Tactical Decisions to Improve Service Contract Performance

May 2010

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S0093270

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TACTICAL DECISIONS TO IMPROVE SERVICE CONTRACT PERFORMANCE

A CASE STUDY AT THALES NETHERLANDS

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Thesis submitted in partial fulfilment for the degree of Master of Science in Industrial Engineering and Management, Production and Logistics Management

MAY 2010

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Preface

This Master of Science thesis is the result of my graduation period at Thales Netherlands in Hengelo at the department Logistic Engineering. The research has been conducted during the period August (2009) and May (2010).

I am very thankful to Thales Netherlands for giving me the opportunity to graduate for my master study Industrial Engineering and Management with specialisation Production and Logistics Management at the faculty Management & Governance of the University Twente in Enschede. I would like to use this opportunity to thank the following people.

First, I especially thank my daily supervisor at Thales Netherlands, Rindert Ypma. He made this assignment possible and he freed enormous amounts of time to help me with this research. Besides, I thank Ivo Schukkink. I thank both Rindert and Ivo for their knowledge, practical insights, and suggestions that were of great value to me. Next, I am grateful to my colleagues at the Logistic Engineering department for providing a pleasant working atmosphere in which I could perform this research.

Second, I thank my supervisors from the University of Twente. Matthieu van der Heijden, Marco Schutten, and Elisa Alvarez freed lots of time, provided steady supervision, and gave extensive feedback on the draft versions as well as the research in general.

Finally, I thank my girlfriend, parents, brothers, and friends. I appreciate that they listened to the stories about my graduation project.

Looking back at my graduation period, I consider it as a pleasant and valuable experience and recommend other students looking for an internship or graduation period to apply for at Thales Netherlands.

Maurice van Zwam
Enschede, May 2010

Management Summary

Thales Netherlands is the Thales Group's Naval Centre for radar and combat management systems and is the largest defence company in the Netherlands. A growing trend to closer working relationships with the customer are performance-based contracts. For these kinds of contracts, Thales takes over all services for fixed costs. Thales will then manage the customer's service and supply chain and the spare part stocks. The key performance indicator is the average system supply availability over a certain time period. The supply availability is the time the system is up divided by the total system's operating time (uptime + downtime). The downtime of a radar system is measured as the time the system is waiting for a spare part.

During a standing contract, it is possible that the attained system availability is lower than required and Thales may get a penalty. Due to the variation in the average availability, it is possible that Thales gets high bonuses and penalties. Besides this, operating hours of the ships vary and there may be more or less failures than expected (this affects the average availability). Estimating the results (bonuses and penalties) of a contract may become difficult and may have a large impact on the customer's service perception. Currently, Thales increases the availability only by stocking extra spares. Since this is expensive, Thales wants to know which other tactical decisions there are that may increase the system performance.

The goal of this research is to get insights into the impact of different tactical decisions on the system performance (availability and its variability). We focus on logistic parameters, which are stocking spare parts, repair throughput times, and order-and-ship times. With the goal in mind, we formulate the main research question as: "*How can Thales use tactical decisions to improve the service contract performance at low costs, focusing on extra spare parts, decreasing order-and-ship times, and lowering mean repair throughput times?*"

It is possible that the original stock allocation is not optimal anymore since the demand or time parameters may have changed. The spare part allocation is optimally calculated using the spare part inventory tool "INVENTRI". This tool is based on the Multi-Echelon Technique for Recoverable Inventory Control (METRIC). The multi-echelon, multi-indenture optimisation gives an optimal trade-off curve between spare part investment and average supply availability, in which maximising the average supply availability is seen as minimising the expected ship backorders.

The impact of a tactical decision for an item is calculated as the expected ship backorder reduction per invested euro per year. We implemented the effects of the tactical decisions for an item in Excel. To improve the average availability, we defined three different greedy heuristics. The first heuristic looks at all items in the system and takes each time a tactical decision for a specific item, the second mainly focuses on availability killers, and the third takes each time the same tactical decision for all items together in the system. The third heuristic will never be optimal, since decisions are taken for items for which no backorder reductions may be attained. We use this heuristic only to see the impact of tactical decisions in general.

In our case study we focus on a 3-echelon, 2-indenture supply network with six ships, one shore location, and one supplier (Thales). We used the heuristics to see whether the average availability, the variability, initial investments, and the robustness to changing annual

operating hours (AOH) can be improved with less costs than only stocking spare parts (INVENTRI solution). Based on the results, we draw the following conclusions:

(1) ***"Heuristic one (tactical decisions over all LRUs) results in the lowest costs."*** Using the first heuristic in the optimisation method results in the lowest annual costs, but the second heuristic leads to less tactical decisions for less items and has only slightly larger annual costs (6.3% versus 5.6% compared to INVENTRI).

(2) ***"A combination of reducing time parameters and stocking extra spare parts leads to lower costs, a better variability, and a better robustness to changing AOH than only stocking spare parts."*** Using the developed heuristics results in lower costs than the INVENTRI solution (only stocking spare parts).

(3) ***"Lowering the gross mean repair throughput time at Thales is the best option to improve service contract performance."*** Lowering gross repair throughput times has the largest impact on all aspects we looked at.

(4) ***"Including subcomponents of expensive items with a high failure rate in the spare part allocation optimisation results in large savings in initial investments."*** In our case, a reduction of 35 percent (€960,000) may be attained when subcomponents of the most expensive item (with the highest failure rate) are included in the spare part optimisation.

(5) ***"Using a buffer in the net repair throughput time is disputable."*** Since it seems that in the different processes of the net repair throughput time a buffer is used already, it is disputable whether including an extra buffer of two weeks is necessary.

Finally, we give the following four most important recommendations for Thales to improve the service contract performance:

(1) ***"Consider reductions in time parameters besides stocking spare parts."*** Compared to stocking extra spare parts, using a combination of reducing time parameters and stocking extra spares is more cost effective, decreases the variability more than proportional, and make the system more robust to changes in annual operating hours.

(2) ***"Analyse the impact of a tactical decision with the second heuristic."*** Using the developed heuristics results in lower costs than the INVENTRI solution. Although the first heuristic results in the lowest costs, we recommend the second heuristic since this requires less tactical decisions and it is less difficult to use in practice.

(3) ***"Better control the repair transaction process."*** We showed that lowering the gross repair throughput times at Thales is the best option to improve the system performance. To catch up with variation in the different processes, a two-week buffer is used. However, decreasing the buffer already improves the performance and it has no extra costs.

(4) ***"Always include subcomponents of expensive items with a high failure rate in the spare part allocation optimisation."*** In this case, including subcomponents of only one item of this kind, results in a 35 percent reduction in the initial investment. When subcomponents are cheap, place plenty of them on stock and the gross repair throughput time can be reduced with the average waiting time for those subcomponents.

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1. Business Description of Thales Netherlands

To get an overall picture of Thales Netherlands, we describe the history of Thales Netherlands in Section 1.1 and the organizations of Thales Group and Thales Netherlands in Section 1.2. To understand the logistic area in which we conduct this research, we elaborate in Section 1.3 on the activities of the Business Unit Naval Services and the department Logistic Engineering and we discuss some trends and developments Thales has to deal with in Section 1.4.

1.1. History

The history of Thales Netherlands started in 1922 by the establishment of “N.V. Hazemeyers fabriek van Signaalapparaten” in Hengelo (the Netherlands). Hazemeyer started to produce fire control equipment and became one of the world’s leading suppliers of naval surface systems and a first-tier contractor to the Royal Netherlands Navy. By time, the company grew and customers from Sweden, Spain, and Greece were welcomed. After World War II, the factory was plundered and deserted. However, the Dutch government bought the company, because they knew that having a good defence industry was important, especially after World War II. After this, the company got the new name “Hollandse Signaalapparaten B.V.”. A lot of techniques and systems were developed in these years, for example the radar, fire control systems for the army, and air traffic equipment.

In 1956, Philips became the main shareholder, because it bought a large part of the shares. The business was growing well and led to the opening of other plants in Eindhoven, Huizen, and Delft. Hengelo remained the main office. At the end of 1980, there were more than 5000 employees, and customers were served in more than 35 countries. The end of the Cold War had a big negative impact on Hollandse Signaalapparaten B.V., because major cuts in defence budgets were made. At the same time, it was decided that “Defence and Control systems” were not part of Philips’ core business. Hollandse Signaalapparaten B.V. was therefore taken over by the French company Thomson-CSF in 1990 and in the year 2000 the name of Thomson-CSF was changed to Thales. As a result of this, the name of Hollandse Signaalapparaten B.V. was changed to Thales Netherlands B.V. [Annual report, 2008] [Thales, 2009].

1.2. Organisation

The Thales Group is a world leader for mission-critical information systems. The Thales group consists of three core businesses: Aerospace & Space, Defence, and Security. These businesses consist of six divisions: Aerospace, Space, Air Systems, Land & Joint Systems, Naval, and Security Solutions & Services. Together the annual revenues are about 12.7 billion Euros of which about 18 percent is invested in Research and Development. Research is of vital importance for Thales and therefore it cooperates closely with universities from Twente, Delft, Amsterdam, and also with the association for radar development in the Netherlands. The Thales Group consists of 68,000 employees in 50 countries of which 2,000 employees work in the Netherlands. [Annual report, 2008][Thales, 2009].

Thales Netherlands is the Thales Group’s Naval Centre for radar and combat management systems and is the largest defence company in the Netherlands. Customers of Thales are publicly owned defence companies (such as the Royal Dutch Navy). The products that are developed, produced, and supplied by Thales Netherlands are divided in the categories Naval, Land & Joint Systems, Air systems, and Transport Security. The revenues of Thales

Netherlands were about 306 million Euros in 2008. Thales Naval Nederland, as part of Thales Nederland, wants to be "a major contributor to the success and development of its customers and employees, and to the leading position of Thales in the areas of combat-, radar-, and sensor systems as well as industrial and logistic services." [Annual report, 2008][Thales, 2009]

Thales is divided into five business units. Four business units refer to the product categories and the other is the business unit Services. This research concerns the business unit Naval Services, department Logistic Engineering. In Section 1.3, we discuss the main tasks of Naval Services and Logistics Engineering.

1.3. Naval Services and Logistic Engineering

Customers require support (from their supplier, Thales) after the regular guarantee period, since radar systems have a lifetime of more than twenty years. However, lack of knowledge, resources, or budget leads to the outsourcing of this after-sales support to Thales. Within the Thales Naval division, the business unit Naval Services delivers after-sales support for the radar systems to assist the customers to keep their systems up and running. More than 85 customers, spread over 42 countries, are served by Naval Services. The core services consist of delivering spare parts and carrying out repairs. Besides this, overhaul, upgrade programs, and modifications are offered to the customers, as well as documentation and training. Naval Services allows the customer to use, modify, and maintain the radar systems by delivering the information, resources, training, and support needed during the whole lifecycle of the system. It differs per customer whether they require only initial logistic support or trough life support. [Annual report, 2008] [Intranet, 2009]

The Logistic Engineering department plays a key role in the processes of Naval Services. One of the activities of Logistic Engineering is to conduct logistic support analysis to determine what logistic support is needed for a system. During the design of the system, they watch over the related supportability costs. Other activities are designing service concepts for specific customers and systems, supporting technical authors with system knowledge, performing life cycle cost analysis, and calculating optimal allocation of spare parts by taking costs and system availability into account. [Intranet, 2009]

1.4. Trends and Developments

Thales faces lots of technical developments, such as increasing technical system complexity (and shorter technology lifecycle) and more commercial of the shelf items, which leads to increasing obsolescence. Other technical developments are increasing design for maintainability (modular design) and the decreasing need of maintenance for systems. Customer developments are that they have an installed base that is getting smaller, they cannot afford their own maintenance facilities (due to increasing technical complexity), they do not consider maintenance anymore as a core competence, they select systems on basis of life cycle costs, and, in an increasing degree, they are open for cooperation with industrial companies. The Logistic Engineering department tries to deal with all these technical and customer based developments. Performance-based contracts (long-term service agreements) are a growing trend towards closer working relationships between Thales and the customers. Thales Naval sees this as an opportunity to create more revenues. Besides performance-based contracts, Thales Naval Services offers total through-life support contracts in order to reduce overhead costs further. [CLS2, 2009] [Rustenburg, 2008]

2. Research Design

In order to understand the context in which we perform our research, we will give a short introduction in Section 2.1 about the long term service contracts that Thales offers to their customers, the structure of the product under consideration (radar systems), and how Thales' repair network is organized. In Section 2.2 we further motivate why this research is of interest for Thales Netherlands, and in Section 2.3, we define the problem we focus on. This leads to the research objective and research questions in Section 2.4. We end this chapter in Section 2.5 with the research methodology and outline of this thesis.

2.1. Context Description

2.1.1. Long Term Service Agreements

Thales has to deal with lot of technical and customer developments. One of the developments is the closer working relationship between Thales and the customers. Performance-based contracts are a growing trend towards these closer working relationships. Instead of offering separate services (see Section 1.3), Naval Services can take over all services at a fixed fee. This leads to predictable and possibly lower costs for the customer, because Thales then defines the optimal support strategy and has more system knowledge than the customer. In this case a certain performance is settled in a long-term service agreement, which covers a period of 5 to 25 years. The vision of Thales Netherlands for long-term service agreements is being "*a visible and reliable partner in 'Contracting for Support and Availability' in a customer focused environment*" [Annual report, 2008]. The key performance indicator is the system *(operational) availability*. Operational availability is the time a radar system is up divided by the total system's operating time (uptime + downtime). According to Sherbrooke (2004) operational availability is commonly expressed as:

$$Operational\ Availability = \frac{Uptime}{Downtime} = \frac{MTBM}{MTBM + MDT} \cdot 100\%$$

Increasing the mean time between maintenance (MTBM) or decreasing the mean down time (MDT) increases the system operational availability. The MDT consists of mean preventive maintenance time (MPMT), mean corrective maintenance time (MCMT), and mean supply delay (MSD). Thales however, means with downtime the time the radar system is waiting for a spare part. This is only the mean supply delay. Sherbrooke defines this kind of availability as *supply availability*. Supply availability depends on the stocking policy and is expressed as:

$$Supply\ Availability = \frac{MTBM}{MTBM + MSD} \cdot 100\%$$

When we say availability in this thesis, we refer to supply availability. Thales gets paid a fixed fee on a monthly basis and gets, depending on the contract, a penalty or bonus that depends on this supply availability. The length of the interval in which the availability is measured is agreed upon in the contract. Usually this is one year. To understand how Thales complies with the contract agreements with respect to stocking policies (where spare parts inventory is located and repairs are done), we elaborate on the product and repair network at Thales in Sections 2.1.2 and 2.1.3.

2.1.2. Product Network

Radar systems have a modular design. This means that a radar system is built of several sub-systems, which all consist of different modular units (multi-indenture structure, see Figure 2.1). A radar system may have six or more indenture levels. Line Replaceable Units (LRUs) are complex items that are designed to be replaced quickly. LRUs are repaired by replacement. LRUs consist of different shop Replaceable Units (SRUs), which in their turn consist of different parts. A failure of one of these SRUs (or parts) will lead to a failure of the LRU and leads, depending on the item criticality, to downtime of the whole radar system. SRUs and LRUs are in most cases expensive parts and may fail during missions when the system is operating.

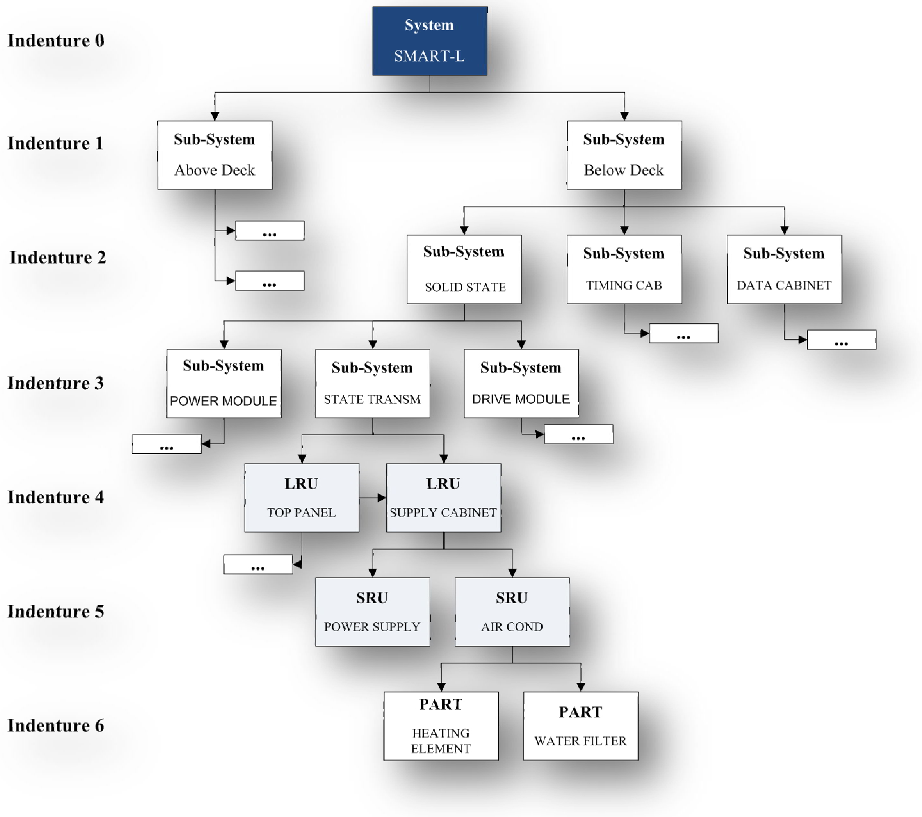

Figure 2.1: Partial Multi-Indenture Structure of a Radar System

2.1.3. Repair Network

A radar system needs to be maintained in order to keep the system operational. When an item in the system fails, it has to be repaired. This repair is called corrective maintenance. The operational repair and supply (distribution) process starts with the demand for an item at a location due to the failure of that item in the (radar) system and the system being down (unavailable). A spare item immediately replaces the failed item or the demand is backordered. The failed item is taken out of the system and is brought to a repair facility (onboard, onshore, or at Thales). If the failed item cannot be repaired at a base (ship), the part is sent upstream to a higher echelon location (shore organisation) and a replenishment order is generated for a ready-to-use item. If that location has a spare item on hand, that part is directly sent to the base and will be put into the radar and the radar is operational again. Otherwise the demand is backordered and is satisfied when a part becomes available from the repair shop at Thales. The latter backordered demand is satisfied using a First Come First Serve policy at Thales. The situation described assumes that all inventory locations use a one-for-one replenishment (s-1, s) policy. [Rustenburg, 2000] [Verrijdt, 1997]

The availability of the system is important to the customer, most of the times this has to be around 90 or 95 percent of the total operating hours of the system. Components may be repaired onboard, onshore, at Thales, or even further upstream in the supply network. This kind of repair network is called a multi-echelon network (see Figure 2.2). It consists of different supply, stock, and repair locations. Supply locations (suppliers) supply Thales with new items, where supply and stock locations can be located everywhere in the service network. The goal of Thales is to minimize the costs related to repairs and spare parts. Choices have to be made whether to repair or discard an item (lead times for procurement of new items are longer than repair times), where to repair a failed item (there are lead times between the echelon levels), and how to allocate spare parts optimally.

