cannot be ignored if we want to minimise the total life cycle costs. For both Case 1 and Case 2 we see that more expensive test equipment is procured downstream in the repair network.

Sensitivity analysis shows that the MTBF is the most sensitive parameter
The sensitivity analysis shows that the repair probability and the MTBF have the greatest impact on the total life cycle costs. The repair probability parameter is more sensitive than the MTBF parameter. However, if we take into account that the value of the MTBF is much more uncertain than we conclude that the MTBF is a very important parameter.

The cost factor for tools and test equipment, the repair cycle time and the MTBF significantly influence the decisions that are made in LORA. The cost factor for tools and test equipment seems to be the most sensitive parameter followed by the MTBF. The repair probability has almost no impact at all on the repair decisions that are made for components. This can easily be explained by the fact that unsuccessful repair can also occur at the contractor. The costs for unsuccessful repair in the repair network are the same as the cost for unsuccessful repair at the contractor.

Implementation
The basic concept of the optimisation approach is to include the spare part costs from an inventory optimisation as fixed costs in the LORA optimisation. The LORA model of Basten et al. (2008-b) must be connected with METRIC. This needs to be implemented by software a development company such as Ortec. Details of the optimisation approach are described in the report. Details on how to use the LORA model are given in Appendix L.

8.2 Recommendations

Use of simplified algorithms for the optimisation approach
The LORA model of Basten et al. (2008-b) is rather difficult to understand for people who are not familiar with flow models and linear programming. In order to solve the model, a solver such as CPLEX is required. For implementation it might be wise to consider the possible use of simplified algorithms or an approximation method instead of a mixed integer program. The use of simplified algorithms can decrease the model's complexity, which has many advantages. Simplified algorithms do not

depend on an expensive solver and are easier to implement. Simplified algorithms increase the understanding of employees of Thales LE and potential customers. However, the performance of an approximation method might be worse. During the project we found that many parameters hold a certain degree of uncertainty. Due to this uncertainty, a simplified method with a slightly worse performance will be acceptable.

Improve parameter estimation of MTBF, repair cycle time and cost factor TTE
More and more customers request an integrated service contract where Thales holds responsibility for the maintenance and upkeep of the radar systems that are sold. If this trend continues and Thales is in the future directly responsible for the maintenance and upkeep of systems, then it is very important that the total life cycle costs are minimal. As life cycle costing becomes more important, the position of Thales LE within Thales Nederland becomes more important. It is then important to have a good life cycle cost minimisation approach. The quality of the solution that is provided by a life cycle cost minimisation approach largely depends on the quality of the logistical data that is used during the analysis. Internal research pointed out that the logistical data that is used at Thales LE has a high degree of uncertainty. The sensitivity analysis pointed out that some logistical data, such as the MTBF, the repair cycle time, and the cost factor for tools and test equipment directly influence the decisions that are made. In order to reduce life cycle costs it is important to improve the quality of the logistical data. Reliability prediction is currently already a topic in the IOP-IPCR research program. However, other data is also important for a life cycle cost analysis. According the sensitivity analysis the focus must be on the cost factor for tools and test equipment, the repair cycle time and the MTBF. The quality of logistical data can be improved for example, by studying the factors that influence the data or by collecting and analysing field data. High quality logistical data can in the long term reduce the costs of maintenance and the costs of upkeep of radar systems.

Study the factors that influence the MTBF and the repair probability
We see a trend nowadays where more and more customers request for an integrated service contract. When Thales is responsible for the upkeep and maintenance of radar systems that are being used by customers then Thales profits from systems that have low life cycle costs. The sensitivity analysis shows that the MTBF and especially the repair probability are important parameters that have a large impact on the total life cycle costs of a system. It might be wise to study how these system characteristics can be improved efficiently.

Improve the robustness of the optimisation approach
The optimisation approach has two drawbacks that are both discussed in Section 4.3. We reduce the effect of one drawback with a combination of two improvement techniques. For the other drawback we did not offer a solution. Test results show however, that the improvement techniques are not very robust. We offer two possible solutions to increase the robustness of the optimisation approach.

Evaluate alternative repair decisions for the most important components
In the case study there is a significant difference between the costs of inexpensive components and expensive components. There is also a difference in the demand of components. Expensive components with a high demand have a large effect on the

total life cycle costs. The optimisation approach that is proposed in this report ends in a so-called steady state. For each component it is possible to multiply the demand of the component with the procurement price. These values can be sorted in a list that is sorted from high to low. The most important component is on top of the list. Try, for this component, all alternative repair decisions and lock the repair decision where the system has the lowest total life cycle costs. During this approach, the decisions for the other components do not change. Now apply this approach for the next component on the list. Continue this approach for example, for the first 10% of the components that are on the list.

Forbid inefficient repair decisions

As mentioned above, the optimisation approach ends in a so-called steady state. At this moment we decrease the costs in the database with 5% to overcome the overestimation of spare part costs. The solution that is found in the next iteration is most of the times worse but some times better than the solution that is found at the steady state. If we keep track of all the decisions that are made in the previous solution than we can indicate for which component the decision has changed. If the total life cycle costs are less than the total life cycle costs that are found in previous solution then we permanently forbid the repair decision that was chosen in the previous solution for the component that changed. If the life cycle costs are higher then we forbid the repair decision that is chosen in the current solution for the component that changed. With this approach we gradually exclude inefficient repair decisions.

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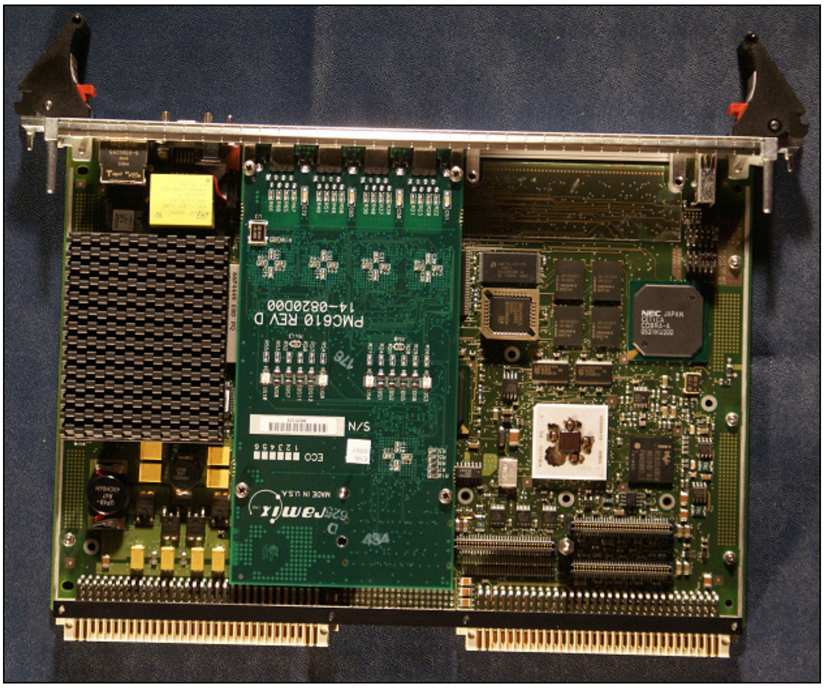
Appendix A – Subsystems and components

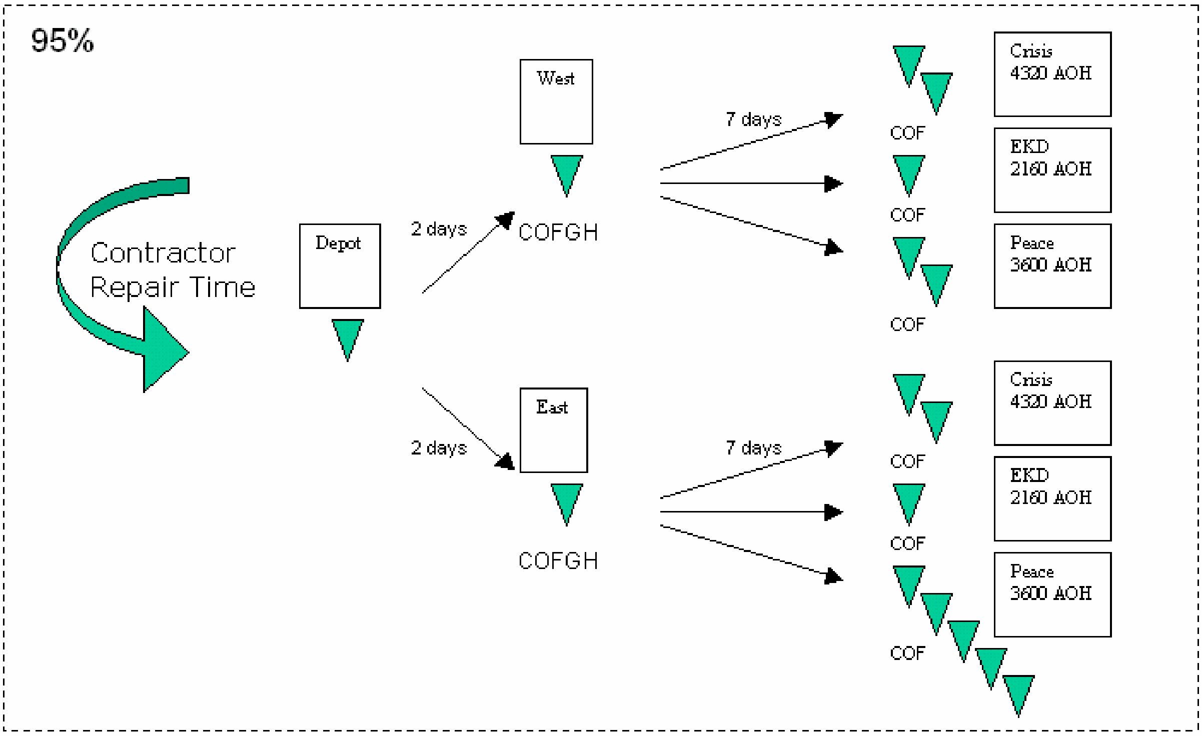
Radar processing cabinet

Close up of processing cabinet with inserted VME boards (LRUs)



VME board (LRU) equipped with a SRU (green print board).
The chips on this board are referred to as parts.

Appendix B - Multi-echelon repair network



The days between echelons indicate the lead-time to transport products to a lower echelon level. In this figure the contractor is located at echelon 4, depot at echelon 3, west and east coast at echelon 2 and the ships are at echelon 1.

COFGH or COF are maintenance policies that can be handled by echelon locations. The third character of a SMR code represents the level of exchange that a component needs. The fourth character of this SMR code represents the echelon level a repair needs. SMR codes are a series of symbols used to indicate the source of supply of an item, its maintenance implications, and recoverability characteristics. If the fourth letter of a SMR code for a component is for example G then the component requires at least an intermediate level repair. As shown in the figure ships (COF) are not capable of repairing at intermediate level. In the contrary, the east and west coast are capable of repairing this component (COFGH).

C = crew, on board, operator
O = organisational, on board, basic skilled maintainer
F = intermediate forward, on board, extended skilled maintainer
G = intermediate
H = intermediate rear
D = depot level
L = specialised, industry level

Appendix C – Maintenance concepts PRICE-HL

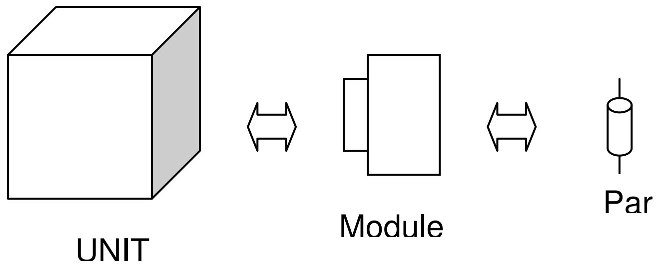
This table lists all available maintenance concepts of Price-HL. The grey marked concepts are non-applicable.

1: Discard UNIT at failure.
2: Replace mods at ORG. Scrap bad mods.
3: Replace mods at INT. Scrap bad mods.
4: Replace mods at DPT. Scrap bad mods.
5: Replace mods at ORG. Repair mods at INT.
6: Replace mods at ORG. Repair mods at DPT.
7: Replace parts at INT.
8: Replace mods at INT. Repair mods at DPT.
9: Replace parts at DPT.
10: Replace parts at ORG.
11: Replace mods at EQP. Scrap bad mods.
12: Replace mods at EQP. Repair mods at ORG.
13: Replace mods at EQP. Repair mods at INT.
14: Replace mods at EQP. Repair mods at DPT.
15: Replace mods at contractor. Scrap bad mods.
16: Replace mods at EQP. Repair mods at contractor.
17: Replace mods at ORG. Repair mods at contractor.
18: Replace mods at INT. Repair mods at contractor.
19: Replace parts at contractor.
20: Recheck UNIT at ORG. Scrap bad UNIT.
21: Recheck UNIT at ORG. Replace mods at INT. Scrap bad mods.
22: Recheck UNIT at ORG. Replace mods at DPT. Scrap bad mods.
23: Recheck UNIT at ORG. Replace parts at INT.
24: Recheck UNIT at ORG. Replace mods at INT. Repair mods at DPT.
25: Recheck UNIT at ORG. Replace parts at DPT.
26: Recheck UNIT at ORG. Replace mods at contractor. Scrap bad mods.
27: Recheck UNIT at ORG. Replace mods at INT. Repair mods at cont.
28: Recheck UNIT at ORG. Replace parts at contractor.

ORG = Organisational level
INT = Intermediate level
DPT = Depot level

The APAR and SMART-L Maintenance Concept is (system) Repair By Replacement of LRUs.

An LRU can be a Unit, Module or even a (Piece) Part or Component. These LRUs can be discarded or repaired by replacement of Module and/or Parts.



In general the Printed Circuit Boards are the Line Replaceable Units used in repair of the system and equivalent to Modules of the LORA modeling. The equipment (EQP) diagnostics/Fault-Isolation goes down to the level of these Printed Circuit Boards/Modules, without the need for additional test stations. These modules are plug-in and easily replaceable. Faulty modules are discarded (MC=11) or repaired. Repair to parts can take place at Depot (DPT, MC=14) or Contractor (MC=16).

In some cases (e.g. Column Assembly, PA Book) a unit is the Line Replaceable Unit. On the test station repair of the unit is performed by isolation and replacement of SRUs, Shop Replaceable Units (i.e. Printed Circuit Boards and Parts). So the same Maintenance Concepts can be applied, where Column Assembly/PA Book is a 'Module' and the SRUs are the Repair 'Parts'.

Repairable SRUs, such as Printed Circuit Boards, are subject to LORA trade-off in other Boxes, where they are modelled as Modules together with the Printed Circuit Board LRUs repairable on the same test set-up.

Because of Box dependencies (e.g. repair costs and demands) due to 2-stage repair CQ modelling, the LORA will be performed iteratively.

Consequently UNIT related Global- and LC Input parameters in the model are Not Applicable.

Appendix D – Parameter uncertainty

Price data uncertainty

For logistical analysis, such as the generation of maintenance concepts, Thales LE uses Rough Order of Magnitude (ROM) price data. ROM prices, also referred to as "Standaard Nederland Prijs", are averages of component sales prices from projects in the past. Systems are sold to customers in different countries. Before an average (ROM) price is calculated, sales prices from the past are corrected with a factor. These factors are different for each country due to profit margins.

At the moment, most sales prices in the system are released between 2004 and 2007. It is questionable how accurate ROM prices are. Prices may deviate due to, for example, inflation, new processing techniques, and raw material availability.
The country correction factor is only used to calculate a ROM price, but when a maintenance analysis is made for, for example, Greece, the ROM price is not converted backwards with the same country factor. In other words, for analysis, Thales LE always uses the same, country independent, ROM price. In contradiction, when customers need a spare part in practice, these factors are included in the sales price.

According to logistic engineers at Thales, the actual price can deviate for approximately twenty percent compared to the ROM price.

Failure data uncertainty

Compared to price data, the reliability of failure data is more complex. The easiest and best method for generating failure data is to take actual field data. Field data is gathered from components that have been used in the field.

In most cases it is not possible to collect field data. Several reasons for the unavailability of field data are:

- Field data does not exist for new products, which still have to be introduced in the market. Capital goods are, in general, low volume series and if field data exists, it is based on a limited number of observations.
- For existing products, customers, mostly defence related companies, have failure data but they do not want to share this data with Thales.
- The cause of a failure is in most cases unknown. The cause is important, because failure of a component can be caused by inappropriate use or mistakes. These failures do not contribute to the theoretical MTBF used at Thales. Frequently, a Thales service engineer marks a repair action with "failure" only.
- Operational hours of failed components are in most cases unknown. An MTBF cannot be calculated in this case.

Since it is hard to collect field data, Thales used the MIL-HDBK-217F handbook, until 2005, to generate component failure data. The handbook has been released in 1991 and procedures used in this standard not very accurate. Reliability predictions, such as the MIL-handbook, are generally based on the following assumptions (Economou, 2004; Jones, 2001):

- Failure rates are constant with an exponential distribution.

- The failure of one component will cause system failure.
- Statistical independency between components. Failure of one component does not affect other components in the system.

It is questionable whether these assumptions accurately reflect practical situations.

Currently Thales started with the use of the reliability prediction package 217Plus from RIAC. The main reason for implementing 217Plus is to pay attention to reliability in the design phase of a product. This reliability prediction method is a successor of the MIL-HDBK-217F. 217Plus tries to solve several of the criticisms on MIL-HDBK-217F, and although most improvements may appear promising, scientific foundations cannot be found (Widdershoven, 2008). The 217Plus method is very recent and its value still has to be proven.

According to employees, failure data is one of the most inaccurate data used in the field of engineering. The next example will illustrate the inaccuracy of failure data.
Reliability predictions performed using traditional techniques, such as MIL-HDBK-217F, result in a failure rate estimate with relative wide confidence bounds. Tests, with both predicted and observed data, indicated that using traditional approaches, one could be 90% certain that the true failure rate was less than 7.51 times the predicted value (217Plus Handbook).