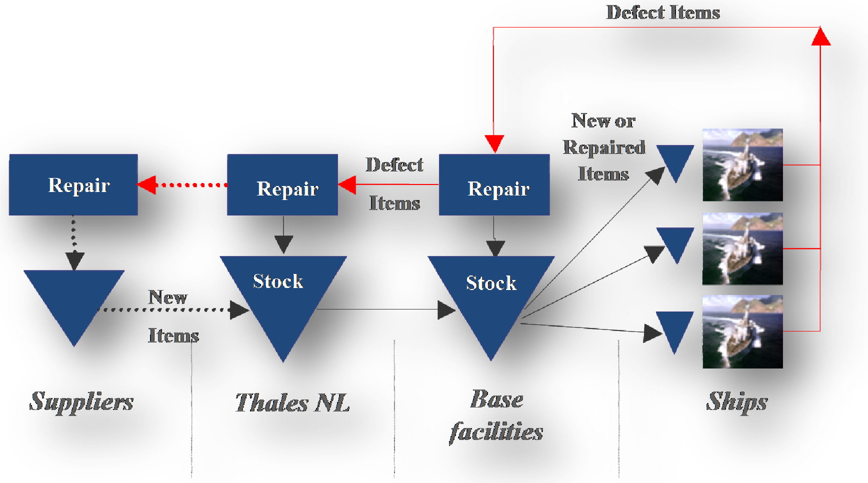

Figure 2.2: Multi-Echelon Supply Network

Level of Repair Analysis (LORA) determines whether to repair an item and where to repair that item. This depends on variable costs (such as manpower, spare part acquisition and holding, transportation, and repair) and fixed costs (such as test and maintenance equipment and technical documentation) [Basten, 2009]. Based on the beforehand-calculated LORA solution, Thales' spare part inventory tool "INVENTRI" determines the spare part allocation (see Section 3.4.4). These calculations are based on the VARI-METRIC theory (see Section 4.5).

2.2. Research Motivation

A problem with the availability driven contracts is that Thales has to estimate the contract cost before the start of the contract. The estimated costs depend on the expected amount of failures and the interest rate. The expected amount of failures, and therefore the demand, is not accurately known. Also in practice the annual operating hours of the ships vary, which results in more or less failures than expected. This leads to difficulties in estimating the contract costs, but it also affects the average availability during a standing contract. All these things may impact the service perception of the customer.

A same kind of problem occurs with multiple contracts and when ships operate independently of each other. When ships are sent together on mission at the same time, this will lead to a high demand for spare parts that period. However, when they are not sent on mission at the same time, the demand over the year will be more stable. Also the repair throughput times are not accurately known, and estimated values are used in current spare part allocation calculations. There is not enough insight yet what the effect is on system availability when investing in reducing these repair throughput times.

During a standing contract, it is possible that the attained system supply availability is lower than required. Thales gets a penalty when the system availability is lower than agreed upon. The main reasons for this are that there are too few spare parts on-hand, the spare part allocation is not good, or more failures occurred than expected. This leads to long system downtimes and results in low system availability. Thales wants to know which other tactical decisions there are to increase the system availability and reduce the expected variability of the availability than only investing in extra spare parts during the runtime of the contract.

The higher the variability of the system availability, the higher the bonuses and the penalties will be. This leads to difficulties in estimating the results (bonuses and penalties) of a contract and may have a large impact on the service perception of the customer. The variability of the attained availability decreases as the length of the time interval in which the availability is measured increases, decreases as the number of systems in the service contract increases (due to the "risk pooling" effect), and decreases as the average availability increases [Coenen, 2009]. The variability of availability decreases as the interval length increases, because the larger the interval length the more the effects of very high (100 percent) or very low (0 percent) availabilities average out.

2.3. Problem Statement

We focus on the trade-off between different tactical decisions (extra investments) to increase the average system availability and decrease the system availability variability under currently running availability-based contracts, with the aim of fulfilling the requirements of the service contracts. The following *tactical decisions* in the supply chain are possible:

- *A spares inventory on-board and onshore* to cover the demand during the repair or replenishment of a part. The time required to re-supply/repair can then become larger without impacting availability to a large extent.
- *A spares inventory at a central location (Thales)*, which reduces lead-times and repair throughput times. This reduces the number of required spare parts onboard and onshore.
- *A reduction of return times* of failed items from various locations (upstream).
- *A reduction of repair throughput times* (for certain repairable parts at a location).
- *A reduction of order-and-ship times* of parts at certain locations (downstream).

We have to keep in mind that when investing in a central location inventory the availability of all ships are influenced, whereas investing in onboard inventory only influences the concerned ship. Furthermore, the number of different components among the central location stock is larger than amongst the onboard spares.

The return times of failed items to an upstream location are included in the repair throughput times. Return times are dependent on the policy of the customer, because they can wait to send the item to shore (to repair it) until the ship is back from a mission. The failed item may also be sent directly after its failure back to shore (by helicopter). Since it depends on how many spare parts are on stock of the item, the criticality of the item and the policy of the customer, we will not further analyse and not focus our research on return times of failed items.

Order-and-ship times are in most cases negotiated by Thales and the customer, and play in absolute values a minor part compared to repair throughput times (days versus months). However, risk-pooling effects can be realized with very short order-and-ship times, because more spare parts are therefore placed at a higher echelon location. We will check whether the influence of these times on system availability is significant or not.

Other factors that may influence system availability are the demand, the probability that the failure of an LRU at a location is caused by a failure of an SRU, and the probability that an item can be repaired at a location. We will not focus on these three factors, because research about the design of the product has to be done then or a LORA analysis is needed.

In this research we will only focus on extra investments that decrease repair throughput times, decrease order-and-ship times, and investments in extra spare parts onboard and onshore. The performance indicator we will look at is the average system availability over a year and its variability.

2.4. Research Objective

The goal of this research is to get insights into the impact of tactical decisions on the system performance (availability and its variability). Using a case study and a structural approach, we will investigate the influences on the average system availability and the variability when investing in extra spare parts, reducing order-and-ship times, and lowering the mean repair throughput times at Thales. The main assumption of this research is that we will look at a contract that is already in its operating phase. During its operating phase, the initial spare part allocation has already been calculated and spare parts are already on stock. Due to practicability, we will not reallocate the current spare parts but only look at possible extra investments (tactical decisions). However, it still is interesting to see whether the spare part investment can be reduced when the tactical decisions are implemented before the spare part optimisation. Also, in practice the annual operating hours of the ships vary. Thales would therefore also like to know to what extent the tactical decisions make the system more robust to changes in annual operating hours. With the goal in mind we formulate the main research question as follows:

> *“How can Thales use tactical decisions to improve the service contract performance at low costs, focusing on extra spare parts, decreasing order-and-ship times, and lowering mean repair throughput times?”*

Optimal spare part allocations are calculated with Thales’ spare part inventory tool “INVENTRI”. This tool uses the VARI-METRIC approach and therefore we perform a literature research about this approach. We will answer the main research question by answering the following set of questions:

1. *What long-term service agreements are made at Thales, and how does Thales currently manage these service contracts?*
2. *What literature about service contracts and the VARI-METRIC approach is applicable, and how do different parameters influence system performance?*
3. *How can we determine the impact of the tactical decisions on the average availability?*
4. *In which general way can we determine which tactical decisions Thales needs to take?*
5. *What is the impact of the tactical decisions on the average availability, the variability, initial investments, and the robustness to changing annual operating hours, and what general conclusions can be drawn?*

2.5. Methodology and Outline of Thesis

In order to get a better understanding about the service contracts Thales offers to its customers so far, we will analyse the different service contracts in *Chapter 3*. Since we focus on performance-based contracts, we elaborate on how these service contracts are established, the content of those contracts, and how Thales tries to comply with contractual agreements by logistic services. Finally, we will have to get a thorough understanding of Thales' spare part inventory tool "INVENTRI". We will use INVENTRI to calculate the optimal spare part allocations for our case study. This will lead to an answer on our first research question.

In *Chapter 4*, we will perform a literature review about service contracts in general. Since INVENTRI is based on the VARI-METRIC theory, we will also perform a literature review of the theories and concepts used in this logistic area. Based on the METRIC and VARI-METRIC approach, we try to understand how and in which way different parameters influence the supply availability. This will lead to an answer on our second research question.

The tactical decisions that can be taken at Thales will be based on Chapters 3 and 4. In *Chapter 5* we will calculate the impact of each tactical decision for a certain LRU on the average supply availability. To compare the impact of the different decisions, we will calculate the influence per invested euro per year. To determine the costs per year, general cost models will be made. This leads to an answer on our third research question.

To determine which tactical decision Thales needs to take for a certain contract, we will develop a tool in Excel that calculates all needed information (based on the results from Chapter 5) and supports the decision making process. In *Chapter 6*, we will elaborate on greedy heuristics which determine which tactical decisions should be taken for a certain performance-based contract. This leads to an answer on the fourth research question.

In *Chapter 7*, we test the heuristics of Chapter 6 on a case study and answer our fifth research question. In cooperation with Thales we choose a case and calculate the spare part allocation with INVENTRI for a certain target availability level. Different databases give us insights in the time parameters and the costs of reducing them.

We are also interested in the variability of the average availability. However, the (VARI-) METRIC method calculates only the average system supply availability under steady state situations and does not deal with variability in availability. Coenen (2009) developed a discrete event simulation model, where he analysed the impact of service level variability on service contract violation. Because of the system complexity at Thales and because we are not able to analytically calculate the variability in the availability, we will use this simulation model. Discrete event modelling concerns the modelling of a system as it evolves over time by representation in which the state variables change (a discrete event occurs) instantaneously at separate points in time [Law&Kelton, 2007] [Simulation, 2008]. We will also use this model to analyse to what extent the tactical decisions make the system more robust to changing annual operating hours. Next to this, we investigate (with INVENTRI) the costs savings in the initial investment that can be made when taking a tactical decision and optimise the spare part allocation afterwards.

This thesis ends with *Chapter 8*, in which we give conclusions, recommendations, research limitations, and aspects that are of interest for further investigation.

3. Service Contracts at Thales

In this chapter, we answer the first research question: "What long-term service agreements are made at Thales, and how does Thales currently manage these service contracts?" To this end, we start in Section 3.1 with an introduction about the definition of long-term service agreements at Thales. We elaborate on the different service contracts Thales offers in Section 3.2. In Sections 3.3 and 3.4 we describe the contract content and the way Thales tries to comply with contract agreements by logistic services. This chapter ends with conclusions in Section 3.5.

3.1. Introduction

Long-term service agreements (LTSA) are defined as: "*An agreement between a service provider and a customer on a (partial) take-over of management, execution and/or the ownership of the service logistics chain of the customer, required to upkeep systems*" [Buijs & Jongebloed, 2008]. At Thales, Long Term Service Agreements are also called Contractor Logistics Support (CLS) contracts. Contractor Logistics Support can be defined as: "*The portion of Operational Logistics Support provided by civilian (non-military) organizations or entities*". [Buijs & Jongebloed, 2008][CLS, 2009]

The way finances are organized at the customers influences the decision to sign a LTSA contract or not. Customers of Thales are publicly owned defence companies and have yearly fixed budgets. When doing their own maintenance and there is no budget left, the system will be down until there is new budget again. LTSA contracts have fixed monthly costs and Thales takes the risks of repair. Also part of the LTSA contract is that the customer does not have to worry about training people in how to find possible problems in the system and how to repair them.

3.2. After-Sales Service Contracts

Thales distinguishes four levels of LTSA contracts: the *traditional* after-sales support, the *spares inclusive* contract, the *contract for availability*, and the *contract for capability*. Each level is an extension of the previous level. The contract for capability however, is currently not offered, but will be done in near future.

- *<u>Traditional after-sales contract</u>*: In the *traditional* after-sales LTSA contract (Repair contract), Thales takes care of the repairs, re-supply of spares, and technical assistance. The customer agrees upon a certain repair throughput time with Thales.
- *<u>Spares Inclusive Contract:</u>* In the *spares inclusive* contract (Repair and Supply contract), including after-sales support, Thales guarantees a certain repair throughput time or a certain availability of LRUs or keeps a stock of LRUs and repairable parts.
- *<u>Contract for Availability:</u>* In the *contract for (system) availability* (Full Support contract), Thales guarantees a certain level of system supply availability and costs. Thereby they take over the service and supply chain of the customer (i.e. management tasks, preventive and corrective maintenance, repair of defective items, supply chain management, and other support tasks) and they manage the spare part stocks over the complete supply chain.
- *<u>Contract for Capability:</u>* At the highest level of LTSA contracts, there is the *contract for capability*. Here the customer pays for the services used and the equipment is leased, in which Thales (the manufacturer) remains the owner of the system. However,

this is a plan for the long term; neither the market nor Thales is ready yet for such contracts.
[CLS 2009][CLS2, 2009][Buijs & Jongebloed, 2008][Buijs, 2009][INVENTRI, 2009]

Our research focusses on increasing system supply availability (and reducing its variability) during standing LTSA contracts. We therefore focus on performance-based contracts (Contracts for Availability). These contracts include the guarantee of spare part availability, contractual commitments on repair throughput times, and guarantee of overall system supply availability for a fixed price per month (where penalties and bonuses are given that depend on system performance). These service contracts are also called the "*Full Support option*", where Thales is responsible for the repairs and spare part stocks in the supply chain (see Figure 3.1). Thales Naval Services has only established two availability-based contracts so far and one is still in the quotation phase. In Sections 3.3 and 3.4, we will elaborate on the content of these kinds of contracts and how Thales tries to comply with the contractual agreements by logistics services. [INVENTRI, 2009]

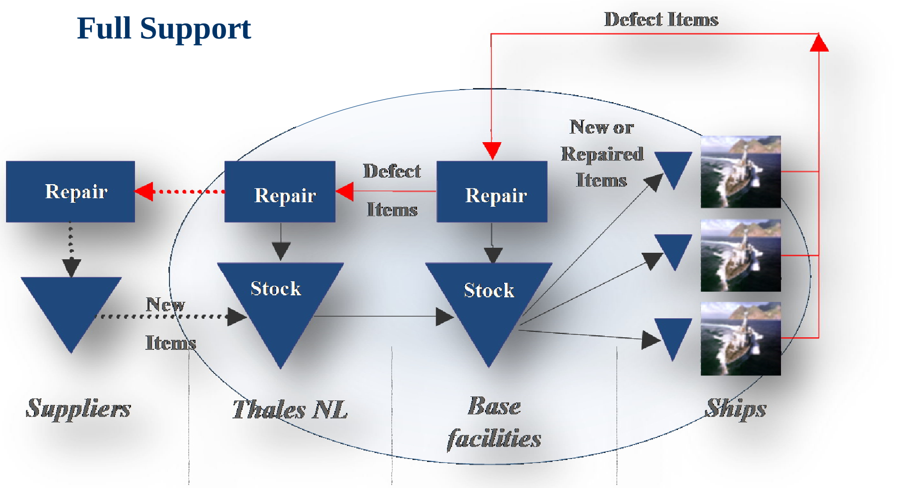

Figure 3.1: Service Part Supply System: Full-Support Option [INVENTRI, 2009]

3.3. Content of Contract for Availability

When a customer wants to buy a Thales product or the warranty period of a Thales product has expired, a LTSA contract will be established. A contract can vary in scope and duration. LTSA contracts are established for a period of 5 to 25 years, where the costs of the contract are interrelated with the duration. During long-term contracts, parameters (such as failure rates, demand, item characteristics, and repair times) can change, which leads to risks. These risk types are contract related risks (the customers requires more than agreed upon), system risks (e.g. low availability), maintenance risks (more assistance needed), supply risks (throughput times are larger than expected), and resources/skills/knowledge risks. Thales asks high contractual costs in order to deal with these risks. They also have to increase those costs when the customer asks for more service. However, no customer wants to pay high costs only to reduce the risks Thales takes by offering LTSA contracts. Short-term contracts (duration of about 5 years) including an intention statement to continue the participation can solve this problem. After a few years, negations are held for a new contract under possible new conditions. This leads to more accurate cost estimates and therefore to lower costs for the customer. [Buijs & Jongebloed, 2008] [Buijs, 2009] [CLS2, 2009]

Based on the currently running availability-based contracts and the contract that is still in the quotation phase at Thales, the following agreements are made in a Contract for Availability:

- The service type, price, and duration of the contract (including intention statement)
- Guarantee (responsibilities, terms and conditions)
- Performance Indicators
- Penalties and Bonuses

The first agreements made in contracts at Thales are the service duration, the guarantee duration and conditions, the purchase price of the system, and the fixed monthly costs that have to be paid for the services. When the system becomes operational, Thales is responsible for the costs of all defaults and defects of the system for a certain guarantee period. After this period the service contract will run and Thales gets paid a fixed fee per month to maintain the systems and keep them operational for a certain availability level. Penalties and bonuses reflect the customer's perception of having more or less downtime than required. The actual system availability on each ship is measured over a specific time interval, of which the length is negotiated and set in the contract. Measuring the total downtime (by onboard crew) during an interval length, and knowing the total operation hours of the system (total mission time of a ship), the system availability is calculated. If the average system availability in an interval is above the required level, a bonus is awarded, whereas a penalty is given when the average availability in an interval is below the requirement.

Bonuses and penalties are expressed as a percentage of the contract value. The total percentage in penalties or bonuses over the full duration of the contract cannot exceed a certain percentage level (there may for example be a maximum of 30 percent of the contract value). For example, when the required average system availability is set as 90 percent, Thales gets a maximum bonus of two percent when the average system availability is 98 percent or more, and gets a maximum penalty of two percent when the average system availability is less than 75 percent.

In the service contract, a required availability level is set. Thales distinguishes Key User Requirements, Key Performance Measurements, and Performance Indicators. Appendix A displays this in a framework. The Key User Requirement is that a certain supply availability level is achieved. This is defined as the Key Performance Indicator "*system availability on ship*" [Buijs, 2009]. The logistic support Thales offers is broken down into performance indicators for several services. Four of them are standard contractual agreements. The others are possible services and extensions the customer is free to choose. Figure 3.2 displays the contractual agreements. The performance indicators must be clear to avoid discussions afterwards.