Appendix E – Improvements to METRIC

Although this research will not explicitly focus on the improvement of the METRIC approach, some opportunities are discussed that might be interesting, as they came up from the literature review in Chapter 4. The improvements discussed in this section are more or less radical and need additional research.

Emergency supply and lateral shipment

Alfredsson and Verrijdt (1999) and Wong et al. (2006) proposed a model that accounts for emergency supply. Direct shipment and lateral shipment are two possible options for emergency supply. In the case of direct shipment, a spare part is directly delivered to the demanding location without travelling through the repair network. In the case of lateral shipment, a spare part that is located at an operational location can be used to satisfy the demand of any other operational location. The model of Rustenburg (2000) does not allow for lateral shipment. Although in practice most operational sites will have different mission objectives and lateral shipment is not applicable, it might still be useful for situations in which it is possible. It is an effective procedure to increase system availability.

Limited repair capacity

Sleptchenko et al. (2002) show that repair capacity is important to take into account when the utilisation rate of the repair stations is high. A high utilization rate (say > 70%) will cause more waiting time for the components that need to be repaired. Their model supports repair capacities and simulation results show a 4% average increase of accuracy in situations where repair shops have a high utilisation rate. However, the utilisation rates of tools and test equipment in the case of Thales LE are currently not expected to be over 70%. In the near future, when Thales offers integrated service contracts to several customers, demands (return of faulty components) will increase and the utilisation rate of 70% is likely to be exceeded.

Obsolescence

Obsolescence, as described by Tanaydin (2007), occurs when components that have to be procured, are no longer available. Due to technology development the physical characteristics of, especially, electronic components will change over time. Obsolescence is commonly applicable to small electronic parts, such as computer chips. There are a few solutions to remedy this problem:

(1) Use a form and fit function. In this case a similar component is found that has the same characteristics and performance as the obsolete component.

In case the first option is not available then two possible alternatives solutions are:

(2) Modify and redesign the current system. The use of new technology can be adopted to solve the problem.
(3) Do a last-buy order. Before a component becomes obsolete, enough spares are bought to ensure availability of spares until the system's end of life.

Basten et al. (2008) do not explicitly model the implications of obsolescence. The costs of maintenance change if spare parts are not available and alternative solutions have to be adopted. However, these are hard to predict. Currently it is not clear how obsolescence can be included in the model. More research is needed to investigate obsolescence at Thales and the solutions that are present in the literature. In the future this might be an interesting aspect to research, but for now the focus is on linking the LORA model to the spare part allocation model.

Appendix F – Different OEM repair prices

LSACONXB	Procurement price	OEM repair
MS03AB70AM	€ 126,712	€ 100,000
MS03AB70AN	€ 130,469	€ 10,000
MS03AB71	€ 43,981	€ 8,796
MS10AA	€ 200,000	€ 10,000
MS20AB02	€ 5,775	€ 2,000
MS20AB03	€ 15,315	€ 4,000
MS20AB04	€ 49,505	€ 5,000
MS20AB05	€ 6,855	€ 2,000
MS20AB07	€ 2,965	€ 1,000
MS20AB08	€ 24,840	€ 5,000
MS20AB09	€ 19,775	€ 5,000
MS20AB10	€ 250,000	€ 20,000
MS20AC	€ 869,410	€ 10,000
MS20AC02	€ 5,775	€ 2,000
MS20AC03	€ 13,495	€ 4,000
MS20AC04	€ 49,505	€ 5,000
MS20AC05	€ 6,855	€ 2,000
MS20AC07	€ 2,965	€ 1,000
MS20AC08	€ 24,840	€ 5,000
MS20AC09	€ 19,775	€ 5,000
MS20AC10	€ 250,000	€ 20,000
MS21	€ 76,044	€ 10,000
MS21AB	€ 3,310	€ 1,000
MS21AD	€ 8,767	€ 2,000
MS21AE	€ 1,532	€ 1,000
MS22	€ 82,305	€ 10,000
MS22AH	€ 6,344	€ 2,000
MS22AJ	€ 2,647	€ 1,000
MS22AK	€ 3,740	€ 1,000
MS22AM	€ 4,211	€ 2,000
MS22AN	€ 3,225	€ 2,000

Thales LE adjusted the OEM repair price for some expensive components. In case a component contains children the OEM repair price of the children is also adjusted.

Appendix G – Improvement methods for Case 1 & 2

Exponential smoothing – Case 1

Improvement method	Start solution	Best solution	Improvement	# iterations
None	98,307,842	78,380,508	0.00%	8
Smooth factor 60%	98,307,842	78,385,697	-0.01%	20
Smooth factor 70%	98,307,842	78,380,508	0.00%	20
Smooth factor 80%	98,307,842	78,380,508	0.00%	20
Smooth factor 90%	98,307,842	78,385,697	-0.01%	17
Smooth factor 95%	98,307,842	78,380,508	0.00%	15

Exponential smoothing – Case 2

Improvement method	Start solution	Best solution	Improvement	# iterations
None	97,830,255	70,831,720	0.00%	10
Smooth factor 60%	97,830,255	70,918,029	-0.12%	20
Smooth factor 70%	97,830,255	70,039,728	1.12%	20
Smooth factor 80%	97,830,255	70,712,413	0.17%	9
Smooth factor 90%	97,830,255	70,832,005	0.00%	15
Smooth factor 95%	97,830,255	70,836,740	-0.01%	10

Spares estimates – Case 1

Improvement method	Start solution	Best solution	Improvement	# iterations
None	98,307,842	78,380,508	0.00%	8
Spare estimates k = 0.5	96,388,214	78,332,083	0.06%	8
Spare estimates k = 1	96,388,214	78,332,083	0.06%	8
Spare estimates k = 1.5	96,388,214	78,332,083	0.06%	8
Spare estimates k = 2	81,524,355	78,424,215	-0.06%	7
Spare estimates k = 2.5	82,399,037	78,332,083	0.06%	7
Spare estimates k = 3	82,399,037	78,332,083	0.06%	7

Spares estimates – Case 2

Improvement method	Start solution	Best solution	Improvement	# iterations
None	97,830,255	70,831,720	0.00%	10
Spare estimates k = 0.5	90,854,642	70,062,761	1.09%	8
Spare estimates k = 1	90,854,642	70,062,761	1.09%	9
Spare estimates k = 1.5	90,854,642	70,062,761	1.09%	8
Spare estimates k = 2	90,854,642	70,062,761	1.09%	8
Spare estimates k = 2.5	74,352,234	71,477,312	-0.91%	7
Spare estimates k = 3	74,763,199	71,477,312	-0.91%	7

Decrease factor – Case 1

Improvement method	Start solution	Best solution	Improvement	# iterations
None	98,307,842	78,380,508	0.00%	8
Decrease database 1%	98,307,842	78,380,508	0.00%	8
Decrease database 3%	98,307,842	78,267,833	0.14%	93
Decrease database 5%	98,307,842	78,380,508	0.00%	8
Decrease database 10%	98,307,842	78,380,508	0.00%	8

Decrease factor – Case 2

Improvement method	Start solution	Best solution	Improvement	# iterations
None	97,830,255	70,831,720	0.00%	10
Decrease database 1%	97,830,255	70,831,720	0.00%	10
Decrease database 3%	97,830,255	70,831,720	0.00%	10
Decrease database 5%	97,830,255	69,962,247	1.23%	34
Decrease database 10%	97,830,255	70,831,720	0.00%	10

Appendix H – Test equipment description

GI-HPA
The GI-HPA tester is required for performance testing and fault-finding of units of the GI-band (9 GHz frequency) High Power Amplifier. These units are a Travelling Wave Tube power amplifier and a High Voltage supply unit with Powersupply and control unit.

CAM tester
The Camera tester consists of a workbench, with collimator equipment for test and alignment of the optical and mechanical axes of the cameras, and various test equipment for performance testing and fault-finding of the electronic units for the (infrared) image to digital video conversion.

OBJ tester
For testing the lens unit of the camera on performance of optics, focus and shutter the objective tester is required.

PA tester
The Power Amplifier tester is required for performance testing and fault-finding of units of the Solid State L-band (1-2 GHz frequency) Power Amplifier books and (pre) Driver. Units of the PA-book and Driver are in general RF or MIC technology SRU's and tested and repaired on the respective testers

IFF tester
The IFF tester is required for fault-finding and test of the separate Identification of Friend or Foe (IFF) subsystem to fulfil corrective maintenance on OLM/ILM.

RF tester
The RF test system is designed to provide in one compact enclosure all facilities required aligning (tune), testing and troubleshooting small units or electronic circuitry. The circuitry to be operated may be of analogue, (linear) digital or hybrid nature technology. The RF test system is comprised of the station (cabinet + desk-structure) and extension kits. The test station has been developed to finish and check assembly-line output, to provide acceptance testing under standard laboratory conditions and to perform as a module maintenance station.

MIC tester
The MIC tester is in set up similar to the RF tester, but is especially meant for Hybrids/Microwave Integrated Circuits.