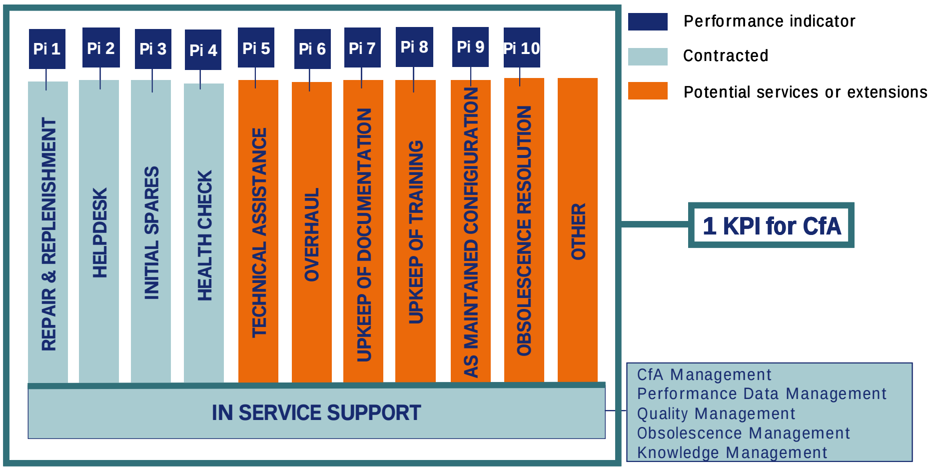

Figure 3.2: Contract for Availability Performance Indicators [Buijs, 2009]

Standard Contractual Agreements

Initial Spare Part Package: Standard agreements in the contract are made about the initial spare part package that is calculated for a certain budget the customer has or for a certain availability level. The spare part allocation is calculated with the spare part tool “INVENTRI” (see Section 3.4.4).

Repair and Replenishment Agreements: An important performance indicator here is the mean repair throughput time. For long-term service contracts, repairing or replacing parts within a certain timeframe is a must. Thales has to deliver or repair critical parts. When a product cannot be repaired anymore for an amount of money less than a certain percentage of the original product price (that is agreed upon with the customer) it is called “Beyond Economical Repair”. The goal of the repair process is to repair items from customers in a controlled way. When the customer asks for maintenance or (fast / normal) repair of a product, the commercial person in charge at Thales gives the approval for the repair, and whether it will be a normal or a fast repair. For *normal repairs* there are no contractual agreements made between Thales and the customer and the items first have to be inspected (in general the costs of a normal repair are 20 percent of the original item price). After the approval of the customer, Thales can start to repair the item. For *fast repairs* contractual cost agreements between Thales and the customer are made, based on assumptions and historical data. In this way it is possible to start to repair items directly (in general the costs of a fast repair are 40 percent of the original item price). Because fast repairs also get priority in the repair process, this process is faster than normal repairs. Because the costs are set beforehand in the contract, the customer does not have to approve the repair cost calculation (no negotiations are needed) each time a failed item arrives at Thales. The repair department’s target for normal repairs is that the mean repair throughput time must be less than 150 days and for fast repairs less than 30 days. Besides this, the delivery reliability for normal repairs has to be more than 40 percent and for fast repairs more than 85 percent. Section 3.4.3 elaborates further on the repair process at Thales. [BER, 2009] [Repair, 2009] [Iping & De Wit, 2002]

Helpdesk: For continuous learning and to improve organization wide processes, Thales needs to deal with customer complaints about systems and services delivered. Therefore a helpdesk is set up. The performance indicator for the helpdesk is that Thales does anything they can to solve the problem. The target is to solve problems within 20 weeks. However, this strongly depends on the kind of complaint, whether the complaint is really appropriate, and whether

Thales is really responsible for the problem the customer complains about. When technical errors occur, first the helpdesk will try to solve the problem, otherwise an engineer will be sent to the customer to look and solve the problem. [Alvarez, 2007]

Health Check: Thales performs a yearly health check of the systems. This can be done at a marine basis and consists of checking the limited lifetime parts. This first check is done within twelve months after delivering the radar in order to check, replace, and repair items within the guarantee period. [Helpdesk, 2009]

Potential Services and Extensions

Technical Assistance: The customer can make an appeal to the technical assistance of Thales when a customer itself has installed the system and the system does not operate as expected. The technical assistance takes care for a solution such that the system will be operational. The customer cannot only make an appeal to the technical assistance by installation of a system, but also when a certain failure in the system occurs. [Levers, 2006]

Overhaul: An overhaul is a revision of a system. Thales offers minor and a major overhauls. In general, a minor overhaul is executed once every five years, whereas a major overhaul is executed once every ten years. A minor overhaul is done at the same moment as the major overhaul. The function of an overhaul is to make the parts of the radar and the radar itself serviceable and operational again (to make it as good as new). This occurs by revising and modernising the parts. A minor overhaul is executed onboard, when the ship is at the shore location. At a major overhaul most parts and modules of the systems are taken off the ship. The systems are inspected, revised, and modernised at a workshop, but not onboard. [Levers, 2006] [Buijs, 2009]

Upkeep of Documentation: Once a year, at the same time with the yearly report, Thales announces what documentation needs to be updated. The documentation enables the customer to use and maintain the systems. When changes are made to comply with maintenance obligations, Thales will change their documentation, trainings material, and spare parts. Technical documents are updated with new information about preventive maintenance, maintenance schedules, and corrective maintenance. When reviewing draft documentation it is possible that some technical content errors are found. The performance indicator is that per three months less than 35 percent of the book may consist of technical content errors, for final or updates of books 25 percent is maximal allowed. [Documentation, 2009]

Training programs: Thales offers training programs and supporting training products for the users of Thales' systems. The target group of initial user trainings are operators and officers of commando centrals, maintenance staff of the operational organisations, and organisations onshore. Because knowledge goes down with the years, these trainings are also given at the service phase. The performance indicator is that the customer satisfaction for each training program is rated with a seven or higher. [Intranet, 2009] [Training, 2007]

As Maintained Configuration: The configuration of a radar unit before repair is compared to the configuration as known at Thales. A difference in configuration is reported. Relevant data of the inspection activities are recorded in the FRACAS (Failure Reporting, Analysis, and Corrective Action System) database. The goal of this system is to recognize structural differences and to take corrective actions after analysis. [Levers, 2006]

<u>Obsolescence Resolution:</u> When a part is not obtainable anymore, this is referred at Thales with the expression “obsolescence”. A product is called obsolete when it is not available and deliverable anymore by Thales, because the supplier of Thales has stopped the production of that product. The supplier will stop the production of the part when there is almost no demand for it anymore or there is an improved version of the product. Because Thales guarantees the functionality of systems for a long time (20 years) it is possible that parts get obsolete but are still needed for production or repair. When a product is obsolete Thales checks whether there is a part with the same functionalities that can replace the obsolete part. Thales also checks the costs of adapting the systems such that they can operate without the obsolete part. A possible conclusion can be that there is a need for an “all-time buy”. This is a last purchase of the product such that there is enough to cover the demand during the lifetime of the system. To overcome the obsolescence problem, obsolescence management (monitoring and resolution) is needed. A two-yearly update of obsolescence is agreed upon in a service level agreement. The goal of an obsolescence analysis is to gather different data for each part to analyse the risk of obsolescence. [Levers, 2006]

Finally a yearly report is made and it contains the following contractual agreements:

- The actual repair throughput times
- The minimum and average system availability per year
- Overview of all repairs
- Claims that are (not) part of the conditions of the maintenance contract
- Modifications of the system
- Software maintenance
- Trend analysis with respect to obsolescence
- Trend analysis with respect to repairs
- Resolutions with respect to special preventive maintenance

3.4. Maintenance, Repair, and Supply Process

3.4.1. Resource and Activities

At Thales, resources and activities are needed to fulfil the requirements of the contracts. These are divided into the following categories:

- *<u>Personnel</u>*: These are the front officer, national engineers, and personnel secretariat. The software and hardware engineers provide the actual (maintenance) service.
- *<u>Supply</u>*: Within this category are the initial and resupply of spare parts, transportation, support equipment, and stock locations. Also the disposal, obsolescence, and reallocation of spare parts are considered.
- *<u>Maintenance</u>*: At Thales, there are several different types of maintenance, which we will describe in Section 3.4.2.
- *<u>Support</u>*: These are resources that support maintenance, repair, and supply. Most important here are the front office, helpdesk, and configuration management.
- *<u>Management</u>*: This is the contract, program, and financial management that are needed to fulfil contract agreements.
- *<u>Related disciplines</u>*: These are management resources (such as commercial, product/system, and Integrated Logistics Services management), which are not directly attributable to a specific service contract. [Alvarez, 2007]

3.4.2. Maintenance Process

To better understand the maintenance process, we first clarify what we mean with a replaceable item, a repairable item, and repair (throughput) time. The terms and their definitions are based on the Military Reliability Design Handbook (1998).

- *Replaceable Item*: "An item, unit, subassembly, or part that is normally intended to be replaced during corrective maintenance after is failure".
- *Repairable Item*: "An item which, when failed, can be restored by corrective maintenance to an operable state in which it can perform all required functions".
- *Repair Throughput Time*: "The elapsed time from receipt of a failed item at the maintenance level, until the item is ready for issue as a serviceable item".

Currently spare part stocks are placed on the ships and onshore. The maintenance process starts when an item in the radar fails. The item is replaced when a spare item is available at the ship (*repair-by-replace policy*). Depending on the failed item, it is repaired at the ship, onshore, or at Thales. A problem occurs when no spare item is available at the ship. The system will be down until a new spare is available or the failed item is repaired. The average time until a new spare arrives (and therefore the time that a system is down) depends on the location where the item can be repaired and on the spare part inventory at that location.

According to Buijs (2009) and Buijs & Jongebloed (2008), the current service part supply system has four lines of maintenance and repair: *onboard-*, *onshore-*, *depot-*, and *industry maintenance.* Figure 3.3 gives an overview of the maintenance process.

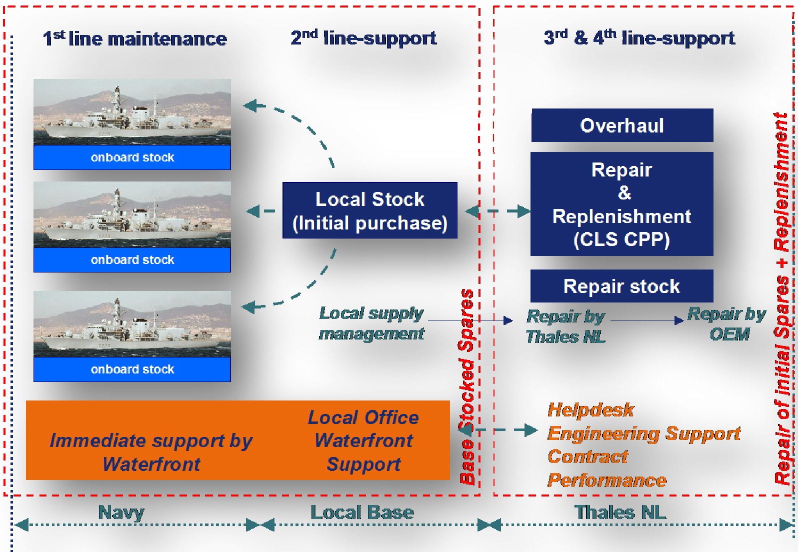

Figure 3.3: Service Part Supply Chain [Buijs & Jongebloed, 2008]

Onboard Maintenance: Within the organisation the ship is seen as the user of the system and has a certain repair and maintenance demand. During missions, preventive and corrective maintenance is executed. The users of the system and onboard technicians perform onboard maintenance and repair. Onboard spare parts are stocked to follow the "repair-by-replacement of Line Replaceable Units (LRU)" policy. When no spare part is on stock during a mission, an emergency shipment may be done and a spare part is flown in (by helicopter).

Onshore Maintenance: This maintenance is carried out when the ship is docked at the naval basis or parts are repaired that have been transported (by helicopter) from the ship at sea to the dock facility. Onshore maintenance is performed, when it is not possible to do this onboard due to unavailability of spare parts, lack of knowledge, or rough sea conditions. Another reason to maintain at the dock is that when a ship is on a mission (i.e. at sea) the system is used and it is not possible to maintain a system while it is operating. Main tasks performed onshore are pre and post mission checks, giving ship engineers technical assistance, or advising on repairs and doing remote maintenance.

Depot Maintenance: Depot maintenance is the third line maintenance. The failed parts that are replaced by a spare part and could not be repaired onboard or onshore are brought to the depot. The depot decides whether to repair the part or to replace it (make or buy a new one). The depot field services engineers try to repair the part before the system breaks down again due to a failure of the same kind of part. In this way the operational availability is kept high. Main tasks of the depot are repair and replenish spare parts, overhaul items, supply of support equipment and facilities, procurement and disposal of items, inventory control, and supply chain management.

Industry Maintenance: Some items cannot be repaired at the depot and have to be returned and repaired by the Original Equipment Manufacturer (OEM). Some parts are nowhere placed in stock, because they are too expensive or the mean time between failures is very high. When these parts fail, they are immediately sent to Thales for repair or replacement in order to get the system up and running again as soon as possible. The maintenance activities are done at depot level and consist of LRU repairs at the Thales facility.

3.4.3. Repair Process

Reducing the internal repair throughput times at Thales reduces the time a repairable item spends at Thales. The profit gained in time can be reflected in days, in saved costs, and especially in system availability. In this research only the repairs at Thales are investigated, and not the repairs that are outsourced to third parties. If reduced repair lead times result in a serious reduction in inventory investment, then management might have an additional incentive to better control the processes in the repair shop.

The repair transaction process consists of four phases; the *quotation* phase, the *order-handling* phase, the *repair* phase, and the *dispatching* phase. However, the repair throughput time at Thales consists of the last three phases, because the quotation phase is dependent of the customer and in a performance-based contract there is no quotation phase. We already defined that the repair throughput time starts when the failed item is present at the maintenance level and stops at the time that the item is ready for issue as a serviceable item and can be sent back to the customer. The order handling phase starts when the order and the failed item have been received at Thales. Therefore this is also the starting point of measuring the repair throughput time.

Order-Handling Phase: The order-handling phase consists of releasing the order (duration of about three working days) and consists of an incoming inspection including data storage in FRACAS (seven working days). According to Donderwinkel (2005) the order-handling phase has a time span of two weeks (14 days). Waiting times (for inspection), because it is not always possible to directly start the inspection when the item has been received at Thales, are included in these times.

Repair Phase: The repair phase consists of accepting the order at the repair department and the repair time. At Thales the repair time consists of the net repair time (in general two weeks) and the waiting time (for lower-indenture spare parts). There is a waiting time for lower-indenture parts since in traditional after-sales contracts and spares inclusive contracts the customer pays for the spare parts and only LRUs are used in the INVENTRI optimisation. Thales therefore, uses *gross* mean repair throughput times (net repair throughput time + waiting time for subcomponents). This conflicts with the repair times as defined in Sherbrooke (2004), because Sherbrooke uses *net* mean repair throughput times (no waiting time for lower-indenture parts is included).

Since for performance based-contracts the customer does not pay for the LRUs (they only pay a fixed fee per month/year), subcomponents should be included in the INVENTRI optimisation and net repair throughput times should be used (instead of gross repair throughput times). However, we focus on *gross repair throughput times* since for many LRUs at Thales the subcomponents (including prices and MTBF values) are hard to find out. The gross mean repair throughput time differs per LRU and therefore has to be estimated or based on historical data. We will decrease the waiting time for lower-indenture parts by stocking subcomponents at Thales. Since the costs for those subcomponents are hard to determine, we will make a generic model in Section 5.3 that determines those costs.

Dispatching Phase: The dispatching phase consists of multiple processes. First the repaired item has to be accepted at the Material Handling department. Then the product has to be packed and to be approved before it will be sent to the customer. Most of the time exists of administration tasks and data entry in different databases. Some customers want multiple repairs sent to them in one batch, instead of one by one (cost issues). Also the time to get an export license depends on how fast the customer sends this to Thales (can differ from a few hours to a few days). So the dispatching phase consists of some customer specific time. On average, the dispatching phase takes about two weeks. In case of military supervision, the dispatching phase will take about one week more.

Buffer: To catch up with time variation in the different processes and since there is some slack time when going from one department to another, Thales uses a two-week time buffer.

The *gross* repair throughput time consists now of the *net* repair throughput time (eight weeks) plus the waiting time for a subcomponent plus some customer specific time (see Figure 3.4).

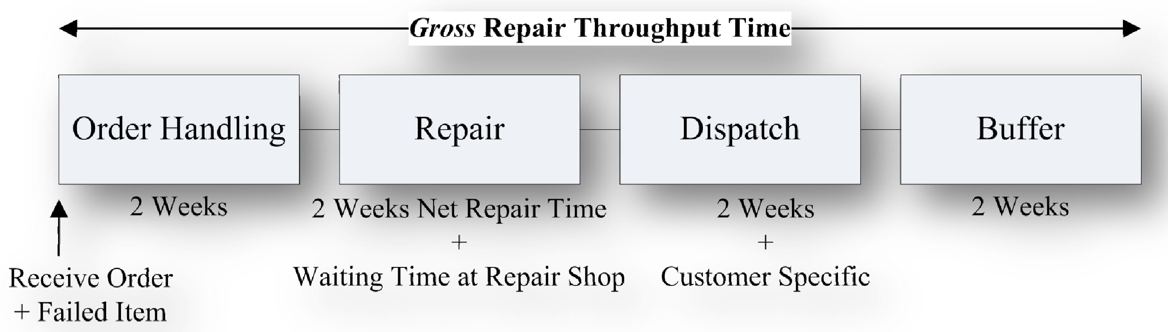

Figure 3.4: Repair Throughput Time [Donderwinkel, 2005]

Waiting time reduction: The waiting time for subcomponents that is needed to repair the failed item will decrease when lowering the purchase lead-time of subcomponents or stocking those subcomponents at Thales. It is hard to reduce purchase-lead times and to know the investment for it, because this depends also on the contract conditions that Thales has with its suppliers. Therefore, we will only focus on stocking subcomponent to reduce the waiting time in the gross repair throughput time.

Fast Repair: Besides, Thales distinguishes normal and fast repairs (this is a binary choice and there is no option in between). A fast repair is done when priority is given to a failed item (see also Section 3.3). The failed item gets priority in the repair transaction process and administration tasks may be done afterwards. At Thales, the order-handling and dispatch phase will reduce by 50 percent and the buffer time will be removed for a fast repair. This results in a net mean repair throughput time of four weeks. The target at Thales is to complete 85 percent of the fast repairs within four weeks.

Problems occur when a failed item is sent to Thales, because the maintenance lines (see Figure 3.3) are also the communication lines. Thales never communicates with the crew onboard, but only with the personnel at the shore organisation. The failed item follows the route that is the same as the maintenance lines (from board to shore to Thales). It is possible that the original problem description made by the crew onboard is lost and Thales does not know the original problem. This may lead to unnecessary inspections and inefficiency in repair processes.

3.4.4. Supply Process

The availability of the systems can be increased by spare parts inventory onboard, onshore, or at Thales. When customers order a radar system, they also do an initial purchase for spare items in order to be able to replace failed parts and keep the systems up and running. A special developed software program, called INVENTRI, calculates initial spare part allocations. This spare part inventory tool is made by the company ORTEC under the authority of Thales (and is not sold to any other party or company besides Thales) and is based on Rustenburg (2000). The model is used by Thales Naval Services to calculate the recommended spare parts lists for the customer and for the support of the Contracts for Availability. The Royal Netherlands Navy is one of the biggest customers of radar systems at Thales and is therefore regularly confronted with the results of INVENTRI. Calculations made by INVENTRI are based on the VARI-METRIC approach. In Chapter 4 we elaborate on the VARI-METRIC approach and what the relation is between availability and spare part inventory, repair throughput times, and order-and-ship times. In INVENTRI, spare part allocations can be calculated under budget restrictions or for a certain system availability level. It calculates the highest possible system availability per invested euro. Besides initial supply, there is also the resupply option.

Initial and Resupply: In *Initial Supply,* the amount and allocation of spare parts needed are calculated for a certain contract (depot repair, depot repair & supply, and full support). In *Resupply (tactical or operational)*, repairing failed items or buying new items to compensate discarded items is done to keep spare part stocks up and to continuously fulfil the objectives (of the contract). *Tactical Resupply* determines an efficient resupply strategy to keep spare parts stocks up for a certain fixed annual budget. *Operational Resupply* determines the point in time when a repaired or discarded item will be repaired or replaced to keep spare part stocks up to the required level. The strategies used for resupply are divided in Rough (only for tactical resupply) and Balanced Focus strategy.

Rough and Balanced Focus Strategy: In the *Rough strategy,* failed items are directly repaired or replaced if there is any budget. Customers use this strategy often. It shows that in case of small budgets or high uncertainties the performance (availability) decreases rapidly in years. In the *Balanced Focus strategy,* failed items are repaired or replaced depending on the remaining annual budget and added value of the item to the chosen objective. Items with a high purchase price and a low added value will not directly be repaired or replaced. It shows that in case of small budgets or high uncertainties the performance (availability) is better than for the rough strategy.

3.5. Conclusion

In this chapter we answered the first research question about which after-sale services and contract conditions are used at Thales and in which way Thales currently manages their availability-based service contracts. We focus this research on the "Contract for Availability" with the average system supply availability on a ship as a performance indicator. We elaborated on contract conditions and further examined different performance indicators of Thales, where we see that there are four standard indicators. Because of the *repair-by-replacement* policy, spare parts are needed when an item in the radar system fails. The spare part allocation is optimally calculated at Thales with INVENTRI, which uses the VARI-METRIC method. Maintenance (and also stocking items) in the current service part supply system can be done onboard, onshore, at Thales, and at the industry level. We analysed the repair process, where it is remarkable that there is, besides the two-week repair time, a four-week administrative time and a two-week buffer.

In Chapter 4 we elaborate on after-sales services business models and general contract content in literature. To find out what parameters influence system availability in the availability calculations, we also elaborate on the (VARI-) METRIC method.

4. Literature Review

In this chapter we answer the second research question: "What literature about service contracts and the VARI-METRIC approach is applicable, and how do different parameters influence system performance?" We start this chapter with an introduction and define after-sales business models and general contents of service contracts in Sections 4.1 and 4.2. In Section 4.3, we define different spare part strategies and in Sections 4.4 and 4.5 we elaborate on the METRIC and VARI-METRIC model that deal with the Spare Part Management strategy. Finally, in Section 4.6, we draw conclusions and show how and which different parameters influence the system supply availability.

4.1. Introduction

In this chapter, we present the results of the literature study that is relevant to this thesis. We first look at what after-sales business models correspond to the LTSA contracts Thales offers, and what the generic content of a service contract is. Furthermore, we want to know what parameters influence the average system supply availability. For this, we first need to investigate how spare parts are classified and which strategy is used for each class. We will elaborate on the model used (METRIC and its extension VARI-METRIC) that deals with the spare part management strategy and see how the optimal spare part allocation is calculated. It assumes that in case of repairable items the repair structure (the repair locations and the probabilities that an item can there be repaired) is given, and tries to determine the optimal allocation of spare part inventories in the supply chain. We show which parameters influence supply availability, and how supply availability is exactly calculated with these parameters.

4.2. Service Contracts

4.2.1. After-Sales Business Models

Cohen et al. (2006) define different after-sales business models that companies can deploy in order to support their service products (see Appendix B). The business models differ by product ownership. It differs from traditional ownership-based models to performance-based models for customers that are not the product owner. In the performance-based models, the customer pays the service provider for the delivered output. Therefore, performance-based models align the manufacturer, service provider, logistics provider, and the customer better than traditional ownership-based models. Companies should in general use the performance-based after-sales business model when the service product is expensive, the product performance can be measured, and the supplier is able to own the asset. Because of the LTSA contracts Thales offers, Thales prioritises the after-sale services high. The different contracts offered by Thales can be compared to the the cost-plus (fixed price based on costs and prenegotiated margin), performance based (pay based on product's performance), and the power by the hour (pay for services used) after-sales business models. Table 4-1 shows the comparison of the LTSA contracts of Thales with the business models of Cohen et al. (2006).

LTSA Contract	Guarantee upon	Corresponding Business Model
Traditional	*Discrete Support and Design Services*	*Cost-Plus*
Spares Inclusive	*Repair (and Supply) Services*	*Cost-Plus*
Contract for Availability	*System Availability*	*Performance Based*
Contract for Capability	*System Capability*	*Power by the hour*

Table 4-1: LTSA Contracts at Thales compared to Cohen's Business Models

4.2.2. Service Contract Content

To reduce the risks and uncertainties, it is important to make clear contractual agreements based on predetermined standards by Thales and the customer. We see that the service contract agreements at Thales correspond to the generic ones from Verna (1999). However, the second to the fifth aspect of Verna are together included in the “Guarantee” agreement at Thales. The generic service contract aspects of Verna (1999) are:

- The provided *service type* and *nature*
- The *problem reporting process* (includes contact information, format of filed complaints, and steps to be taken to quickly solve the problem)
- The *time frame* for response and problem resolution
- The service level *monitoring and reporting process*
- *Constraints and escape clauses* under which the required service level is not applicable or is unreasonable
- The *consequences* when the service provider does not meet the requirements
- The *service performance level* (availability requirements and how soon the service is performed)

4.3. Spare Part Strategies

4.3.1. Introduction

Rustenburg (2005) distinguishes different strategies (see Figure 4.1) for different kind of items. He classifies the items into the categories ‘*maintenance concepts*’ (corrective and preventive) and ‘*item costs*’ (high or low). Maintenance concepts are distinguished between preventive and corrective maintenance. *Corrective Maintenance* is the set of activities that is performed to restore the functionality of the system or item, when a failure has occurred. This maintenance concept is therefore not predictable. *Preventive Maintenance* is the set of activities that is performed to reduce the probability that a failure occurs and its consequences. Preventive maintenance is performed regardless of the item’s actual condition in the system, and has therefore the characteristic that it is predictable.

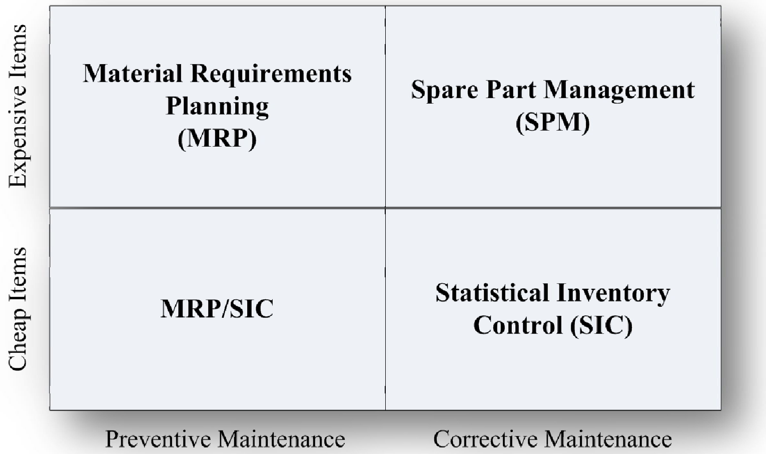

Figure 4.1: Spare Part Strategies [Rustenburg, 2005]

In this research, important characteristics of item failures in a technical complex system are that the probability of a failure of a spare part is generally low, spare parts are expensive, and the whole system is down when an item fails**.** The demand is usually for a specific single item and the ordering costs are not significant compared to the item’s value. We focus this research on the Spare Part Management strategy. However, we first look at the idea behind the classification and what characteristics of the other strategies can be used in the spare part management strategy.

4.3.2. Cheap Items with Preventive Maintenance

This strategy focuses to manage the cheap items as less as possible. Stocking spare parts is generally done for these items. Managing this stock, methods based on statistical data are used, also called Statistical Inventory Control (SIC) (e.g. Silver et al., 1998). SIC models focus on minimizing the sum of the ordering costs, holding costs (of inventory), and penalty costs (when having shortage of stock) and may be subject to a target service level. For further explanation of SIC models we refer to Appendix C and Silver et al. (1998).

Attention has to be paid to many spare part requests (from large-scale maintenance). These requests may not be taken from the spare part inventory and should not be put in the demand history. The peak demands should be filtered and the spare parts should be available ‘just in time’ (JIT) for as low as possible costs. Keeping inventory for this is not desirable and the so-called Material Requirements Planning (MRP) method (see Section 4.3.3) may then be applied. In fact the spare parts are in this case purchased (or delivered) on order and the goal of the MRP method is to optimally plan this order over time.

4.3.3. Expensive Items with Preventive Maintenance

The strategy for these items focuses on satisfying the need for spare parts with as low as possible spare part inventory. Because the demand is predictable and can be planned, the MRP method is used. Material Requirements Planning (MRP), see Silver et al. (1998), is based on the product structure of a system and consists of the system’s breakdown which is of importance for spare part management. MRP is a production management method that takes care that the demand for an item leads to demand for all lower level items. This is not the same as the assumption in spare part management that a failure of an item is caused by one lower level item failure. However, MRP does not calculate system availability or takes budget restrictions into consideration.

4.3.4. Cheap Items with Corrective Maintenance

This strategy focuses, just as for cheap items with corrective maintenance, on managing these items as little as possible. Because for these items almost no peak demands will occur, managing this stock is done with statistical information (SIC models). Only large-scale maintenance (or modifications) has to be filtered and the MRP method can be used for that.

4.3.5. Expensive Items with Corrective Maintenance

This is the most difficult category. This category consists of most of the invested money and also the system critical items. To manage this category effectively, advanced methods are needed. These methods have to deal with the “lumpy” demand behaviour. Moreover, looking at the influence of an item on the system availability is needed. Managing this category is difficult and takes a lot of time (there is a high data demand and therefore the preparation is time-consuming). A method that deals with this problem is the “Multi-Echelon Technique for Recoverable Inventory Control” (METRIC) model, developed by Sherbrooke (1986).

The METRIC model decides how much to reorder for a specific item. It uses the system approach (see Section 4.4.1) and it is the basis for inventory control that optimises inventory levels of expensive and slow moving repairable service items in a multi-echelon system. In this model, the product structure in MRP and the one-for-one replenishment (s-1, s) policy of SIC seem relevant. The goal of the METRIC model is to calculate optimal stock levels for each item for every inventory location (ship, shore organisation, and depot), such that the system supply availability is maximised given limited inventory investment budgets. [Sherbrooke, 2004] [Rustenburg, 2005]

4.3.6. Conclusion

We distinguished four different spare part categories. The most important one is the spare part management strategy. The METRIC model is an advanced method that is used to manage this strategy effectively. From the categories, the one-for-one replenishment (*s*-1, *s*) policy from SIC models and the product structure used in MRP are useful in the spare part problem. In Section 4.4 we elaborate on the METRIC model to see how optimal spare parts allocations are calculated and what parameters influence the system availability.

4.4. Multi-Echelon Technique for Recoverable Inventory Control (METRIC)

4.4.1. Introduction

Sherbrooke (2004) uses in the METRIC model the system approach, instead of the traditional item approach. The item approach (where spares are calculated separately for each item by simple formulas that balance costs of holding inventory, ordering, and stock out) is inappropriate, because the required system (not item) availability in combination with available budgets is input for the decision process. In the system approach, the installation is approached with all its components as one system, and the performance indicator is the system availability. According to Sherbrooke (2004), the required availability and investment should be an input in the decision making process. An availability-cost curve (Figure 4.2) provides insights into different alternatives and the direct relation between costs and availability. All points below this curve are seen as “inefficient”, because with the same investment a higher availability can be achieved. Points above the curve are unreachable.

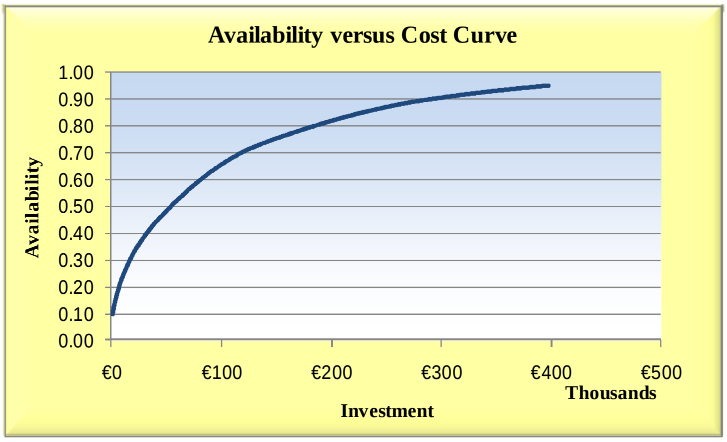

Figure 4.2: Availability versus Cost Curve

Because we want to know how the system availability can be influenced, besides stocking spare parts, we need to know how system availability is calculated and how we can calculate the availability versus cost curve (see Section 4.4.3).

4.4.2. Assumptions

Some important assumptions are made in the METRIC model. One of the main assumptions are the (s-1, s) inventory policy (because it is the optimal policy for the high-cost, low-demand repairable items of which systems are composed) and that the demand (item failures) is assumed to be Poisson distributed. This means that the time of a demand does not influence the time of the next demand and there is a continuous demand such that items will continue failing, even if the system is down. The most important assumption is the infinite repair capacity. The repair time of each item is assumed to be independent and identically distributed with a given mean. Failed items are directly taken into repair and do not depend on the repair shop capacity. The repair shop is modelled as an M/G/∞ queue and is based on Palm's Theorem (1938). Palm's theorem states that when the repair time for each item is independent and identically distributed and the demand is Poisson distributed, the steady state probability distribution for the number of items in repair has a Poisson distribution with a mean equal to the product of the failure rate and the mean repair time. It is called the infinite channel queuing assumption, because there is no interaction between the repair times of the different items. Therefore it is unnecessary to measure the repair distribution shape. This is important because there is no need to collect data of repair distribution shapes and repair capacity is therefore not a bottleneck. For more assumptions of the METRIC model we refer to Appendix D. [Sherbrooke, 2004] [Rustenburg, 2000] [Verrijdt, 1997]

4.4.3. Availability

Availability is the probability that a system operates at an arbitrary point in time. A system is available unless maintenance takes place or the system is down due to a failed item and it is waiting for a spare part. Availability can be measured in different ways, such as the period of time the availability is calculated. Sherbrooke (2004) and Kumar et al. (2000) distinguish between point availability, interval availability, and steady state availability.

- *Point availability* is the probability that a system is available (state of functioning) at a given instant of time t.
- *Interval availability* is the expected fraction of time in an interval the system is available.
- *Steady state availability* is the probability that a system is available, assuming it depends only on the mean time between failure and the mean time to repair distributions. In a steady state situation, the supply network is in a state as it has been operating for many years, and items may be in repair and not all spare parts are available.

Besides different ways to measure availability, also different types exist. Sherbrooke (2004) distinguishes three different types of availability: Inherent availability, achieved availability, and operational availability.

- *Inherent availability*: This measure considers a system unavailable during the time the system needs to be repaired because of a failed item (Mean Time to Repair). Preventive maintenance and delays due to spare part availability are not included in the measure.
- *Achieved availability:* This measure is an extension of inherent availability and considers a system unavailable during the time corrective or preventive maintenance is performed. However, this measure does not incorporate delays due to spare part availability.
- *Operational availability:* This measure considers a system to be unavailable in all events related to maintenance or supply (if there is a part delay or if any kind of

maintenance is taking place). Delays resulting from maintenance action are also included in this downtime. To simplify calculations, operational availability is broken down into maintenance availability and supply availability.

- *Maintenance availability*: This measure is the same as achieved availability. It depends on the Mean Time between Maintenance and not on the stocking policy (and results in a single availability number).
- *Supply availability:* This measure does not depend on the maintenance policy, but is calculated as a function of the stocking policy. The result is an optimal availability versus cost of spare parts curve (see Equation 4.1). The network supply availability is calculated as the average supply availability over all ships. The supply availability per ship is the product of the supply availability over all LRUs. The supply availability of an LRU is calculated with its expected backorders. The backorder calculations are explained in Section 4.4.4.

$$Supply\ Availability = \frac{\sum_{j=1}^{J}\prod_{i=1}^{I}\left(1-\frac{EBO_{ij}(s_{ij})}{N_j Z_i}\right)^{Z_i}\cdot N_j}{\sum_{j=1}^{J} N_j} \quad \textbf{(4.1)}$$

Where I = Number of LRU types
$EBO_{ij}(s_{ij})$ = Expected number of backorders for LRU i at ship j if the stock level equals s_{ij}.
Z_i = Number of LRUs of type i in a single radar
N_j = Number of radar systems at base j

For every value of spare part stock (and the accompanying costs) the supply availability of the system can be calculated. The goal is to invest in spare part inventories such that the availability is maximized given a limited budget. Equation 4.1 shows that maximizing availability is achieved by minimizing the expected backorders. Backorders are, according to Sherbrooke (2004), the number of unfilled demands that exist at a certain point in time. A backorder is established when it is unable to fill a demand and it lasts until there is a resupply for that item or a failed item (of that type) has been repaired. Backorders are related to the fill rate, which is the percentage of demands that can be met at the time they are placed. [Sherbrooke, 2004]. In Section 4.4.4 we elaborate on how backorders are calculated and what parameters influence backorders and therefore supply availability.

4.4.4. Backorders

According to Sherbrooke (2004), the objective is to maximize average system supply availability A given a budget C that can be invested in spare parts (initial stocks). This can be seen as to minimize the average number of expected backorders over all LRUs given a stock s_i for LRU i with costs c_i. The mathematical formulation is as follows:

$$\begin{aligned} &\underset{s_i,\, i=1..I}{Min} \quad \sum_{i=1}^{I} EBO_i(s_i) \\ &s.t. \quad \sum_{i=1}^{I} c_i s_i \le C \end{aligned} \quad \textbf{(4.2)}$$

Where $EBO_i(s_i)$	= Expected number of backorders for LRU i if the stock level equals s_i
c_i	= Costs of LRU i
s_i	= Stock level of LRU i
C	= Budget

Calculations made in INVENTRI are based on Rustenburg (2000). He uses the probability of a backorder (PBO) instead of the expected backorders. Equation 4.3 shows the item availability calculation according to Rustenburg and Sherbrooke. This makes the difference clear between the expected backorders and the probability of a backorder.

$$\text{Item Availability} \approx \left(1 - \frac{EBO_{ij}(s_{ij})}{N_j Z_i}\right)^{z_i} \qquad \text{Item Availability} = \left(1 - PBO_{ij}(s_{ij})\right) \qquad \textbf{(4.3)}$$

Sherbrooke (2004) — Rustenburg (2000), if one system per base

Because the output of both INVENTRI and the simulation model are the expected backorders, we will elaborate on how the expected backorders are calculated.