Appendix I – Sensitivity analysis – Cost per cost driver

TTE	RCT	MTBF	OEM	RP	Solution	Spares	TTE	Repair	Discard
100%	100%	100%	100%	100%	€ 78,332,083	€ 40,559,899	€ 22,005,789	€ 11,563,323	€ 4,203,071
50%	50%	25%	50%	L	€ 177,884,035	€ 74,871,372	€ 32,783,643	€ 54,620,491	€ 15,608,530
50%	50%	25%	50%	H	€ 138,327,777	€ 66,771,355	€ 33,979,190	€ 21,218,731	€ 16,358,501
50%	50%	25%	150%	L	€ 190,981,290	€ 69,040,018	€ 34,792,402	€ 71,541,423	€ 15,607,448
50%	50%	25%	150%	H	€ 153,250,433	€ 57,894,520	€ 38,348,699	€ 41,398,910	€ 15,608,304
50%	50%	200%	50%	L	€ 35,345,500	€ 15,607,871	€ 9,388,614	€ 8,499,042	€ 1,849,973
50%	50%	200%	50%	H	€ 27,811,598	€ 10,766,313	€ 10,517,402	€ 4,289,079	€ 2,238,804
50%	50%	200%	150%	L	€ 37,066,797	€ 15,417,354	€ 10,517,402	€ 9,030,506	€ 2,101,535
50%	50%	200%	150%	H	€ 28,900,773	€ 10,840,743	€ 10,517,402	€ 5,410,583	€ 2,132,045
50%	200%	25%	50%	L	€ 224,577,488	€ 105,753,155	€ 38,652,133	€ 64,544,129	€ 15,628,073
50%	200%	25%	50%	H	€ 169,680,802	€ 77,214,209	€ 42,414,763	€ 33,224,679	€ 16,827,152
50%	200%	25%	150%	L	€ 229,207,672	€ 102,197,439	€ 42,293,385	€ 69,095,741	€ 15,621,108
50%	200%	25%	150%	H	€ 175,476,328	€ 77,401,094	€ 42,293,387	€ 38,405,003	€ 17,376,845
50%	200%	200%	50%	L	€ 48,474,148	€ 27,296,029	€ 11,002,900	€ 8,110,122	€ 2,065,097
50%	200%	200%	50%	H	€ 39,364,941	€ 21,968,915	€ 11,002,900	€ 4,291,591	€ 2,101,535
50%	200%	200%	150%	L	€ 49,374,372	€ 27,296,029	€ 11,002,900	€ 9,051,098	€ 2,024,344
50%	200%	200%	150%	H	€ 40,602,591	€ 21,968,915	€ 11,002,900	€ 5,248,369	€ 2,382,408
150%	50%	25%	50%	L	€ 235,977,411	€ 135,430,223	€ 30,277,734	€ 54,662,006	€ 15,607,448
150%	50%	25%	50%	H	€ 195,690,813	€ 127,232,129	€ 31,370,109	€ 21,481,127	€ 15,607,448
150%	50%	25%	150%	L	€ 250,061,726	€ 128,824,837	€ 32,826,608	€ 72,802,833	€ 15,607,448
150%	50%	25%	150%	H	€ 212,353,434	€ 119,397,400	€ 32,826,608	€ 43,317,140	€ 16,812,286
150%	50%	200%	50%	L	€ 47,014,817	€ 26,683,216	€ 12,814,296	€ 7,386,102	€ 131,202
150%	50%	200%	50%	H	€ 42,510,889	€ 22,180,918	€ 14,999,045	€ 5,199,723	€ 131,202
150%	50%	200%	150%	L	€ 50,668,692	€ 25,630,290	€ 13,906,671	€ 11,000,528	€ 131,202
150%	50%	200%	150%	H	€ 45,297,231	€ 22,180,918	€ 14,999,046	€ 7,986,065	€ 131,202
150%	200%	25%	50%	L	€ 284,898,856	€ 169,453,343	€ 34,756,472	€ 65,080,737	€ 15,608,304
150%	200%	25%	50%	H	€ 233,325,424	€ 147,488,901	€ 34,756,472	€ 34,265,702	€ 16,814,348
150%	200%	25%	150%	L	€ 292,314,358	€ 168,591,746	€ 34,756,472	€ 72,151,792	€ 16,814,348
150%	200%	25%	150%	H	€ 242,410,505	€ 147,503,169	€ 34,756,472	€ 43,336,515	€ 16,814,348
150%	200%	200%	50%	L	€ 69,874,201	€ 29,149,794	€ 30,459,794	€ 8,112,292	€ 2,152,321
150%	200%	200%	50%	H	€ 61,367,368	€ 23,418,915	€ 31,552,169	€ 4,294,750	€ 2,101,535
150%	200%	200%	150%	L	€ 70,753,594	€ 29,149,794	€ 30,459,794	€ 9,027,922	€ 2,116,084
150%	200%	200%	150%	H	€ 61,806,434	€ 28,147,538	€ 24,797,653	€ 4,319,610	€ 4,541,633

The first line shows the results without change to any of the parameters.

Value of parameters
TTE = Cost of tools and test equipment
RCT = Repair cycle time
MTBF = Mean time between failure
OEM = OEM repair price
RP = Repair probability

Cost
Solution = Total life cycle cost
Spares = Spare part cost
TTE = Cost for tools and test equipment
Repair = Cost for repair
Discard = Cost for discard

Fraction of the total cost for each cost driver. The cost for spare parts, tools and test equipment, repair and discard add up to 100%.

TTE	RCT	MTBF	OEM	RP		Solution		Spares	TTE	Repair	Discard
50%	50%	25%	50%	L		100%		42%	18%	31%	9%
50%	50%	25%	50%	H		100%		48%	25%	15%	12%
50%	50%	25%	150%	L		100%		36%	18%	37%	8%
50%	50%	25%	150%	H		100%		38%	25%	27%	10%
50%	50%	200%	50%	L		100%		44%	27%	24%	5%
50%	50%	200%	50%	H		100%		39%	38%	15%	8%
50%	50%	200%	150%	L		100%		42%	28%	24%	6%
50%	50%	200%	150%	H		100%		38%	36%	19%	7%
50%	200%	25%	50%	L		100%		47%	17%	29%	7%
50%	200%	25%	50%	H		100%		46%	25%	20%	10%
50%	200%	25%	150%	L		100%		45%	18%	30%	7%
50%	200%	25%	150%	H		100%		44%	24%	22%	10%
50%	200%	200%	50%	L		100%		56%	23%	17%	4%
50%	200%	200%	50%	H		100%		56%	28%	11%	5%
50%	200%	200%	150%	L		100%		55%	22%	18%	4%
50%	200%	200%	150%	H		100%		54%	27%	13%	6%
150%	50%	25%	50%	L		100%		57%	13%	23%	7%
150%	50%	25%	50%	H		100%		65%	16%	11%	8%
150%	50%	25%	150%	L		100%		52%	13%	29%	6%
150%	50%	25%	150%	H		100%		56%	15%	20%	8%
150%	50%	200%	50%	L		100%		57%	27%	16%	0%
150%	50%	200%	50%	H		100%		52%	35%	12%	0%
150%	50%	200%	150%	L		100%		51%	27%	22%	0%
150%	50%	200%	150%	H		100%		49%	33%	18%	0%
150%	200%	25%	50%	L		100%		59%	12%	23%	5%
150%	200%	25%	50%	H		100%		63%	15%	15%	7%
150%	200%	25%	150%	L		100%		58%	12%	25%	6%
150%	200%	25%	150%	H		100%		61%	14%	18%	7%
150%	200%	200%	50%	L		100%		42%	44%	12%	3%
150%	200%	200%	50%	H		100%		38%	51%	7%	3%
150%	200%	200%	150%	L		100%		41%	43%	13%	3%
150%	200%	200%	150%	H		100%		46%	40%	7%	7%