<u>*Expected Backorders*</u>

For a certain item (LRU) type, the number of items in repair or being resupplied from a higher echelon is called its pipeline μ. The average pipeline μ of an item is dimensionless and is the product of its failure rate and its mean time to repair. Because of Palm's Theorem we know that the average pipeline is Poisson distributed and is used to calculate the expected backorders. Because of this Poisson distribution, the probability that n items of type i are in repair can be formulated as follows:

$$\Pr\{n \text{ items of type } i \text{ in repair}\} = \frac{(m_i T_i)^n e^{-m_i T_i}}{n!} \qquad \textbf{(4.4)}$$

Where m_i	= Mean demand per year for item i	(i=1..I)
T_i	= Mean repair shop throughput time for item i	(i=1..I)

Sherbrooke estimates the EBO from stock level s and the steady state probabilities of the number of spare parts due in from repair and resupply. The total inventory of spare parts is equal to the number of spare parts on-hand (OH), plus the number of spare parts due (DI) in from repair and resupply, minus the number of backorders (BO). This is also called the "*stock balance equation*", where either stock on hand or the number of backorders is zero. Sherbrooke (2004) writes the EBO for an item with stock level s as:

$$\begin{aligned} EBO_i(s_i) &= 1 \cdot \Pr\{DI_i = s_i + 1\} + 2 \cdot \Pr\{DI_i = s_i + 2\} + 3 \cdot \Pr\{DI_i = s_i + 3\} + \ldots \\ &= \sum_{n=s_i+1}^{\infty} (n - s_i) \cdot \Pr\{DI_i = n\} \end{aligned}$$

Then it follows that $$\boxed{EBO_i(s_i) = \sum_{n=s_i+1}^{\infty} (n - s_i) \cdot \frac{(m_i T_i)^n e^{-m_i T_i}}{n!}} \qquad \textbf{(4.5)}$$

For a multi-echelon situation, a different calculation is needed for the pipeline at a base (ship). This calculation is then also dependent on the order-and-ship times. In Section 4.4.5 we elaborate on difference in the pipeline calculations for both a depot (Thales) and a ship.

4.4.5. Spare Part Allocation

The model to determine the optimal spare part allocation of stock levels at different bases in combination with stocks onshore and stocks at depot level is worked out in two steps by Sherbrooke (2004). To simplify calculations we illustrate the METRIC model by a two-echelon system. First, the optimal allocation of stock levels for a single item is determined. Second, the marginal approach is used to combine all items. The marginal approach puts each time an extra spare part on stock for the item that has the highest marginal backorder reduction per invested euro.

In the *multi-echelon, single indenture structure*, an item can be situated in three different kinds of locations: operational in a system (installed base), on stock (at different locations), or in the repair process (at different locations). Figure 4.3 displays these (steady state) situations. The probability that an item can be repaired at a location is r_{ij}, where Sherbrooke assumes that this probability is known for all items. The arrows are the logistic delay, which all can have different values. [REMM, 2008]

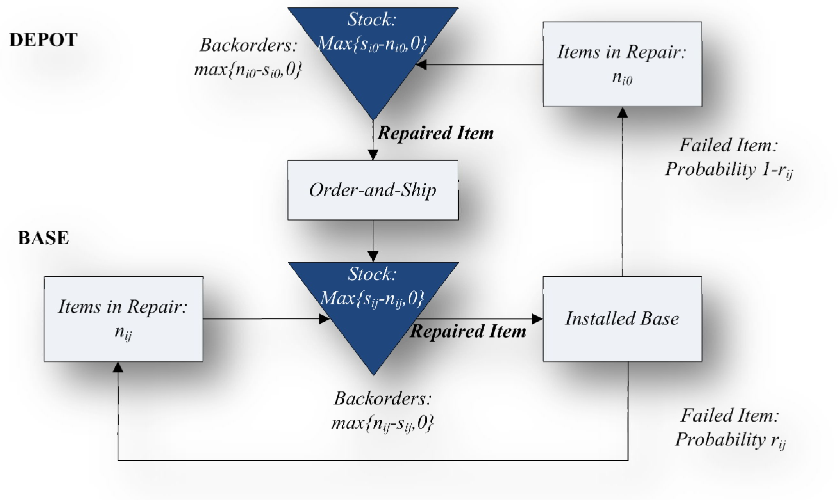

Figure 4.3: Steady State Situation where an item can be located [REMM, 2008]

The order-and-ship time is defined as the time from placing a resupply order from a base until the base receives the item, in case the depot has that item on stock. When the depot does not have that item on stock and hence cannot deliver immediately, this will lead to delay in resupplying bases (e.g. increasing repair throughput time at bases). From this we conclude that the expected backorder of a base depends on the expected backorders of the depot. [Sherbrooke, 2004]

The expected depot backorders depend on the average repair pipeline at the depot μ_{i0}, which is the product of the mean depot demand (total fraction of the demand that cannot be repaired at each base) and the mean depot repair throughput time of an item. However, a different calculation is needed for the expected base backorders. The mean base repair throughput time depends on the probability r_{ij} that an item can be repaired at that base and a probability of $1-r_{ij}$ that there is an order-and-ship time plus the expected waiting time of an item at the depot (which depends on the expected depot backorders) [Sherbrooke, 2004], [REMM, 2008]. Both depot and base pipelines are calculated as follows:

$$\text{Average Depot Pipeline: } \mu_{i0} = m_{i0}T_{i0} \tag{4.6}$$

$$\text{Average Base Pipeline: } \mu_{ij} = m_{ij}\left\{r_{ij}T_{ij} + (1-r_{ij})\left(O_j + \frac{EBO_{io}(s_{i0})}{m_{io}}\right)\right\} \tag{4.7}$$

In the optimisation procedure we first start with a depot stock level of zero for an item. We are then able to calculate the average depot pipeline and the expected depot backorders. From these we calculate the expected base pipelines and the expected base backorders. We then use the marginal approach (see Table 4-2) to obtain the minimum backorders for each number of items at each base. We repeat these steps for increasing depot stock levels. Then we find the minimum backorder value and the corresponding spare part allocation and repeat all steps for all items. Finally we calculate the optimal allocation of spare part stock levels (combine the item solutions) for each policy (total stock) using the marginal analysis again.

We remark that when increasing the depot stock level by one, there is no assurance of convexity. We have to check for convexity because otherwise we misled the marginal approach for combining items. Therefore it is possible to construct examples where the solution obtained with the marginal approach may not be optimal. The non-convex points are easily dealt with by excluding them as potential solutions.

Step	Marginal Approach
1.	Set $s_{ij} = o \quad \forall i, j$
2.	Calculate the marginal expected backorder reduction per invested euro for each item at each base *j* (not at the depot): $\Delta_{ij} = \frac{EBO_{ij}(s_{ij}) - EBO_{ij}(s_{ij}+1)}{c_i} \quad i = 1,\dots,I \quad j = 1,\dots,N$
3.	Select item *i** and the base *j** for which Δ_{ij} is maximal
4.	If $c_{i^*j^*} + \sum_{i=1}^{I} c_i \sum^{N} s_{ij} \le C$, then set $s_{i^*j^*} := s_{i^*j^*} + 1$ and go to step 2, else stop

Table 4-2: Marginal Approach [Sherbrooke, 2004]

4.4.6. Extensions METRIC model

Rustenburg (2000) applies the METRIC model on resupply. He does not only assume an initial budget to buy spare parts, but tries to find an optimal balance between yearly available budgets for resupply and the long-term system availability.

The original METRIC model minimises the expected backorders for all items at all bases, but does not make any distinction between product indenture levels (items, modules, and components), which we have in practice. A shortage of end items has a direct influence on system availability whereas shortages of modules or components have indirect influence. Sherbrooke (1971) recognizes this hierarchical product structure (multi-indenture structure) for a single base. Muckstadt (1973, 1979) on the other hand, implemented this structure in a multi-echelon system. He calls this the MOD-METRIC model, which calculates optimal allocation of end-items and modules. Important here is the assumption that the failure of an LRU (module) at a base is always caused by exactly one SRU.

Sherbrooke (2004) shows that the MOD-METRIC method underestimates the total backorders, because in this method the number of items in all pipelines is Poisson distributed. As a matter of fact, the number of items in the depot pipeline has a Poisson distribution, but this does not hold for the base pipelines. These depend on the depot backorders (which are not Poisson) and those base pipelines have a variance-to-mean ratio larger than one. According to Sherbrooke, the Poisson distributions can be generalized to negative binomial distribution in which the variance exceeds the mean. The probability distribution for the pipelines can therefore be modelled with the negative binomial distribution. This all is the foundation of the VARI-METRIC model, where variances in pipelines are taken into account. The issue is now how to calculate the variance of the pipelines. Since the VARI-METRIC also combines the multi-echelon and multi-indenture structure, we elaborate on this model in Section 4.5.

4.4.7. Conclusion

The underlying basis of the METRIC model is the single-site model. The main assumptions of both the single-site model and METRIC are the single-indenture product structure, the assumption of Poisson distributed demand, the one-for-one replenishment ((s_i-1, s_i) inventory model), and the repair shop is a M/G/∞ queuing model. According to Palm's Theorem, the steady state probability distribution of the pipeline is Poisson distributed with mean m_iT_i. We showed that the availability is calculated as a function of the stocking policy and is called supply availability, which gives us an optimal availability versus cost curve. The METRIC model calculates the steady state supply availability. We have shown that maximising supply availability is achieved by minimizing the expected backorders or by minimizing the backorder probabilities.

We showed that the expected backorders of a base depend on the base stock level, repair throughput times for an item at different bases, order-and-ship times for an item from the depot to a base, and the expected backorders of the depot. Which on its turn depend on the depot stock level, the repair throughput times for an item at the depot, and the mean demand for an item. This is the reason why we focus this research on increasing spare part *stock levels*, decreasing *mean repair throughput times* and decreasing *order-and-ship times* in order to increase mean system supply availability. Current optimal spare part calculations are made by Thales' spare part inventory tool "INVENTRI", which uses the VARI-METRIC approach (see Section 4.5).

4.5. VARI-METRIC

4.5.1. Introduction

The VARI-METRIC model combines the multi-echelon and multi-indenture structure and uses the mean pipeline values and its variance. The multi-echelon, multi-indenture problem is separable per LRU. We first will explain the single site, multi-indenture model. Then we derive the demand per location per item, and finally derive the mean and variance of the number of items in the pipeline per location per item. We refer to Appendix D for most of the equations, but for complete derivations of the equations we refer to Rustenburg (2000) and Sherbrooke (2004).

4.5.2. Single-Site, Multi-Indenture Model

In the *multi-indenture model* a failure of an LRU (module) at a base is always caused by exactly one SRU *i* (component) with probability q_i where the sum of all probabilities is less than or equal to one. An item can be operational in a system (installed base), on stock, or in the repair process. Figure 4.4 displays these (steady state) situations when the repair probability of an item is 100 percent. [REMM, 2008]

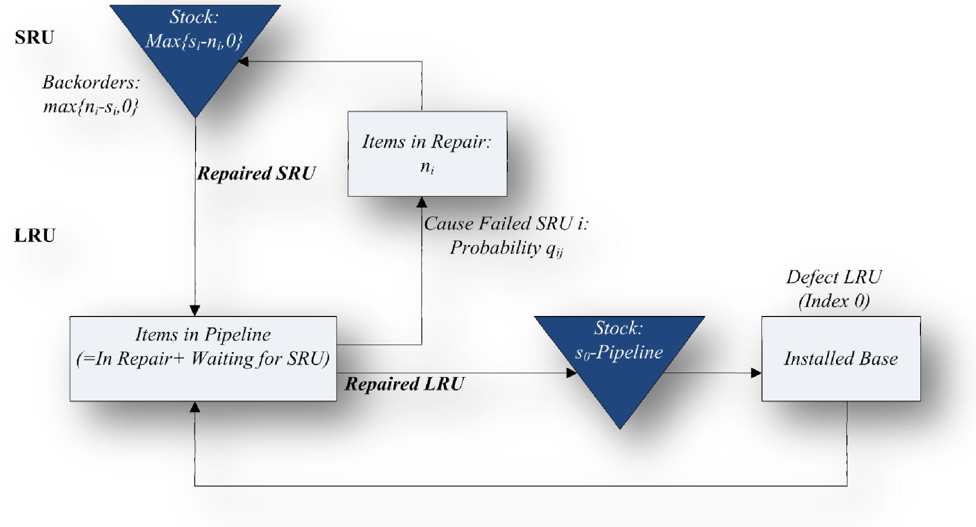

Figure 4.4: Steady State Situation where an item can be located [REMM, 2008]

The mean LRU base demand is the sum over all mean SRU base demands. When the repair time T_i is constant, the expected LRU pipeline equals the demand during the repair time plus the sum of the backorders of all SRUs. To calculate the mean pipeline and its variation we first need to know how to calculate the demands for an SRU and LRU at the depot and base. Section 4.5.3 describes these demand calculations.

4.5.3. Demand Calculations

With the item demand per location (m_{ij}), the item repair probability per location (r_{ij}) and the probability that a failure of a LRU is caused by a certain SRU (q_{ij}), we derive the demand rates. Figure 4.5 displays the calculation sequence used by Sherbrooke (2004) to calculate demand rates (as a function of LRU base demand). From the LRU base demand, we calculate the SRU base demand and the LRU depot demand. From these we calculate the SRU depot demand. Section 4.5.4 shows how to calculate the mean and variance of the pipelines.

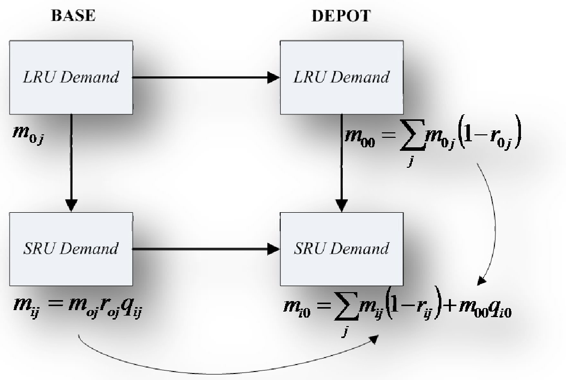

Figure 4.5: Demand Calculation Sequence [REMM, 2008]

4.5.4. Pipeline Calculations

To calculate the expected number of items in the pipeline and the expected variance in the pipeline we use the previous calculation sequence (see Figure 4.5) in *opposite direction*. The expected pipeline variance is also dependent on the variance of the backorders (VBO). The variance of the backorders is calculated as follows:

$$VBO(s_0) = \mathrm{E}\left[BO^2(s_0)\right] - \mathrm{E}^2\left[BO(s_0)\right] \qquad \textbf{(4.8)}$$

We start with SRUs in repair at the depot, because other items and locations do not have any influence on this. The depot SRU pipeline has a Poisson distribution with mean $m_{i0}T_{i0}$. From this we calculate the $\mathrm{EBO}_{i0}(s_{i0})$ and the $\mathrm{VBO}_{i0}(s_{i0})$. After this we calculate the LRU depot pipeline, the SRU base pipeline and finally the LRU base pipeline. For exact equations we refer to Appendix D. The mean base supply availability is calculated from these calculations, because it depends on the expected LRU base backorders $\mathrm{EBO}(s_{0j})$ and therefore on the LRU base pipelines. [Sherbrooke, 2004]

4.5.5. Conclusion

In Section 4.5, we showed the extension of the METRIC model, the VARI-METRIC model. The extension is that it uses the mean pipeline values and its variance. To calculate these, we showed what the multi-indenture model looks like and see that the LRU pipeline depends on the demand during the repair time plus the sum of the backorders of all SRUs. We showed how these LRU and SRU demands are calculated for the base and depot. We use these demand calculations to calculate the mean and variance of the pipelines. From the LRU base pipelines we calculate the LRU base backorders and from this the mean base supply availability. In Chapter 6 we show the method we use to determine which parameters influence the system availability and the variability the most.

4.6. Conclusion

In this chapter we showed that the “Contract for Availability” and the contract content correspond with the performance-based contract and generic service contract agreements in literature. From the four spare part categories, we deal in this research with the spare part management problem and use the METRIC model to manage this. We showed that the availability we focus on is calculated as a function of the stocking policy and is called supply availability. The METRIC model calculates the steady state supply availability. We have shown that maximising supply availability is the same as minimising the expected backorders.

From the (VARI-) METRIC model we see that increasing spare part (LRUs and SRUs) *stock levels*, decreasing *net mean repair throughput times* and decreasing *order-and-ship times* decrease the expected backorders. Figure 4.6 shows the relation between the (time) parameters with pipelines, backorders, and finally on system supply availability. Here we see that the pipeline of a certain location is influenced by the backorders of a location upstream. The pipeline influences the backorders of the same location. Finally, the backorders on the ships influence the average supply availability directly. From this figure we also see that every (time) parameter influences the ship backorders, directly or indirectly. The shaded boxes are the tactical decisions we focus on this research. We only focus on repair throughput times at Thales, and also only focus on stocking SRUs at Thales since that option reduces the waiting time in the gross repair throughput time at Thales (see Section 3.4.3).