Appendix J – Sensitivity analysis – Cost per cost driver per location

					Spares			TTE			Repair			
TTE	RCT	MTBF	OEM	RP	Ship	ILM	DLM	Ship	ILM	DLM	Ship	ILM	DLM	OEM
100%	100%	100%	100%	100%	€ 20,160,795	€ 3,569,388	€ 16,829,716	€ 8,581,716	€ 10,195,500	€ 3,228,573	€ 232,445	€ 7,548,682	€ 1,260,353	€ 2,521,843
50%	50%	25%	50%	L	€ 40,043,392	€ 5,455,256	€ 29,372,724	€ 30,435,036	€ 728,250	€ 1,620,357	€ 3,639,955	€ 105,406	€ 18,707,063	€ 32,168,066
50%	50%	25%	50%	H	€ 36,401,688	€ 5,584,482	€ 24,785,184	€ 30,507,864	€ 2,985,826	€ 485,500	€ 97,025	€ 103,276	€ 20,092	€ 20,998,338
50%	50%	25%	150%	L	€ 40,097,575	€ 4,992,509	€ 23,949,934	€ 30,507,864	€ 728,250	€ 3,556,288	€ 3,650,234	€ 31,982,187	€ 19,364,759	€ 16,544,242
50%	50%	25%	150%	H	€ 36,641,460	€ 4,779,887	€ 16,473,172	€ 30,507,864	€ 2,985,826	€ 4,855,009	€ 103,469	€ 29,560,227	€ 457,877	€ 11,277,338
50%	50%	200%	50%	L	€ 4,833,797	€ 1,452,777	€ 9,321,297	€ 4,290,864	€ 5,097,750	€ 0	€ 433,655	€ 4,020,398	€ 0	€ 4,044,990
50%	50%	200%	50%	H	€ 2,030,572	€ 1,126,696	€ 7,609,044	€ 4,290,864	€ 5,097,750	€ 1,128,788	€ 5,386	€ 3,697,348	€ 17,750	€ 568,595
50%	50%	200%	150%	L	€ 4,833,797	€ 1,452,777	€ 9,130,780	€ 4,290,864	€ 5,097,750	€ 1,128,788	€ 433,655	€ 4,020,398	€ 2,457,409	€ 2,119,045
50%	50%	200%	150%	H	€ 2,030,572	€ 1,201,127	€ 7,609,044	€ 4,290,864	€ 5,097,750	€ 1,128,788	€ 5,386	€ 3,696,952	€ 18,162	€ 1,690,083
50%	200%	25%	50%	L	€ 40,766,992	€ 10,151,137	€ 54,835,026	€ 30,435,036	€ 3,968,964	€ 4,248,133	€ 3,639,955	€ 50,591,529	€ 1,815,181	€ 8,497,463
50%	200%	25%	50%	H	€ 37,470,505	€ 6,124,928	€ 33,618,775	€ 30,507,864	€ 3,956,826	€ 7,950,073	€ 103,469	€ 29,578,447	€ 776,297	€ 2,766,466
50%	200%	25%	150%	L	€ 40,766,992	€ 9,200,653	€ 52,229,794	€ 30,435,036	€ 3,968,964	€ 7,889,385	€ 3,639,955	€ 50,594,337	€ 3,152,611	€ 11,708,838
50%	200%	25%	150%	H	€ 37,470,505	€ 6,243,632	€ 33,686,957	€ 30,507,864	€ 3,956,826	€ 7,828,697	€ 106,277	€ 29,579,617	€ 765,257	€ 7,953,852
50%	200%	200%	50%	L	€ 6,543,418	€ 1,295,343	€ 19,457,268	€ 4,290,864	€ 5,097,750	€ 1,614,286	€ 433,655	€ 4,005,320	€ 2,352,680	€ 1,318,467
50%	200%	200%	50%	H	€ 4,706,099	€ 1,369,774	€ 15,893,042	€ 4,290,864	€ 5,097,750	€ 1,614,286	€ 5,386	€ 3,697,348	€ 20,262	€ 568,595
50%	200%	200%	150%	L	€ 6,543,418	€ 1,295,343	€ 19,457,268	€ 4,290,864	€ 5,097,750	€ 1,614,286	€ 433,655	€ 4,005,320	€ 2,352,680	€ 2,259,443
50%	200%	200%	150%	H	€ 4,706,099	€ 1,369,774	€ 15,893,042	€ 4,290,864	€ 5,097,750	€ 1,614,286	€ 5,386	€ 3,697,348	€ 20,262	€ 1,525,373
150%	50%	25%	50%	L	€ 88,122,213	€ 16,786,047	€ 30,521,963	€ 12,654,084	€ 13,144,912	€ 4,478,738	€ 132,852	€ 169,620	€ 22,146,435	€ 32,213,099
150%	50%	25%	50%	H	€ 83,581,904	€ 15,790,644	€ 27,859,581	€ 12,654,084	€ 15,329,662	€ 3,386,363	€ 32,810	€ 119,225	€ 141,211	€ 21,187,881
150%	50%	25%	150%	L	€ 88,122,213	€ 16,029,329	€ 24,673,295	€ 12,654,084	€ 15,329,662	€ 4,842,862	€ 3,579,575	€ 32,046,402	€ 18,702,707	€ 18,474,149
150%	50%	25%	150%	H	€ 83,581,904	€ 15,570,116	€ 20,245,380	€ 12,654,084	€ 15,329,662	€ 4,842,862	€ 32,810	€ 29,582,620	€ 168,580	€ 13,533,130
150%	50%	200%	50%	L	€ 6,671,115	€ 1,261,261	€ 18,750,840	€ 12,802,644	€ 11,652	€ 0	€ 1,758	€ 16,133	€ 0	€ 7,368,211
150%	50%	200%	50%	H	€ 4,833,797	€ 1,261,261	€ 16,085,860	€ 12,802,644	€ 2,196,401	€ 0	€ 4,197	€ 3,684,113	€ 0	€ 1,511,413
150%	50%	200%	150%	L	€ 6,671,115	€ 1,261,261	€ 17,697,914	€ 12,802,644	€ 11,652	€ 1,092,375	€ 1,758	€ 16,133	€ 4,422,750	€ 6,559,887
150%	50%	200%	150%	H	€ 4,833,797	€ 1,261,261	€ 16,085,860	€ 12,802,644	€ 2,196,402	€ 0	€ 4,197	€ 3,684,114	€ 0	€ 4,297,754
150%	200%	25%	50%	L	€ 88,122,213	€ 21,278,341	€ 60,052,789	€ 12,654,084	€ 22,102,388	€ 0	€ 132,852	€ 54,082,795	€ 0	€ 10,865,090
150%	200%	25%	50%	H	€ 83,581,904	€ 18,905,986	€ 45,001,012	€ 12,654,084	€ 22,102,388	€ 0	€ 32,810	€ 29,633,268	€ 0	€ 4,599,624
150%	200%	25%	150%	L	€ 88,122,213	€ 21,504,117	€ 58,965,416	€ 12,654,084	€ 22,102,388	€ 0	€ 132,852	€ 55,054,598	€ 6,485	€ 16,957,856
150%	200%	25%	150%	H	€ 83,581,904	€ 18,911,235	€ 45,010,031	€ 12,654,084	€ 22,102,388	€ 0	€ 32,810	€ 29,626,823	€ 6,485	€ 13,670,397
150%	200%	200%	50%	L	€ 6,671,115	€ 1,020,266	€ 21,458,413	€ 12,872,556	€ 13,108,500	€ 4,478,738	€ 17,891	€ 21,221	€ 6,880,159	€ 1,193,022
150%	200%	200%	50%	H	€ 4,706,099	€ 1,369,774	€ 17,343,042	€ 12,872,556	€ 15,293,250	€ 3,386,363	€ 5,386	€ 3,697,348	€ 17,750	€ 574,266
150%	200%	200%	150%	L	€ 6,671,115	€ 1,020,266	€ 21,458,413	€ 12,872,556	€ 13,108,500	€ 4,478,738	€ 17,891	€ 20,723	€ 6,880,159	€ 2,109,149
150%	200%	200%	150%	H	€ 2,252,496	€ 1,050,803	€ 24,844,239	€ 12,654,084	€ 2,184,750	€ 9,958,819	€ 4,054	€ 3,682,924	€ 77,788	€ 554,844

Fraction of the total cost for each cost driver. Per cost driver the sum of each location adds up to 100%.

						Spares				TTE				Repair			
TTE	**RCT**	**MTBF**	**OEM**	**RP**		**Ship**	**ILM**	**DLM**		**Ship**	**ILM**	**DLM**		**Ship**	**ILM**	**DLM**	**OEM**
50%	50%	25%	50%	L		53%	7%	39%		93%	2%	5%		7%	0%	34%	59%
50%	50%	25%	50%	H		55%	8%	37%		90%	9%	1%		0%	0%	0%	99%
50%	50%	25%	150%	L		58%	7%	35%		88%	2%	10%		5%	45%	27%	23%
50%	50%	25%	150%	H		63%	8%	28%		80%	8%	13%		0%	71%	1%	27%
50%	50%	200%	50%	L		31%	9%	60%		46%	54%	0%		5%	47%	0%	48%
50%	50%	200%	50%	H		19%	10%	71%		41%	48%	11%		0%	86%	0%	13%
50%	50%	200%	150%	L		31%	9%	59%		41%	48%	11%		5%	45%	27%	23%
50%	50%	200%	150%	H		19%	11%	70%		41%	48%	11%		0%	68%	0%	31%
50%	200%	25%	50%	L		39%	10%	52%		79%	10%	11%		6%	78%	3%	13%
50%	200%	25%	50%	H		49%	8%	44%		72%	9%	19%		0%	89%	2%	8%
50%	200%	25%	150%	L		40%	9%	51%		72%	9%	19%		5%	73%	5%	17%
50%	200%	25%	150%	H		48%	8%	44%		72%	9%	19%		0%	77%	2%	21%
50%	200%	200%	50%	L		24%	5%	71%		39%	46%	15%		5%	49%	29%	16%
50%	200%	200%	50%	H		21%	6%	72%		39%	46%	15%		0%	86%	0%	13%
50%	200%	200%	150%	L		24%	5%	71%		39%	46%	15%		5%	44%	26%	25%
50%	200%	200%	150%	H		21%	6%	72%		39%	46%	15%		0%	70%	0%	29%
150%	50%	25%	50%	L		65%	12%	23%		42%	43%	15%		0%	0%	41%	59%
150%	50%	25%	50%	H		66%	12%	22%		40%	49%	11%		0%	1%	1%	99%
150%	50%	25%	150%	L		68%	12%	19%		39%	47%	15%		5%	44%	26%	25%
150%	50%	25%	150%	H		70%	13%	17%		39%	47%	15%		0%	68%	0%	31%
150%	50%	200%	50%	L		25%	5%	70%		100%	0%	0%		0%	0%	0%	100%
150%	50%	200%	50%	H		22%	6%	73%		85%	15%	0%		0%	71%	0%	29%
150%	50%	200%	150%	L		26%	5%	69%		92%	0%	8%		0%	0%	40%	60%
150%	50%	200%	150%	H		22%	6%	73%		85%	15%	0%		0%	46%	0%	54%
150%	200%	25%	50%	L		52%	13%	35%		36%	64%	0%		0%	83%	0%	17%
150%	200%	25%	50%	H		57%	13%	31%		36%	64%	0%		0%	86%	0%	13%
150%	200%	25%	150%	L		52%	13%	35%		36%	64%	0%		0%	76%	0%	24%
150%	200%	25%	150%	H		57%	13%	31%		36%	64%	0%		0%	68%	0%	32%
150%	200%	200%	50%	L		23%	4%	74%		42%	43%	15%		0%	0%	85%	15%
150%	200%	200%	50%	H		20%	6%	74%		41%	48%	11%		0%	86%	0%	13%
150%	200%	200%	150%	L		23%	4%	74%		42%	43%	15%		0%	0%	76%	23%
150%	200%	200%	150%	H		8%	4%	88%		51%	9%	40%		0%	85%	2%	13%

Appendix K – Sensitivity analysis – Quantity per cost driver

											Spares				TTE				Repair			
TTE	RCT	MTBF	OEM	RP		Spares	TTE	Repair	Discard		Ship	ILM	DLM		Ship	ILM	DLM		Ship	ILM	DLM	OEM
50%	50%	25%	50%	L		1,532	125	142	228		1,032	110	390		120	2	3		14	4	6	118
50%	50%	25%	50%	H		1,567	137	137	233		1,059	135	373		132	4	1		15	7	2	113
50%	50%	25%	150%	L		1,586	137	143	227		1,116	109	361		132	2	3		17	5	13	108
50%	50%	25%	150%	H		1,470	157	143	227		1,047	117	306		132	4	21		17	6	35	85
50%	50%	200%	50%	L		468	124	138	218		271	27	170		120	4	0		14	8	0	116
50%	50%	200%	50%	H		444	125	144	232		245	22	177		120	4	1		15	7	2	120
50%	50%	200%	150%	L		481	125	146	230		271	27	183		120	4	1		14	8	2	122
50%	50%	200%	150%	H		445	125	140	236		245	23	177		120	4	1		15	5	4	116
50%	200%	25%	50%	L		1,985	146	140	230		1,018	227	740		120	8	18		14	9	33	84
50%	200%	25%	50%	H		1925	162	144	232		1090	187	648		132	6	24		17	7	45	75
50%	200%	25%	150%	L		1,940	151	141	229		1,018	208	714		120	8	23		14	10	44	73
50%	200%	25%	150%	H		1,934	160	126	250		1,090	193	651		132	6	22		18	8	43	57
50%	200%	200%	50%	L		637	126	136	234		269	42	326		120	4	2		14	7	6	109
50%	200%	200%	50%	H		629	126	146	230		264	43	322		120	4	2		15	7	4	120
50%	200%	200%	150%	L		637	126	137	233		269	42	326		120	4	2		14	7	6	110
50%	200%	200%	150%	H		629	126	137	239		264	43	322		120	4	2		15	7	4	111
150%	50%	25%	50%	L		1494	114	143	227		967	136	391		108	4	2		11	7	4	121
150%	50%	25%	50%	H		1,480	115	143	227		955	133	392		108	6	1		12	7	3	121
150%	50%	25%	150%	L		1,478	116	143	227		967	134	377		108	6	2		12	8	5	118
150%	50%	25%	150%	H		1,467	116	146	230		955	132	380		108	6	2		12	8	6	120
150%	50%	200%	50%	L		455	110	112	214		276	19	160		108	2	0		12	2	0	98
150%	50%	200%	50%	H		444	112	122	214		271	19	154		108	4	0		13	3	0	106
150%	50%	200%	150%	L		454	111	122	214		276	19	159		108	2	1		12	2	2	106
150%	50%	200%	150%	H		444	112	122	214		271	19	154		108	4	0		13	3	0	106
150%	200%	25%	50%	L		2,041	116	143	227		967	248	826		108	8	0		11	12	0	120
150%	200%	25%	50%	H		2,025	116	146	230		955	270	800		108	8	0		12	12	0	122
150%	200%	25%	150%	L		2,059	116	146	230		967	253	839		108	8	0		11	11	2	122
150%	200%	25%	150%	H		2,031	116	146	230		955	274	802		108	8	0		12	10	2	122
150%	200%	200%	50%	L		652	124	129	247		276	43	333		120	2	2		14	8	4	103
150%	200%	200%	50%	H		631	125	146	230		264	43	324		120	4	1		15	7	2	122
150%	200%	200%	150%	L		652	124	145	231		276	43	333		120	2	2		14	6	4	121
150%	200%	200%	150%	H		631	125	179	230		264	43	327		108	2	3		11	6	2	120

The last four columns show how many of the 146 repairable components are repaired at ship, ILM, DLM and OEM.
The last four columns do not always add up to 146. In case a parent (with children) is repaired at the contractor
the total quantity of components will be less than 146.

Fraction of the total quantity for each cost driver. All cost drivers add up to 100%.
Per cost driver the sum of each location adds up to 100%.

											Spares				TTE				Repair			
TTE	**RCT**	**MTBF**	**OEM**	**RP**		**Spares**	**TTE**	**Repair**	**Discard**		**Ship**	**ILM**	**DLM**		**Ship**	**ILM**	**DLM**		**Ship**	**ILM**	**DLM**	**OEM**
50%	50%	25%	50%	L		76%	6%	7%	11%		67%	7%	25%		96%	2%	2%		10%	3%	4%	83%
50%	50%	25%	50%	H		76%	7%	7%	11%		68%	9%	24%		96%	3%	1%		11%	5%	1%	82%
50%	50%	25%	150%	L		76%	7%	7%	11%		70%	7%	23%		96%	1%	2%		12%	3%	9%	76%
50%	50%	25%	150%	H		74%	8%	7%	11%		71%	8%	21%		84%	3%	13%		12%	4%	24%	59%
50%	50%	200%	50%	L		49%	13%	15%	23%		58%	6%	36%		97%	3%	0%		10%	6%	0%	84%
50%	50%	200%	50%	H		47%	13%	15%	25%		55%	5%	40%		96%	3%	1%		10%	5%	1%	83%
50%	50%	200%	150%	L		49%	13%	15%	23%		56%	6%	38%		96%	3%	1%		10%	5%	1%	84%
50%	50%	200%	150%	H		47%	13%	15%	25%		55%	5%	40%		96%	3%	1%		11%	4%	3%	83%
50%	200%	25%	50%	L		79%	6%	6%	9%		51%	11%	37%		82%	5%	12%		10%	6%	24%	60%
50%	200%	25%	50%	H		78%	7%	6%	9%		57%	10%	34%		81%	4%	15%		12%	5%	31%	52%
50%	200%	25%	150%	L		79%	6%	6%	9%		52%	11%	37%		79%	5%	15%		10%	7%	31%	52%
50%	200%	25%	150%	H		78%	6%	5%	10%		56%	10%	34%		83%	4%	14%		14%	6%	34%	45%
50%	200%	200%	50%	L		56%	11%	12%	21%		42%	7%	51%		95%	3%	2%		10%	5%	4%	80%
50%	200%	200%	50%	H		56%	11%	13%	20%		42%	7%	51%		95%	3%	2%		10%	5%	3%	82%
50%	200%	200%	150%	L		56%	11%	12%	21%		42%	7%	51%		95%	3%	2%		10%	5%	4%	80%
50%	200%	200%	150%	H		56%	11%	12%	21%		42%	7%	51%		95%	3%	2%		11%	5%	3%	81%
150%	50%	25%	50%	L		76%	6%	7%	11%		65%	9%	26%		95%	4%	2%		8%	5%	3%	85%
150%	50%	25%	50%	H		75%	6%	7%	12%		65%	9%	26%		94%	5%	1%		8%	5%	2%	85%
150%	50%	25%	150%	L		75%	6%	7%	12%		65%	9%	26%		93%	5%	2%		8%	6%	3%	83%
150%	50%	25%	150%	H		75%	6%	7%	12%		65%	9%	26%		93%	5%	2%		8%	5%	4%	82%
150%	50%	200%	50%	L		51%	12%	13%	24%		61%	4%	35%		98%	2%	0%		11%	2%	0%	88%
150%	50%	200%	50%	H		50%	13%	14%	24%		61%	4%	35%		96%	4%	0%		11%	2%	0%	87%
150%	50%	200%	150%	L		50%	12%	14%	24%		61%	4%	35%		97%	2%	1%		10%	2%	2%	87%
150%	50%	200%	150%	H		50%	13%	14%	24%		61%	4%	35%		96%	4%	0%		11%	2%	0%	87%
150%	200%	25%	50%	L		81%	5%	6%	9%		47%	12%	40%		93%	7%	0%		8%	8%	0%	84%
150%	200%	25%	50%	H		80%	5%	6%	9%		47%	13%	40%		93%	7%	0%		8%	8%	0%	84%
150%	200%	25%	150%	L		81%	5%	6%	9%		47%	12%	41%		93%	7%	0%		8%	8%	1%	84%
150%	200%	25%	150%	H		80%	5%	6%	9%		47%	13%	39%		93%	7%	0%		8%	7%	1%	84%
150%	200%	200%	50%	L		57%	11%	11%	21%		42%	7%	51%		97%	2%	2%		11%	6%	3%	80%
150%	200%	200%	50%	H		56%	11%	13%	20%		42%	7%	51%		96%	3%	1%		10%	5%	1%	84%
150%	200%	200%	150%	L		57%	11%	13%	20%		42%	7%	51%		97%	2%	2%		10%	4%	3%	83%
150%	200%	200%	150%	H		51%	11%	6%	32%		31%	5%	64%		96%	2%	3%		19%	2%	19%	60%