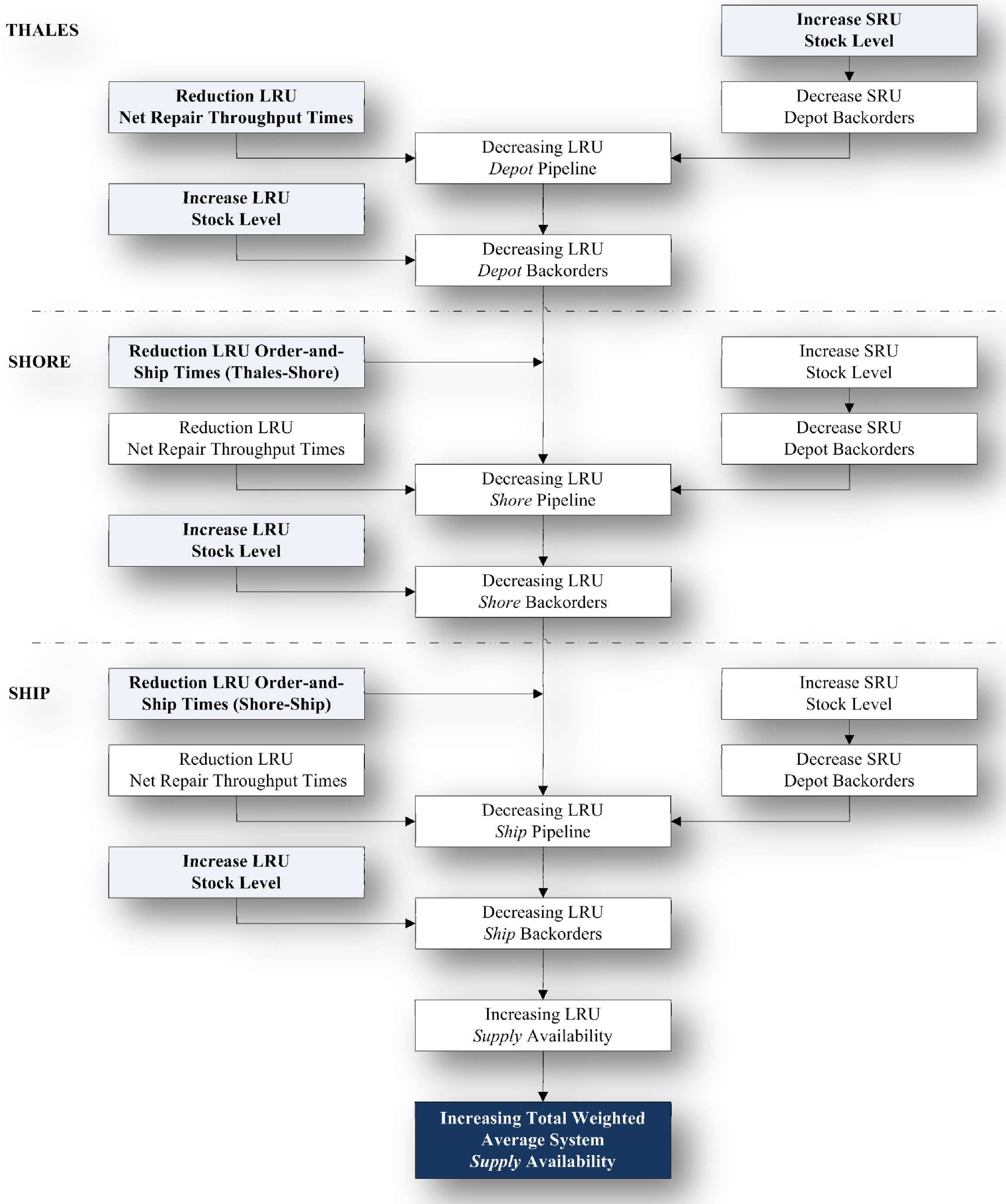

Figure 4.6: Influence of Parameters on System Supply Availability

5. Impact Tactical Decisions

In this chapter we answer the third research question: "How can we determine the impact of the tactical decisions on the average availability?" We start with an introduction in Section 5.1 where we compare tactical decisions by the expected LRU ship backorder reductions per invested euro per year. We separate this in general equations that are used to calculate the marginal expected LRU ship backorder reductions (Section 5.2) and general cost models to calculate the costs per year (Section 5.3). We end this chapter with a short summary and conclusions in Section 5.4.

5.1. Introduction

Based on Chapters 3 and 4, we consider five different tactical decisions to improve the system performance. We will also elaborate on the buffer in the repair throughput time. However, we do not use that as a tactical decision in our optimisation method since Thales consciously chose to use a two-week buffer to catch up with variation in the different processes. The tactical decisions are as follows:

1. Stocking spare parts of LRUs;
2. Stocking spare parts of SRUs at Thales (*such that the waiting time in the LRU gross mean repair throughput time at Thales decreases, see Section 3.4.3*);
3. Reducing order-and-ship times from shore to ship;
4. Reducing order-and-ship times from Thales to shore;
5. Reducing the net LRU mean repair throughput time at Thales (*using a priority rule/fast repair, see Section 3.4.3*)

To compare the tactical decisions, the impact of a tactical decision is calculated as the expected LRU ship backorder reduction (ΔEBO) per invested euro per year. For a reduction in a time parameter (order-and-ship time or the repair throughput time), we approximate that the ΔEBO is equal to the product of the marginal ship backorder improvement per time unit reduction and the reduction in the time parameter. The marginal improvement (influence of a time parameter on the expected ship backorder) is calculated by the partial derivative of the backorder function (see Section 5.2). Besides the marginal backorder reductions, we define general cost models to determine the costs per year for each tactical decision (see Section 5.3). Combining these will lead to equations to calculate the impact (ΔEBO per invested euro per year).

5.2. Marginal Backorder Reductions

5.2.1. METRIC formulas

Before we start, we show the parameters and formulas needed from the METRIC approach (see Chapter 4) to approximate the influence of the tactical decisions. We assume that we have a symmetric supply network, in which all locations at the same echelon level have the same parameters and for which we take the same decisions.

We define location j:		*and item i:*	
$j = 0$	for Thales	$i = 0$	for an LRU
$j = 1$	for the shore location	$i \geq 1$	for an SRU
$j = 2$	for the ships		

Where the following parameters will be used (for readability, the item index i is left out):

c	= Item price
m_j	= Demand at location *j*
q_j	= Probability that an LRU failure is caused by a certain SRU, found at location *j*
r_j	= Probability that the item can be repaired at location *j*
O_j	= Order-and-ship time from location *j*-1 to *j*
T_j	= *Net* mean repair throughput time at location *j*, including the return time of a defect item from the ship
$T_{w,j}$	= Waiting time for SRUs at location *j*
$T_{Gross,j}$	= *Gross* mean repair throughput time at location *j*, (T_j + $T_{w,j}$)
T_P	= Fixed procurement lead-time from external supplier (OEM), identical for all locations
μ_j	= Pipeline at location *j*
s_j	= Stock at location *j*
$EBO_j(\mu_j; s_j)$	= Expected Backorders at location *j*, given pipeline μ_j and stock s_j.
f_j	= Fill Rate of an item at location *j*

And the following equations will be used:

$$\mu_0 = m_0\{r_0 T_0 + (1-r_0)T_P\}$$

$$\mu_j = m_j\left\{r_j T_j + (1-r_j)\left(O_j + \frac{EBO_{j-1}(\mu_{j-1}; s_{j-1})}{m_{j-1}}\right)\right\} \qquad \textit{for j=1,2}$$

$$\mu_{LRU} = m_{LRU} T_{LRU} + \sum EBO(\mu_{SRU}; s_{SRU})$$

$$EBO_j(\mu_j; s_j) = \sum_{n=s_j+1}^{\infty}(n-s_j)\cdot\frac{\mu_j^{\,n} e^{-\mu_j}}{n!} = \mu_j \sum_{n=s_j}^{\infty}\frac{\mu_j^{\,n} e^{-\mu_j}}{n!} - s_j \sum_{n=s_j+1}^{\infty}\frac{\mu_j^{\,n} e^{-\mu_j}}{n!} \qquad \forall j$$

$$f_j = \sum_{n=0}^{s-1}\frac{\mu_j^{\,n} e^{-\mu_j}}{n!} \qquad \forall j \ \textit{(Assumption under METRIC, and not for VARI-METRIC)}$$

Section 5.2.2 elaborates on the influence of the different parameters (see Figure 4.6) that are needed to calculate the marginal backorder reductions.

5.2.2. Parameter Influence

Based on Chapter 4, Figure 5.1 shows the influence of (time) parameters on pipelines and expected backorders for a certain location *j*. The influences of one parameter on another are calculated using partial derivatives. From Figure 5.1 we see that there are seven possible options for a certain location. We follow the sequence in which different parameters influence each other and use the differentiation chain rule to finally approximate, for each combination of LRU and tactical decision, the marginal improvement in the expected ship backorders.

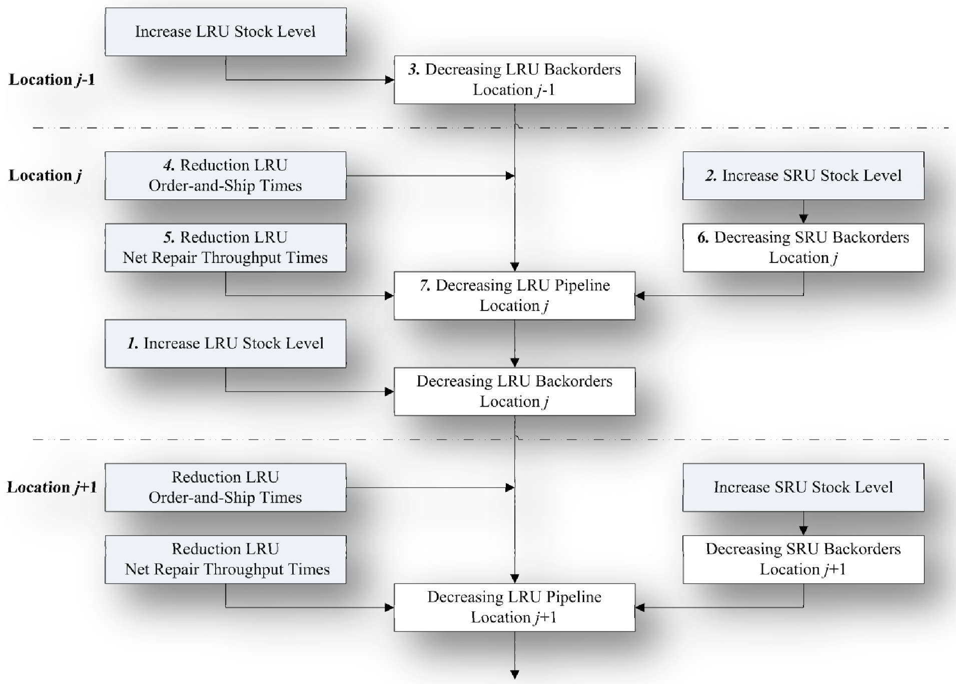

Figure 5.1: Influences of one parameter on another for a certain location *j*

Next we define the influence of one parameter on another. *Parameters 1 and 2*, the influence of increasing spare part (LRU or SRU) stock level, are easily calculated using the EBO equation since the expected backorders are a function of the stocking policy. For the other five parameters, we define the influence as follows (see Appendix E-1 for more details):

3. The influence of the LRU backorders at location j-1 on the LRU pipeline at location j

$$\frac{\partial \mu_j}{\partial EBO_{j-1}\left(\mu_{j-1}; s_{j-1}\right)} = \frac{m_j\left(1-r_j\right)}{m_{j-1}}$$

4. The influence of the LRU order-and-ship time on the LRU pipeline at location j

$$\frac{\partial \mu_j}{\partial O_j} = m_j\left(1-r_j\right)$$

5. The influence of the net LRU mean repair throughput time on the LRU pipeline at location j

$$\frac{\partial \mu_0}{\partial T_0} = m_0 r_0$$

6. The influence of the SRU backorders at location j on the LRU pipeline at location j

$$\frac{\partial \mu_{LRU}}{\partial EBO_{SRU_i}\left(\mu_{SRU_i}; s_{SRU_i}\right)} = 1$$

7. The influence of the LRU pipeline at location j on the LRU backorders at location j

$$\frac{\partial EBO_j\left(\mu_j; s_j\right)}{\partial \mu_j} = \sum_{n=s_j}^{\infty} \frac{\mu_j^{\,n} e^{-\mu_j}}{n!} = 1 - f_{LRU,j}$$

5.2.3. Marginal Backorder Reductions for Reducing a (Time) Parameter

Using the equations from Section 5.2.2, we approximate the marginal ship backorder reduction for reducing a (time) parameter. Using the sequence in which different parameters influence each other (see Figure 5.1) and using the differentiation chain rule, the marginal backorder reductions (influence of a parameter on the expected ship backorders) for all tactical decisions are defined as follows (we refer to Appendix E-2 for detailed calculations):

Stocking LRUs

The influence of stocking LRUs is easily calculated using the EBO equation of Sherbrooke (2004), since the expected backorders are a function of the stocking policy. For this, we calculate the marginal ship backorder reduction as follows:

$$\Delta EBO = EBO_2(\mu_2; s_j) - EBO_2(\mu_2; s_j + 1)$$

Stocking SRUs

Since for many LRUs at Thales the subcomponents (including prices and MTBF values) are hard to find out, we are not able to calculate the SRU backorders. We therefore focus on *gross* LRU repair throughput times, where stocking SRUs reduces the waiting time in the gross LRU repair throughput time (see Section 3.4.3). Since both stocking SRUs and reducing the *net* LRU repair throughput time are part of the gross repair throughput time, we assume that the marginal ship backorder reduction for stocking SRUs is equal to the marginal backorder reduction for lowering the net LRU mean repair throughput time at Thales:

$$\frac{\partial EBO_2(\mu_2; s_2)}{\partial T_0} = r_0(1 - r_1)(1 - r_2)m_2 \cdot (1 - f_{LRU,0})(1 - f_{LRU,1})(1 - f_{LRU,2})$$

Reducing the order-and-ship times from shore to ship:

The influence on the expected ship backorders for a unit order-and-ship time reduction is defined as follows:

$$\frac{\partial EBO_2(\mu_2; s_2)}{\partial O_2} = (1 - r_2)m_2 \cdot (1 - f_{LRU,2})$$

Reducing the order-and-ship times from Thales to shore:

The influence on the expected ship backorders for a unit order-and-ship time reduction is defined as follows:

$$\frac{\partial EBO_2(\mu_2; s_2)}{O_1} = (1 - r_1)(1 - r_2)m_2 \cdot (1 - f_{LRU,1})(1 - f_{LRU,2})$$

Reducing the net LRU mean repair throughput time at Thales

The influence on the expected ship backorders for a unit net LRU mean repair throughput time reduction at Thales is defined as follows:

$$\frac{\partial EBO_2(\mu_2; s_2)}{\partial T_0} = r_0(1 - r_1)(1 - r_2)m_2 \cdot (1 - f_{LRU,0})(1 - f_{LRU,1})(1 - f_{LRU,2})$$

Multiplying those marginal improvements with the decrease (Δ) of the time parameter (order-and-ship time or mean repair throughput time) results in a local approximation for the improvement in the expected ship backorders. In Section 5.3 we define the costs per year for each tactical decision.

5.3. Costs per Year of the Tactical Decisions

5.3.1. Stocking LRUs

The investment of stocking an extra spare LRU is equal to the LRU price. However, we use the inventory holding costs to calculate the invested euro *per year* of stocking an extra spare part. This is a percentage (h) of the LRU price (c). The extra investment / costs (C) per year for stocking an LRU is therefore defined as:

$$C_{LRU} = h \cdot c$$

5.3.2. Stocking SRUs

Stocking subcomponents (SRUs) of an LRU lowers the waiting time for those SRUs and thereby the gross repair throughput time of the LRU. Since at Thales for many LRUs the SRUs are hard to find out (including the prices and MTBF values), we will make a generic model that determines the costs per year for stocking SRUs. However, it will be a rough model since the results are only an indication of whether it is useful to stock SRUs of an LRU or not. If it is useful, the SRUs including their prices and MTBF values have to be found out and the exact cost should then be calculated.

When SRUs are stocked, the gross LRU mean repair throughput time decreases at most with the average procurement lead-time of the SRUs. The marginal backorder reduction equations (see Section 5.2) are only a good approximation for small reductions in a time parameter. Since the average waiting time of SRUs ($T_{w,j}$) are large (months instead of days), we use a stepwise reduction (iterative procedure) in the waiting time such that the marginal backorder equations are a good approximation for calculating the impact of this tactical decision.

Since the SRUs of an LRU are currently not known, we approximate that all SRUs are aggregated to one overall SRU for which q_{ij} is equal to one (the probability that the LRU failure is caused by the aggregated SRU, found at location j, is one). We reduce the average waiting time for this aggregated SRU with a percentage (k). Each time we increase k with a predetermined step size (s). For example when k=0.20, the SRU waiting time reduces with 20 percent. When k=1, the waiting time for the aggregated SRU is reduced to zero and the *gross* LRU repair throughput time is equal to the *net* LRU repair throughput time. The gross LRU mean repair throughput time at Thales and the reduction (Δ) are defined as follows:

$$T_{Gross,0} = T_0 + T_{w,0} \cdot (1 - k)$$
$$\Delta T_{Gross,0} = T_{w,0} \cdot \Delta k = T_{w,0} \cdot s$$

According to Little (1961), the SRU waiting time is calculated by dividing the expected SRU backorders by the SRU demand. Decreasing the backorders, decreases the waiting time. The expected backorders are a function of the stocking policy and the more the backorders have to be decreased, the more stocks are needed. We therefore assume in our model that the more we want to decrease the SRU waiting time, the more SRUs need to be stocked. The costs are very low when there is a low probability that the aggregated SRU is on stock. For high probabilities the costs are very high. When the LRU waiting time for an SRU is reduced to zero (k =1), we assume that the total (maximum) SRU costs is a percentage (p) of the LRU price. This percentage has to be estimated and based on expert opinions. Multiplying this with the inventory holding cost percentage (h), the total costs per year are determined. [Ypma, 2010]

Next, we define the total costs (C) per year (inventory holding costs) for a percentage (k) reduction in the SRU waiting time and the extra investment (I) if the SRU waiting time is reduced further with a certain step size (s). Since we assume that the larger the reduction in the waiting time the more expensive this tactical decision will be, we square the probability k (*we think this is a simple but reasonable good approximation, because this model is only used as an indication to find out whether it is useful to stock SRUs or not. However, further research may result in a better cost approach).*

$$C_{SRU} = k^2 \cdot h \cdot p \cdot c$$
$$I_{SRU} = \{(k+s)^2 \cdot h \cdot p \cdot c\} - \{k^2 \cdot h \cdot p \cdot c\}$$

Where

k = Percentage reduction in SRU waiting time
h = Inventory holding cost percentage (of the LRU price)
p = Percentage of LRU price to determine the total SRU costs when the SRU waiting time is reduced to zero (k = 1).
c = LRU price
s = Step size (=Δk)

We remark that when for an LRU a significant large ship EBO reduction can be attained when stocking SRUs, we should determine the exact SRUs (including their costs, purchase lead-times, and MTBF values) using a breakdown list of the LRU. Then we determine, with INVENTRI or the (VARI-) METRIC approach, which subcomponents to stock and in which sequence we should do so. The correct extra investment per year for a certain $\Delta T_{Gross,0}$ and corresponding waiting times may then be calculated.

5.3.3. Order-and-ship times from shore to ship

A provisioning ship usually resupplies the repaired items from shore to the ship that is on mission. The time it takes to resupply the spare parts depends on the customer. In order to decrease the order-and-ship time from shore to ship (O_2), we assume an emergency supply is possible (for example by a helicopter). Since these order-and-ship times only take a few days (and not months) we do not use a stepwise reduction for this tactical decision. The reduction (Δ) in the order-and-ship times from shore to ship is defined as:

$$\Delta O_2 = O_{2(Current)} - O_{2(Emergency)}$$

Since the costs of sending an LRU with a provisioning ship are not known (at Thales), we assume the extra investment / costs (C) per year for decreasing this order-and-ship time is equal to the costs of an emergency shipment multiplied with the annual shore demand of that LRU. [Ypma, 2010]

$$C_{O_2} = C_{EmergencyShipment} \cdot m_1$$

5.3.4. *Order-and-ship times from Thales to shore*

Spare parts are usually sent from Thales to the shore location by a transport organisation. Most repairs are sent to the shore location in a batch, instead of one-by-one. The largest part of the order-and-ship times from Thales to shore consists of waiting time (to form a batch). Making smaller batches or sending LRUs one-by-one to the shore location reduces this waiting time. Since it is hard to know which LRUs form a batch, the size of the batch, how many batches there will be in a year, and the transport costs per LRU, we focus only on the one-by-one policy. Since these order-and-ship times, just as the shore to ship times, only take a few days (and not months) we do not use a stepwise reduction for this tactical decision. The reduction (Δ) in the order-and-ship times from Thales to shore (sending LRUs using the one-by-one policy instead of the batching policy) is defined as:

$$\Delta O_1 \quad = O_{1(Current)} - O_{1(One-by-One\,Policy)}$$

Since the transport costs per LRU for the batching policy are hard to determine, we assume that the extra investment / costs (*C*) per year for sending one LRU from Thales to shore is equal to the transport costs (of a transport organisation) multiplied with the annual LRU demand at Thales. [Ypma, 2010]

$$C_{O_1} \quad = C_{Transport} \cdot m_0$$

5.3.5. *Net mean repair throughput time at Thales*

We explained the different processes in the net mean repair throughput time in Section 3.4.3. The net mean repair throughput time at Thales can be lowered in two ways. One possibility is to reduce the net mean repair throughput time by giving a failed LRU priority in the repair and administrative process (it becomes a *fast* repair at Thales). The other way is to decrease the two-week buffer.