Appendix L – How to use the LORA model

Introduction

This document explains how input parameters are obtained for the Thales case and how these parameters are converted and used in an input file for the LORA model. Section 2 shortly describes what the model does. Section 3 explains what the model needs and where the Case data can be found. The actual parameters required by the model are discussed in section 4. Section 5 identifies difficulties encountered while processing the data for the Thales case.

What the model does

The model makes a decision for every component at a certain echelon level, whether it will be discarded at that echelon level, repaired at that echelon level or moved to a higher echelon level. If the option move is chosen, a decision will also be made on the next echelon level for that component and all its children.

What the model needs

The model needs appropriate input parameters to achieve valid results. The model uses a TEXT file as input. All parameters that are needed are discussed in the upcoming section. A short preview is given below the parameter name. The input file is generated with a Microsoft Excel file with the name “TNLCaseData ****.xls”. Note that all parameters must be filled. For example: if there are 16 locations than in each case parameters must be given for this all these 16 locations. Parameters cannot be omitted. In the examples used in this document some parameters are omitted, otherwise they will not fit on one line in this word document.

Parameters

#FailureName

MS
MS01
MS01AF
MS01AF03
MS01AF04
MS01AF05
……………

This parameter is used to by the model identify the different components that are subject to failure. It is important that the positions of all names are identical to the position of other parameters in the input file. Each line represents a component.

We use LSACONXB (sheet “component input”) to identify a component. REFNUMHA is not sufficient because some components are used more than once. Different decisions can be made for identical components in different locations in the product structure. The model does not accept identical names at different locations in the product structure. Each name must be unique.

Structure parts are also included. Main reason is that some structure parts need an exchange tool for exchange of components. If a component must be exchanged from its parent or structure part we link the tool that is required for the exchange to the parent or structure part. A component can require a tool for exchange and it can require a tool for repair. The repair tool is always linked to the component and the exchange tools is always linked to the parent of the component.

#LocationName

Ship1
Ship2
……..
EAST
WEST
DEPOT
OEM

This parameter identifies all locations. The last line must ALWAYS be the OEM. This data is obtained from the sheet "project input". Each line represents a location. Locations must be listed from OLM first to OEM last.

#PHII

EAST:Ship1;Ship2;Ship3;Ship4;Ship5;Ship6;Ship7
WEST:Ship8;Ship9;Ship10;Ship11;Ship12
DEPOT:EAST;WEST
OEM:DEPOT

This parameter identifies the repair network structure. The last line ends with the highest echelon level, in this case echelon 4: OEM. The first location on a line must end with ":". All subsequent parameters must be separated by ";".

#ResourceName

CAM Tester
CamAlign
Dig Tester
GI-HPA Tester
……………

This parameter represents the name of testers, exchange tools and adaptors that certain component need for a repair or exchange action. Each line represents a Test tool, exchange tool or adaptor.

#Echelon1

Ship1;Ship2;Ship3;Ship4;Ship5;Ship6;Ship7;Ship8;Ship9;Ship10;Ship11;Ship12

This parameter represents all locations at system level. In the above example there are 7 ships at EAST and 5 at WEST. All parameters must be separated by ";". Only one line has to be filled here.

#Indenture1
MS

This parameter identifies which components are at indenture 1. If the whole product structure is modelled (with structure parts), only one part will have to be listed here. If structure parts are excluded in the analysis then there are more components at indenture 1. In this case the components have to be listed like #Echelon1. All parameters must be separated by ";". Only one line has to be filled here.

#Mfl

47.4;47.4;47.4;47.4;47.4;47.4;47.4;47.4;47.4;47.4;47.4;47.4

This parameter represents the total number of failures for each system listed at #Echelon1 during the entire service duration. In our case it is the total number of failures for each ship during 15 years of service. Since all ships are identical, only one radar system per ship, all values are the same (47.4). All parameters must be separated by ";". Only one line has to be filled here.

The total number of failures per ship for the duration of the project are calculated with the formula in Section 4.4.4.2 in the report.

#GAMMAf
MS:MS01;MS02;MS03;MS07;MS10;MS19;MS20;MS21;MS22
MS01:MS01AF;MS01AG;MS01AH;MS01AI;MS01AJ;MS01AK;MS01AL;MS01AM;….
MS01AF:MS01AF03;MS01AF04;MS01AF05;MS01AF06;MS01AF08;MS01AF09;…...
………………………………………………………………………

This parameter is used to identify the product structure. The first component listed is the parent. All children within this parent are listed subsequently. LSACONXB is used to identify all parent/children relations. The first value (parent) must end with ":". All subsequent children must be separated by ";".

#Resource
CAM Tester:MS20AB;r;MS20AC;r
CamAlign:MS20;r
……………………………

This parameter identifies the relation between a component and the resource that is needed to repair (or exchange), move or discard the component. In this case component "MS20AB" and "MS20AC" need the resource "CAM Tester" for a repair action.

The first name/value of the line represents the resource. The subsequent name represents the component that needs that resource. The component's name is followed by "d", "r" or "m", which stands for discard, repair and move.

IMPORTANT: If an exchange tool is needed for the exchange of a component then the exchange tool has to be linked to the parent of the component and not to the component itself.

The resource name must end with ":". All subsequent parameters must be separated by ";".

#FCrl

900000;900000;900000;900000;900000;900000;900000;900000;900000;900000
110000;110000;110000;110000;110000;110000;110000;110000;110000;110000
550000;550000;550000;550000;550000;550000;550000;550000;550000;550000
………………………………………………………………………………………………..

This parameter identifies the cost of a resource at a certain location. Line number one refers to line number one of the parameters #Resource and #ResourceName. In this case line number one refers to CAM Tester and line number 2 to CamAlign. For each location in the repair network the costs are given. The first part of a line refers to the first location (ship1) named in #LocationName and the last part of the line refers to the last location (OEM) in #LocationName. Suppose the above example gives the costs for the locations of Ship1, Ship2, Ship3, Ship4, Ship5, Ship6, EAST, WEST, DEPOT and OEM. Costs for are the same for all locations in this example but in practice these might be different.

All costs must be separated by ";". Each line represents a fixed cost set.

#VCfld

4792.15;37.5;0;4792.15;37.5;0;4792.15;37.5;0;4792.15;37.5;0;4792.15;1881.86
3552.45;37.5;0;3552.45;37.5;0;3552.45;37.5;0;3552.45;37.5;0;3552.45;1385.98
…………………………………………………………………………………………………

This parameter is used to identify the variable costs for a discard, repair or move action of a component at a certain location. The line number represents the component listed in #FailureName. The first line represents component MS, the second line component MS01, etc. The above example does not represent actual data because MS and MS01 are structure parts that cannot be repaired or discarded. In this case the cost must be 0.

The first 3 values of a line represent the cost of discard, repair and move at location 1, in this case ship1. The next three values represent the cost of discard, repair and move for location 2 (ship2), etc. For the last location, OEM in this case, only two options remain: discard or repair. The above example could be data for ship1, ship2, EAST, DEPOT and OEM. Not all locations are listed here because they would not fit on one line in this word document. All values are separated by ";".

Variable costs are calculated on the "variable costs" sheet. Structure components must always have variable costs of 0. The action of repair is always forced for structure parts. They cannot be discarded and they cannot move.

We assumed that, if there is no TEMTBFBD, no ItemPrijs and no RepairPrijs given for a component, it has to be a structure component. All variable costs are set to 0 and the restrictions assure that can only be repaired (at every location).

Section 4.4.1 explains how the variable cost can be calculated.

#Qfg
MS:0.17;0.15;0.39;0.00073;0.062;0.022;0.15;0.013;0.022
MS01:0.43;0.20;0.20;0.022;0.015;0.015;0.015;0.028;0.028;0.028
…………………………………………………………………..

This parameter is used to identify the fraction of the time a child is responsible for failure of the parent. The set-up of this parameter is the same as #GAMMAf (product structure). Instead the parent's name is now followed by the fraction that a component is responsible for failure of the parent. All fractions behind a parent name must sum up to 1.

Because parent-child failure fractions are not given by the data that is provided by Thales LE, it is calculated with VBA on the "Sys&Cost-data" sheet (see column Z "Demand"), .Qfg is calculated by dividing a component's failure rate with its parent failure rate. After the fractions are calculated they must be placed in the same layout as #GAMMAf (grey area on sheet "failure rate").

The first value (parent) must end with ":". All subsequent fractions must be separated by ";".

#Restrictions
0;1;0;0;1;0;0;1;0;0;1;0;0;1;0;0;1;0;0;1
-99;-99;-99;-99;-99;-99;-99;-99;-99;-99;-99;-99;-99;-99;-99;-99;-99;-99;-99;-99;-99
………………………………………………………………………

This parameter is used to identify if there are any restrictions for certain components. For example some components cannot be repaired and thus only be moved or discarded at a certain location. The layout (position of values) is the same as #VCfld. The first line refers to the first component listed at #FailureName, in this case MS. The second line refers to the second component, etc. The first three values refer to the discard, repair and move option at system location 1, in this example ship1. The next three values refer to the discard, repair and move option of system location 2, in this example ship2. Note that there are only listed 7 locations in this example: ship1, ship2, ship3, EAST, WEST, DEPOT and OEM.

A value of –99 means that the model is free to choose this option. A value of 0 means that this option may not be chosen at this location. A value of 1 means the option must be chosen (if a decision has to be made at this location).

In the above example the first line represents the structure part MS. MS cannot be discarded and moved. The second line represents a component with no restrictions. All options at every location can be chosen.

In the sheet "Restrictions" we filled all restriction parameters for all components and all locations.

We assumed that, if there is no TEMTBFBD, no ItemPrijs and no RepairPrijs given for a component, it has to be a structure component.
We used "Repair level" to indicate the minimum repair location for a certain component. If the minimum repair level is "H" it can only be repaired at ILM or higher.

In the restrictions, we placed a “0” for the option repair at all locations below ILM. “L” stands for special and blocks the option repair for all locations except OEM.

Encountered difficulties

The aspects described in the section below are not directly supported in the current model of Basten et al. (2008-b). However, some sort of work-around procedure enables the model to cope with the situation. It is important to know how they can be used.

Exchange location

Basten et al. (2008-b) do not explicitly model the exchange location of components. There are situations in which the exchange action of a component requires a expensive exchange tool. There are situation where the component also needs a repair or test tool. In the case both an exchange and a repair tool are needed, the model needs to make two choices. One is related to the exchange location of the component, the second is related to the repair location of the component. Both can be different. In the current model only one decision per component can be made. The problem can be solved by linking the exchange tool to the repair action of the component’s parent instead of to the component itself.

Failure modes

Although the model of Basten et al. (2008-b) currently supports the concept of “failure modes”, it is important to known how it can be used and which additional information is needed. The previous model of Basten et al. (2008-a) assumed that, if a system fails, it is not exactly known in advance, which part of the system’s sub-assembly causes the system failure. We shall explain this concept with an example. Consider a parent component and its children A, B, C, D and E (Figure 1). The procurement cost of a new parent and the procurement costs of its children are listed in Figure 2. We assume that the summation of the procurement costs of all the children is equal to the procurement cost of the parent. We also assume that the parent fails five times a year due to the failure of a child. The probability of a failure is equal for all its children, and thus each child will fail once a year. Upon failure, a choice can be made whether the parent will be discarded or repaired. Discarding the parent will require the procurement of a new parent with the cost of € 10,000. If the parent is repaired, the faulty child will be replaced with a new procured child. In the case child (A) needs to be exchanged, an alignment action is required that costs € 2,000. For simplicity we assume that the exchange action of the other children incur no labour cost.

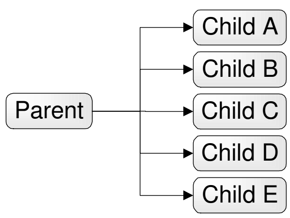


Figure 8: Parent-child example

	Labour Cost	Item Cost
Parent	€ 0	€ 10,000
Child A	€ 2,000	€ 9,000
Child B		€ 250
Child C		€ 250
Child D		€ 250
Child E		€ 250

Figure 9: Labour and procurement costs

According to Basten et al. (2008-a) the optimal solution would be to repair the parent every time it fails. The total costs of discarding, and thus procuring a new parent, are 5 x € 10,000 = € 50,000 for one year. The total costs of repairing the parent by replacing its children, assuming each child will fail once, will be € 2,000 + € 9,000 + € 250 + € 250 + € 250 + € 250 = € 12,000. It is obvious that a repair strategy for the parent is far more cost effective than procuring a new one. Now consider the situation in which it is known beforehand that child A caused the failure. Repairing the parent will cost € 11,000, but procuring a new parent will cost only € 10,000. It is now better to procure a new parent. In this case the model should make two decisions. In case of failure of child A, the parent should be discarded, and in case of failure of the other children a repair action should be adopted. However, this strategy can only be applied if the model knows in advance which child causes the system failure. In many cases this might not be known, but for some components it might always be clear in advance whether they are responsible for the system's failure or not. The model of Basten et al. (2008-b) supports this concept by using different failure modes. This can only be applied if additional data is gathered that indicates if it is known in advance that a component will be cause of the failure.

Fixed spare part cost in the LORA model

We incorporate the spare part costs that are related to a repair decision as fixed cost in the LORA model (see the report). We use a database where we store the cost of spare parts that belong to a certain decision (for example depot repair for a certain component requires 4x€1000 spare parts). If we use the spare part cost as fixed cost in the LORA model the repair probability function not work anymore. In case of unsuccessful repair, a fraction of the components is discarded and there are also (fixed) spare part cost in the database for the option of discard. The fixed spare part cost in the database for discard however, do not belong to discard of unsuccessful repair.

Problems that came up during testing of the LORA model

Problem 1: The component exchange level is not modelled. A component can be exchanged at echelon 1 and repaired at echelon 3.

Solution: If a component requires an exchange tool it must be linked to the parent. If a component uses a repair tool it must be linked to the component itself.

Problem 2: LRU units are exchanged at ILM or DLM. Now Inventri does not take the lead-time between ship and base into account. The result is that Inventri places less spare parts in the repair network because it does not use the lead-time between ship and base.

Solution: We force that an LRU is always repaired immediately (at ship).

Problem 3: When the model chooses the option of repair for a certain component, also a decision has to be made for all children. The model uses this principle also at the contractor. In case of contractor repair however, only the parent is repaired for the contractor repair price.

Solution: We added an option to the LORA program in Delphi. When the option of repair is chosen at OEM, no decision has to be made for its children.

Problem 4: When the model uses the option of repair at OEM, it also procures the test equipment that is needed to repair the components. In practice the customer does not procure test equipment at the OEM, but only pays a repair price.

Solution: We set the procurement price of test equipment at the contractor at 0. Now the model can chose to procure test equipment but it cost no money.

Problem 5: There are cases in which, for example, the costs of repair at ship are equivalent to the costs of repair at base. The model is free to choose for every component on every ship, whether to repair at ship or at ILM due to the same cost constraint. Due to modelling techniques, in practice the model does not make the same decision for every ship. It looks like the model makes a random decision.

Solution: The option "fix incorrect one's" in the LORA program solves this problem. It converts all variables, which are 0 to a very small number like 0.00000001. In the case a move option has the costs of zero, the model was free tot choose. Now it will not move the component because of costs of 0.00000001.

Problem 6: Some components, in the Case data excel sheet, did not have a TEMTBFBD but they did have a repair time.

Solution: We considered these components as structure parts.

Problem 7: Repair probabilities do not work when spare parts are included in model as fixed cost. Consider the situation in which a component is repaired at depot with a repair probability of 95%. In 5% of the cases components will be discarded. The choice to discard 5% of the components requires that the fixed spare part costs that are related to the option of discard must be paid in the model. This is not correct.

*Solution: We solve this problem by using the no fault found option instead of the repair probability option. Consider a component with a repair probability of 95%, variable discard cost of €10.000 and variable repair cost of €4.000. We change the situation to a repair probability of 100%, variable repair cost of 95% * €4.000 + 5% * €10.000 and a no fault found probability of 5%. If the model chooses discard in the old situation, no decisions has to be made for the children. By using the no fault* *found probability we account for this effect. Now in 5% of the cases the model uses the no fault found concept. In the case of no fault found, the component is returned to stock in an as-good-as-new state. We account full repair cost in this situation but the children of the component do not need a repair action.*