<u>Priority rule</u>

A fast repair decreases the *net* mean repair throughput time of an LRU with a certain percentage (*f*). We do not use a stepwise reduction for this tactical decision, since there is only the possibility to have a fast repair or a normal repair at Thales and nothing in between. The reduction (Δ) in the *gross* LRU mean repair throughput time for a fast repair is defined as:

$$\Delta T_{Gross,0} = T_0 \cdot f$$

Repair costs at Thales are in general calculated as a certain percentage of the LRU price (*c*), where fast repairs are more expensive than normal repairs. However, these costs are charged to the customer (and are higher than the actual costs made by Thales) and therefore do not represent the actual extra investment for Thales in case of performance-based service contracts. Since it is hard to determine the costs of decreasing the administrative time or giving priority in the repair process, we assume that for a fast repair the total repair costs (excluding the costs of material and subcomponents) are doubled [Ypma, 2010]. From Wevers (2007) we know that the repair costs at Thales are divided in direct repair costs, material costs, and costs of the material-handling department. Since we assume that the direct repair and material-handling department costs are doubled, the extra investment / costs (*C*) per year for the priority rule is calculated as the sum of the average direct costs (*D*) for a repair and the material-handling department costs (*MH*) for a repair, multiplied with the LRU demand at Thales.

$$C_{Priority} = (D + MH) \cdot m_0$$

Buffer
The two-week buffer in the repair throughput time may also be reduced. Since this is a small (at most two-week) reduction, we do not reduce this time stepwise. Reducing the buffer is not an extra investment. Therefore this will always be the best tactical decision that should be taken. However, since Thales consciously uses this two-week buffer to catch up with process variation and slack time when going from one department to another, we only focus to what extent the buffer affects the system performance and we do not include this decision in our optimisation method (which we will develop in Chapter 6).

Since we now know the marginal improvements of each tactical decision and the corresponding costs, the approximated impact (ΔEBO per invested euro per year) for each tactical decision can be calculated. For these equations we refer to Appendix E-3. Section 5.4 gives a summary of this chapter and answers the third research question.

5.4. Conclusion

In this research we focus on five different tactical decisions: Stocking spare parts (both LRUs and SRUs), reducing order-and-ship times (from shore to ship and from Thales to shore), and reducing the mean repair throughput time (using the priority rule). We do not consider the buffer time in the repair throughput time as a tactical decision in our optimisation method because Thales consciously uses a two-week buffer. In this chapter we answered the third research question "*How can we determine the impact of the tactical decisions on the average availability?*"

To compare the tactical decisions, we calculate the impact (reduction (Δ) in the ship EBO per invested euro per year). Multiplying the marginal ship backorder improvement per time unit reduction with the decrease (Δ) in the time parameter approximates the ΔEBO of the tactical decisions for each LRU. From Section 5.2 we see that for each tactical decision for an LRU, the marginal ship backorder reductions are calculated using repair probabilities, demands, and fill rates.

From the developed cost models, the costs per year for adding extra LRUs on stock are determined by the inventory holding costs (percentage of the LRU costs). The costs for stocking extra SRUs are based on a stepwise reduction in the waiting time for the SRU. For this, we use a generic cost model and use an iterative procedure where each time we decrease the waiting time with a predetermined step size and calculate the extra investment. For the order-and-ship times from shore to ship we use the costs of an emergency shipment, whereas we use the transport costs of a transport organisation for the order-and-ship times from Thales to shore. The last tactical decision is the priority rule in the repair process, where the costs per repair are the sum of the direct and material-handling costs.

6. Decision Making Process

In this chapter we focus on the fourth research question: "In which general way can we determine which tactical decisions Thales needs to take?" For this end, we developed a tool in Excel that calculates all needed information and supports the decision making process. We start this chapter with an introduction in Section 6.1 and elaborate in Section 6.2 on different greedy heuristics to determine which tactical decision(s) Thales should take for a certain performance-based contract. For each heuristic we elaborate on the optimisation procedure and end this chapter with a brief summary of the decision making process in Sections 6.3 and 6.4 respectively.

6.1. Introduction

Based on Chapter 5, we implemented the effects of the different tactical decisions per LRU in Excel (see Appendix F for a short overview of the tool). This tool supports us in the decision-making process. It uses the METRIC approach and calculates per location (ship, shore, Thales) the demand, pipeline, backorders, and fill rates. With this output, the impact (expected LRU ship backorder reduction (ΔEBO) per invested euro per year) for each combination of LRU and tactical decision is calculated. Section 6.2 elaborates on different greedy heuristics that determine which tactical decisions should be taken for which LRUs.

6.2. Greedy Heuristics

To improve the average availability, we define the following three different greedy heuristics:

Heuristic 1: Tactical decisions over all LRUs

The first heuristic looks at all LRUs in the system and each time (iterative procedure) chooses the combination of LRU and tactical decision that contains the largest ΔEBO per invested euro per year. The procedure stops when the target (e.g. average system supply availability) is reached.

Heuristic 2: Tactical decisions over the availability killers

To reduce the amount of combinations of LRUs and tactical decisions, it is also possible to only look at the so-called "*availability killers*". These are the bottleneck LRUs that have the largest expected ship backorders. The LRUs with the largest ship backorders cause the largest downtime and therefore influence the average availability the most. In this heuristic we reduce the expected ship backorders of the availability killers, where we start with the first availability killer and proceed with other availability killers until the target (e.g. average system supply availability) is reached. We will develop a rule (Section 6.3) to determine the point when to go from one availability killer to the other.

Heuristic 3: Tactical decisions for all LRUs together

Tactical decisions may also be taken for all LRUs together in the system. Thales [Ypma, 2010] indicated that a certain time parameter might be changed for all LRUs together in a system due to practical issues. Since this heuristic will never be optimal (because parameters are also changed for LRUs for which no backorder reductions may be attained), we will use this heuristic only to see which tactical decision in general has the largest influence on the expected ship backorders and we may draw some overall conclusions from these results.

The *first* heuristic may be the best approach since each time the combination of LRU and tactical decision are chosen that has the largest impact. However, this takes a lot of work and may be difficult to use in practice since there are many combinations of LRU and tactical decisions (five tactical decisions for a system of 100 LRUs results already in 500 different combinations). Although it is possible to use this heuristic in the developed Excel tool, we do not recommend it. We recommend this heuristic when it is programmed (e.g. in Delphi) or when it is possible to integrate it in INVENTRI.

The *second* heuristic may be better to use in practice, because we then only look at a few LRUs (availability killers) and not at all LRUs in the system. However, since we then ignore many LRUs it is possible that we do not take the optimal decision each time (best combination of LRU and tactical decision) and the total costs may become larger than for heuristic one.

Heuristic *three* is only an approach to see which tactical decisions in general have the largest impact. This heuristic is worse than the other two heuristics, because money is then also invested in tactical decisions for LRUs for which no backorder reductions will be attained. Also using the priority rule for all LRUs in the system may not be feasible in practice, because giving priority to one LRU means another LRU has to wait and its repair throughput time becomes longer. In the case study we will analyse the impact of all three heuristics to see the differences (in costs). We elaborate in Section 6.3 on the optimisation procedures.

6.3. Optimisation Method

Before we start with the optimisation method for the different heuristics, data needs to be gathered about the LRUs and the tactical decisions. Before we are able to calculate the expected ship backorders for each LRU, we need data about item characteristics, time parameters, repair probabilities, and stock allocations. This data should already be available, since the initial spare part allocation has already been calculated with this data in INVENTRI.

Besides this input data, we need to determine to what extent the time parameters can be reduced (feasibility in practice). Order-and-ship times from shore to ship for example, can be reduced to two days when using a helicopter to fly in the spare part onboard. However, this is an expensive option. Therefore also the corresponding costs need to be determined for each tactical decision. For this, we use the cost models from Chapter 5. With all the data, we calculate for each LRU the ship EBO and we calculate for each combination of LRU and tactical decision the ΔEBO per invested euro per year. Since the three heuristics (See Section 6.2) slightly differ from each other, they all have a different optimisation procedure:

Optimisation Procedure for Heuristic 1:

1. Initialise the total ship EBO for each LRU and the corresponding total costs. Where for each LRU the $\mathit{Total\ EBO} := \mathit{Initial\ Value\ EBO}$ and the $\mathit{Total\ Costs} := 0$.

2. Calculate for each combination of an LRU and tactical decision the impact (ΔEBO per invested euro per year).

3. Choose the combination of LRU and tactical decision with the largest impact (that contains the maximum ΔEBO per invested euro per year) and obtain the ΔEBO and

the extra investment for that LRU. Adapt for the chosen LRU the *Total EBO* and adapt the *Total Costs*.

$$Total\ EBO := Total\ EBO\ - \Delta EBO\ for\ chosen\ tactical\ decision\ and\ LRU$$

$$Total\ Costs := Total\ Costs\ + Costs\ for\ chosen\ tactical\ decision\ and\ LRU$$

4. Take the chosen tactical decision for the LRU and change the corresponding parameter in the input data. Go back to step 2 and stop the procedure when the average system supply availability is at least equal to the predetermined target level.

Optimisation Procedure for Heuristic 2:

1. Calculate the ship EBO of all LRUs, and sort the ship EBOs of all LRUs in decreasing order. Initialise the total ship EBO for each LRU and the corresponding total costs. Where for each LRU the $Total\ EBO := Initial\ Value\ EBO$ and the $Total\ Costs := 0$. Start with the LRU that is the number one in the list (number one availability killer).

2. For this availability killer, calculate for each tactical decision the impact (ΔEBO per invested euro per year).

When for this availability killer a large ship EBO reduction can be attained when stocking SRUs (compared to the other tactical decisions), calculate the exact extra investment per year for a certain percentage reduction in the waiting time for SRUs (instead of using the cost model from Section 5.3.2) and determine which subcomponents to stock and in which sequence using INVENTRI or the (VARI-) METRIC approach. Otherwise, use the developed cost model (from Section 5.3.2) to calculate the costs per year for stocking subcomponents.

3. Choose the tactical decision with the largest impact (that contains the maximum ΔEBO per invested euro per year) and obtain the ΔEBO and the extra investment for the availability killer.

However, availability killers are in most cases very expensive. When the best tactical decision is to stock an extra LRU of the availability killer, we will check whether there is another LRU in the whole system that can be stocked for less costs (*because we focus on low costs*). Check for which LRU in the whole system stocking an extra spare LRU is the best option (largest ΔEBO per invested euro per year). If that LRU is the availability killer under consideration or one of the previous availability killers (for which other tactical decisions already have been taken), stock that LRU. Otherwise do not stock an LRU, go to the next availability killer in the list, and go back to step 2.

Finally, adapt for the availability killer the *Total EBO* and adapt the *Total Costs*.

$$Total\ EBO := Total\ EBO\ - \Delta EBO\ for\ chosen\ tactical\ decision\ and\ LRU$$

$$Total\ Costs := Total\ Costs\ + Costs\ for\ chosen\ tactical\ decision\ and\ LRU$$

4. Take the chosen tactical decision and change the corresponding parameter in the input data. Go back to step 3 and stop the procedure when the average system supply availability is at least equal to the predetermined target level.

Optimisation Procedure for Heuristic 3:

1. Initialise the total ship EBO for each LRU and the corresponding total costs. Where for each LRU the $\textit{Total EBO} := \textit{Initial Value EBO}$ and the $\textit{Total Costs} := 0$.

2. Calculate for each tactical decision the sum of the ΔEBO over all LRUs and calculate the sum of the extra investments over all LRUs. Only stocking an LRU is not done for all items together (this is very expensive and will never be optimal). Calculate for this decision only the ΔEBO and the extra investment for that LRU for which stocking an extra spare has the largest impact (ΔEBO per invested euro per year). Although using the priority rule for all items together in the system may not be feasible in practice, we will analyse the impact of this decision.

3. Choose the tactical decision with the largest impact (that contains the maximum sum of the ΔEBO over all LRUs per total invested euro per year) and obtain for each LRU the ΔEBO and the extra investment. Adapt for each LRU in the system the *Total EBO* and adapt the *Total Costs*.
$$\textit{Total EBO} := \textit{Total EBO} - \Delta \textit{EBO for chosen decision}$$
$$\textit{Total Costs} := \textit{Total Costs} + \textit{Sum of costs over all LRUs for chosen decision}$$

4. Take the chosen tactical decision and change with this the parameter for the LRUs in the input data. Go back to step 2 and stop the procedure when the average system supply availability is at least equal to the predetermined target level.

6.4. Conclusion

In Excel we implemented the effects of the different tactical decisions (ΔEBO per invested euro per year) per LRU. We divided the method to improve the average availability into three greedy heuristics. The *first heuristic* looks at all LRUs in the system and takes each time a tactical decision for a specific LRU. The *second heuristic* mainly focuses on availability killers instead of all LRUs in the system. The *third heuristic* takes each time the same tactical decision for all LRUs together in the system.

The optimisation method for each heuristic consists of two phases. The *first phase* is to gather all needed data and determine to what extent the time parameters can be reduced (feasibility in practice) including the corresponding costs. The *second phase* is the optimisation procedure that slightly differs for each heuristic. The procedure consists in general of three steps. In the *first step*, for each combination of LRU and tactical decision the impact (ΔEBO per invested euro per year) is calculated. In the *second step*, depending on the heuristic, the (combination of LRU and) tactical decision that has the maximum impact is chosen. We keep track of the total *EBO* of all LRUs and the corresponding total costs. *Finally*, the procedure stops when the average system supply availability is at least equal to the predetermined target level.

Since we developed three heuristics, we did not give an exact answer on the fourth research question "*In which general way can we determine which tactical decisions Thales needs to take?*". In Chapter 7, we will analyse the results of the three heuristics for a certain case. Based on these results, we will answer the fourth research question (we will choose the best heuristic to determine which tactical decisions Thales needs to take).

7. Case Study

In this chapter we answer the fifth research question: "*What is the impact of the tactical decisions on the average availability, the variability, initial investments, and the robustness to changing annual operating hours, and what general conclusions can be drawn?*" We start this chapter with a case introduction and specific case characteristics in Sections 7.1 and 7.2 respectively. In Section 7.3 we elaborate on the current case performance (availability and variability) and we determine the feasibility and costs of the tactical decisions in Section 7.4. To see which heuristic results in the lowest costs we follow the developed heuristics in Section 7.5. Since we are also interested in the influence of tactical decisions on the variability of the average availability, the savings in initial investments, and the improvement in the system robustness to changes in annual operating hours, we analyse this in Sections 7.6, 7.7, and 7.8 respectively. We end this chapter in Section 7.9 with conclusions.

7.1. Introduction

As a case study, we use a contract for six SMART-L (see Figure 7.1) radar systems that Thales will supply to a customer in the future. SMART-L means "*Signal Multi-beam Acquisition Radar for Targeting-L Bands*". The SMART-L radar is a three-dimensional multi-beam radar and provides long rang air and surface support for surveillance and target designation. The SMART-L provides a large coverage (hundreds of kilometres). [Thales, 2009]

Figure 7.1: SMART-L

In the contract offered, estimated failure rates are used for calculations during the first seven year and information about actual mean time between failures and costs made for maintenance and repair are gathered in this period. The collected information will be used for a 25-year contract. The performance indicator is 88 percent system supply availability. Thales stocks the spare parts (the allocation is calculated with INVENTRI) and provides the necessary people and resources to support the customer. Thales has an internal requirement and allows the average availability to be lower than required once every five years and therefore does not mind to pay a penalty once every five years (while the penalty and bonus structure is even not defined yet for this contract).

Since we also want to know the influence of the tactical decisions on the availability variability, we use a simulation model. Both the input and output (spare part allocation) of INVENTRI is used as input for the simulation model. We use the simulation model that is developed by Coenen (2009) for Thales, where the model mimics the failure and repair process of radar systems as manufactured by Thales (see Appendix G).

A drawback of both INVENTRI and the simulation model is that they both do not use mission profiles in their calculations. In reality there will be different missions where the systems are active, alternated with periods where the radar systems are not in use. *(1)* There is a high demand for spare parts in the period when ships are sent together on mission at the same time, but the demand will be more stable if the ships are not sent on mission at the same time. *(2)* Different missions influence the choice of tactical decisions, because each tactical decision has its lead-time before it affects the availability. A long-term decision (stocking spare parts) may for example be better than a short-term decision (reducing time parameters), when no ship will be sent on mission the coming few months.

Since both the simulation model and INVENTRI do not use mission profiles in their calculations we also do not use mission profiles in this case. We assume, like INVENTRI and the simulation model, that the ships are sent simultaneously on a mission the whole year and we adapt the MTBF values of all items for a given annual operating hours. The question is whether other time parameters (e.g. repair times) should also be adapted besides the MTBF values. Since this is not done in INVENTRI, we also do not adapt other time parameters. We recommend further research on investigating the impact of different mission profiles on the availability and the variability.

7.2. Case Characteristics

In this case the radar systems are used on six ships. The supply chain is a three-echelon network, where all ships are supplied by one shore location, and Thales supplies this shore location (see Figure 7.2). Thales, the shore organisation, and the ships all have a local repair and spare part stock location.

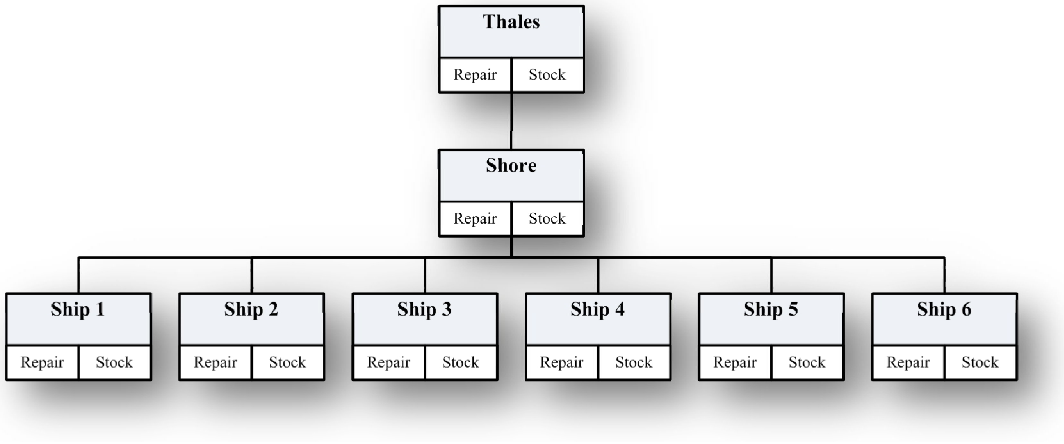

Figure 7.2: Supply Network of the Case

In the simulation model, the SKUs are divided in both line replaceable (LRU) and shop replaceable units (SRU). INVENTRI however, uses the original breakdown (six-indenture structure) of the system. The supply network is a 3-echelon, 2-indenture network, with 179 stock keeping units (SKUs). There are 100 different SKUs, of which four are different SRUs (only the failure rates and repair times of these SRUs are currently known at Thales) and the other 96 are different LRUs. The SKU costs vary between a few Euros to over 100,000 Euros. The estimated mean times between failures differ from 20,000 hours to over one billion hours. It is remarkable that the most expensive LRU also has the highest failure rate and recurrence in the system (22 times). We expect these kinds of SKUs to be critical in the system.

For calculations, we have to make some assumptions about operational hours and time parameters. We assume all ships are sent simultaneously on one mission for four months (one third of a year). This results in fixed total annual operating hours of 2880 and 2920 for respectively the simulation model and INVENTRI (there is a small difference since the simulation model calculates with 30 days a month and INVENTRI calculates with 365 days a year). During these operational hours there is a continuous demand where items fail even when the system is down. The total supply availability a year is then calculated as the total time the system is operating (not waiting for a spare part) over a whole year.

With respect to the time parameters, gross repair throughput times are based on historical data and differ between three and six months. The simulation model uses exponentially distributed repair times. The procurement lead-time of new SKUs is equal for each location but differ for each SKU. Order-and-ship times are assumed to be deterministic, because in practice there is no high fluctuation of these times. Based on Ypma (2010), we assume the order-and-ship times from Thales to shore are 14 days (336 hours) and from shore to ship 5 days (120 hours). The standard transporting time (of a transport company) consists of seven days, where it also takes some time (we assume seven days) until the item is checked and approved by the customer before it is stocked or sent to one of the ships. The five days it takes to ship the item from shore to one of the ships is agreed upon with the customer [Ypma, 2010]. Table 7-1 gives an overview of the case characteristics and assumptions.

Structure

- **Average system supply availability** is set to a target of **88 percent** a year.
- Supply availability is measured as the total time (in a year) the system is not waiting for a spare part.
- There are six ships, all having one radar system onboard.
- Spare parts can be stocked on the ship, on shore, and at Thales, but this differs per item.
- Repairs can be done on ship, on shore, and at Thales, but this differs per item.

Operating Hours

- A month has 30 days and 24 hours a day.
- Each ship is sent once a year on a mission of four months (what results in 2880 operating hours).
- The system has a 100 percent utilisation rate when a ship is on mission.
- We assume continuous demand (items fail even when the system is down).

Time Parameters

- Repair throughput times are based on historical data, differ between three and six months, and in the simulation model they are exponentially distributed.
- There are deterministic order-and-ship times of repaired items to various locations.
    - From Thales to Shore takes 14 days
    - From Shore to Ship takes 5 days
- The procurement lead-time of new items is equal for each location, but this differs per item.

Table 7-1: Summarizing Case Characteristics and Assumptions

7.3. Current Performance

INVENTRI calculates the optimal spare part allocation for a target availability level of 0.88. The total initial spare part investment is then about €2,760,000. We use a simulation model to measure the (performance) variability of the average availability. We will first verify the simulation model, such that we know the simulation results are correct.

In the simulation model we use a warm-up period. From this point in time the system is in its steady state and the performance measurement starts after this period has passed. According to Welch's method, the warm-up period is 150 years (see Appendix H). We currently use a warm-up period of 10.000 years. This is much longer, but situations that occur only on rare occasions (because of some very long MTBF values) will then probably be included and it takes almost no extra runtime. We further use a simulation run length of almost 20.000 years. This long run length allows us to obtain accurate probability distributions of the availability.

Although the performance indicator at Thales is the system availability per ship, we use the system availability of the total network (six ships) since in the analytical calculations (METRIC approach) the ships are assumed to be equal and in the simulation model there is only a very small difference (maximum of 0.002) between the average network availability and the ship availability values (see Appendix I-1). To check whether the simulation model is correct and we have correctly inputted the data, we compare the average network availabilities of the simulation model to the values calculated by INVENTRI (see Appendix I-2 and I-3). Figure 7.3 shows the spare part investment with the corresponding availability levels. Since in service contracts the focus is always on high availabilities levels, we only focus on availability levels from 0.70 and higher. Figure 7.4 shows the convex variability (in standard deviation) versus cost curve. When we compare this to the concave availability versus cost curve (Figure 7.3), we see that the availability variability decreases as the average availability increases.

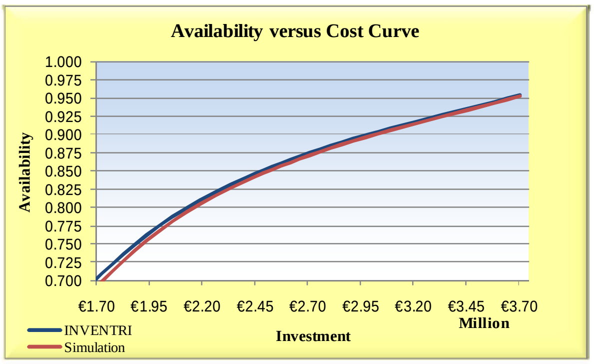

Figure 7.3: Availability versus Cost Curve

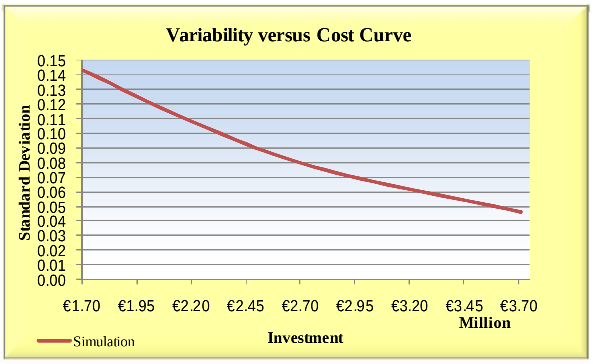

Figure 7.4: Variability versus Cost Curve

The results of the simulations and INVENTRI almost correspond for all availability levels, but there is a difference. This is at most one percent (for target availabilities of 0.60 and 0.70). For the target availability of 0.88, there is a difference of 0.04 (the availability in the simulation model is 0.876). The reason for the differences is not known. This can be due to small differences in input (e.g. AOH) in INVENTRI or the simulation model, or approximation errors made by the VARI-METRIC method in INVENTRI.

Figure 7.5 shows the survival function, which gives the probability that the current availability is at least the target availability. With a target availability of 0.88, we see that in the current situation we have a survival rate of 60 percent. This means we have 40 percent chance (two out of five years) that the system performance is below the target.

The histogram in Figure 7.6 shows the behaviour (distribution) of the yearly network availability when we have optimised the spare part allocation with INVENTRI for the 88 percent target availability. The distribution of the supply availability tends to be skewed to the left. This means that there is more risk that the attained availability will be below instead of above the target. The simulation results show that the average availability is in this case 0.876, with a corresponding standard deviation of 0.077.

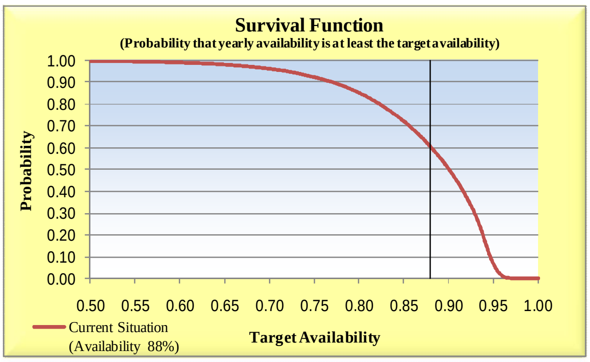

Figure 7.5: Survival Function

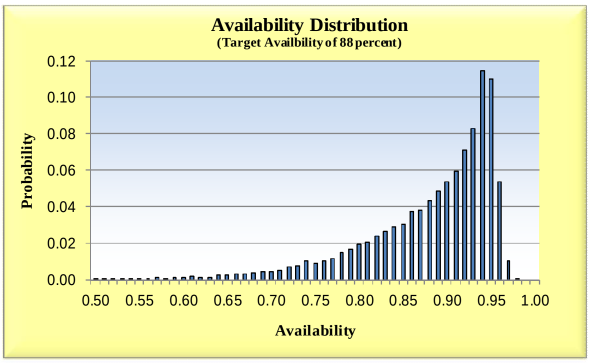

Figure 7.6: Availability Distribution for 88% Target Availability

7.4. Feasibility and Costs of Tactical Decisions

We have measured the current performance of the case and we know that a tactical decision has to be taken. Before we start with the optimisation procedure, we need to analyse the feasibility of the tactical decisions in practice and the corresponding costs. Data about the case and the LRUs are already known since we used this data in INVENTRI to calculate the optimal spare part allocation and we used this data to analyse the current performance with the simulation model. Next, we elaborate on the feasibility and costs of the tactical decisions.

For *stocking LRUs*, the inventory holding costs are calculated. At Thales these are in general 15 percent ($h = 0.15$) of the LRU price [KVM, 2010]. *Stocking SRUs* of the LRU decreases the LRU waiting time for the SRUs in the gross mean repair throughput time. Since the gross mean repair throughput time of the LRUs is known at Thales, the waiting time of the SRUs is calculated by subtracting the net repair throughput time (eight weeks) from the gross repair throughput time. In this case we reduce the SRU waiting time with a step size of 10 percent ($s = 0.10$), since for this step size the marginal backorder equations are still a good approximation for calculating the impact of this tactical decision. We assume that the total (maximum) SRU costs are 50 percent ($p = 0.50$) of the LRU price [Ypma, 2010].

In this case the *order-and-ship times from shore to ship* are reduced from 5 days to 2 days [Ypma, 2010]. We assume an emergency supply is done by helicopter and it takes at least one day to fly with a helicopter from shore to a ship that is on mission. Besides this, it takes some time to pick the spare part from the warehouse and it takes some time to unload the item from the helicopter and replace it in the radar system. We assume this all takes about two days, including the helicopter flight. The total annual costs for a helicopter with an average of 550 flight hours a year are €230,000. For a flight of one day (24 hours) the costs of emergency shipment (sending a spare part with a helicopter from shore to ship) are then around €10,000. [Cox, 2004]

The *order-and-ship times from Thales to shore* are reduced from 14 days to 7 days. In case the items do not have to wait to form a batch (one-by-one policy), it takes the standard transporting time of seven days to ship an item from Thales to shore. We assume the average weight of a spare part is about ten kilogram [Ypma, 2010]. The transport costs (sending an item with DHL delivery) are around €75 for such an item [DHL, 2010].

Using the *priority rule*, where a fast repair instead of a normal repair is done, leads to a 50 percent reduction ($f = 0.50$) in the net repair throughput time of an LRU. Since the net repair throughput time is equal to eight weeks, the reduction ($\Delta T_{Gross,0}$) is equal to four weeks. The extra average direct repair costs are €1,000 and the extra material handling department costs are about €500, which results in an investment of €1,500 per repair [Wevers, 2007].

Lowering the mean repair throughput time by reducing the two-week *buffer* is a tactical decision that does not cost anything, but we do not include this decision in our optimisation method. We only elaborate on the effect of the buffer on the ship EBO values when reducing this for all items together in the system (the third heuristic from Section 6.2), because this gives us an indication to what extent the buffer affects the system performance.

Now we know the feasibility and costs of the tactical decisions, we elaborate in Section 7.5 on each heuristic (from Chapter 6) and follow the developed optimisation procedures.

7.5. Impact of Tactical Decisions on Average Availability

7.5.1. Results of the different heuristics

With the Excel tool we are able to see for which LRU we have to take which tactical decision. Before starting the optimisation procedure we define our target as an availability level of 90 percent. We choose this level to reduce the amount of tactical decisions, since the EBO reductions per tactical decision are low and we expect that already many tactical decisions should be taken before reaching the target availability level of 90 percent. We calculate this availability level with the simulation model, because we then also measure the variability of the availability for the tactical decisions (see Section 7.6).

Table 7-2 shows the results for the INVENTRI solution (stocking LRUs and SRUs) as well as for the three developed heuristics. We see that heuristic one results in the lowest annual costs, but it takes many decisions for many different LRUs. Heuristic two however, has slightly larger absolute annual costs and only a few tactical decisions for two availability killers are needed. Heuristic three is inferior to the other two heuristics, since the annual costs are more than three times as high. We will further elaborate on the results of each heuristic.

	Annual Costs	% of INVENTRI solution	Availability	#Tactical Decisions	# Different LRUs
INVENTRI	€ 47,000	-	0.902	12	7
Heuristic 1	€ 2,664	5.6%	0.900	57	45
Heuristic 2	€ 2,955	6.2%	0.900	6	2
Heuristic 3	€ 8,860	18.9%	0.901	289	96

Table 7-2: Overview of the Results of the Three Heuristics and the INVENTRI solution

<u>Heuristic 1: Tactical decisions over all LRUs</u>

Looking at the LRUs and tactical decisions that have the largest ΔEBO per invested euro per year, we see that we change the first 25 times the order-and-ship times from Thales to shore for items for which there is no stock in the supply chain. Appendix J shows the rest of the iterations of the optimisation procedure (combinations of the tactical decision and LRUs) until an availability of at least 90 percent is reached. 57 tactical decisions for 45 LRUs are required before an availability level of 90 percent is reached. The *Total Costs* are then €2,664. We see that many tactical decisions are needed to increase the availability level only with 0.024, but the investment is very low. The costs are only 5.6% of the costs when only looking at stocking extra spare parts (INVENTRI solution).

<u>Heuristic 2: Tactical decisions over the availability killers</u>

The so called "availability killers" are the bottleneck LRUs that have the largest influence on the supply availability and have the largest ship backorders. To see which LRUs are the availability killers in our case, we sort the ship backorders per LRU in decreasing order. Table 7-3 shows the top three availability killers. We see that item 54 has, compared to all other LRUs, a very large backorder value. In the current situation there are no spares onboard for item 54, but four spares are on stock onshore and 11 at Thales. For item 55 only one spare is held on stock onshore, and for item 18 there are currently no spares in the supply chain.

Item Nr.	Multiplicity	MTBF (Hrs)	MTTR (Days)	Item Costs	Ship EBO
Item 54	22	19,129	180	€ 126,688	**0.0510**
Item 55	2	48,300	180	€ 100,717	**0.0136**
Item 18	1	188,000	180	€ 33,020	**0.0080**

Table 7-3: Top Three Availability Killers

It is possible to reduce the backorders *onshore* or at *Thales* to almost zero when stocking extra spares of an LRU onshore or at Thales. Since in the current situation there is no stock onboard for item 54, there are still *ship* backorders for this item (which in this case are equal to their pipelines). The ship pipeline depends directly on the shore backorders and the order-and-ship time from shore to ship. Reducing the backorders onshore or at Thales reduces therefore only partially the ship backorders. Since other LRUs also have ship backorders, decreasing the ship backorders to zero for item 54 will lead to a maximum improvement in the average availability.

For the first availability killer, a significant large ΔEBO can be attained when stocking SRUs (compared to the other tactical decisions). Therefore we calculate the exact extra investments for stocking SRUs instead of using the cost model from Section 5.3.2 (see Appendix K-1 for the breakdown structure of this availability killer). We use the marginal analysis, using our own spreadsheet calculation, to determine the sequence and the costs of the SRUs to stock (see Appendix K-2). The results show that there is maximum improvement in the ship EBO values when stocking the SRUs at Thales. This is caused by the before mentioned reason that a reduction in the Thales backorders only partially reduces the ship backorders. Finally, a total investment of about €4,000 per year is needed to obtain the minimum ship EBO where the reduction in the waiting time is 74 percent. Figure 7.7 shows the annual costs for a certain percentage decrease in the average SRU waiting time.

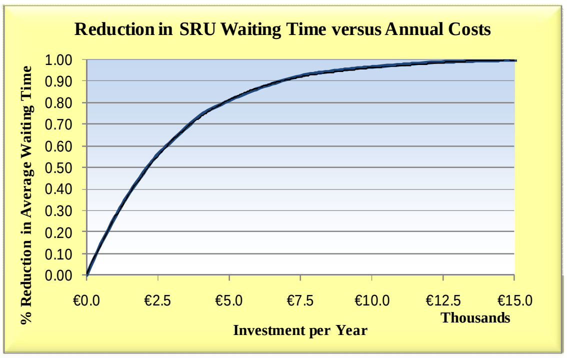

Figure 7.7: Reduction in Average SRU Waiting Time versus Annual SRU Investment

Investing in the SRUs of the first availability killer is better than investing in spare parts as calculated with INVENTRI or investing in extra LRUs of the availability killer (see Appendix K-3). Instead of investing €4,000 in SRUs, an investment of €45,000 per year in spare parts (INVENTRI solution) or €114,000 per year in extra LRUs of the first availability killer is needed to attain the same average availability level.

From the Excel tool, we see that decreasing the order-and-ship time from Thales to shore and stocking SRUs (for k = 0.10) for the first availability killer results in a small ship EBO reduction, but also for very low costs. Those two have therefore a large impact (ΔEBO per invested euro per year) compared to the other tactical decisions. See Appendix K-4 for the results of the first and other iterations for the first availability killer.

In the optimisation procedure we go to the second availability killer (item 55) when we have stocked SRUs of the first availability killer for a weighted fill rate of 0.30 and reduced the order-and-ship time from Thales to shore to seven days. The *Total Costs* are then €2,825. When we have stocked SRUs of the second availability killer for a weighted fill rate of 0.10 and reduced the order-and-ship times from Thales to shore, the *Total Costs* increase to €2,954 and the availability level increases to 0.900. Since the availability level is now equal to our target, we stop the optimisation procedure. For this heuristic only six tactical decisions for two different LRUs are required, instead of 57 tactical decisions for 45 different LRUs in heuristic one. The costs however, are slightly larger than for heuristic one (6.2% instead of 5.6% compared to INVENTRI).

Heuristic 3: Tactical decisions for all LRUs together

We already know the influence on the average availability when investing in extra spare parts as optimised with INVENTRI (see Figure 7.3). The first extra LRU that will be stocked is item 55, since this LRU has the largest impact (largest ΔEBO per invested euro per year). This LRU will be stocked at Thales, where the costs per year for this item are about €15,000.

From the Excel tool we see that decreasing for all LRUs the order-and-ship time from Thales to shore and stocking SRUs (for k = 0.10) results in a small ΔEBO, but also for very low costs. The order-and-ship times from shore to ship have a large ΔEBO, but it is also an expensive investment. Lowering the gross mean repair throughput time by using the priority rule or stocking subcomponents contains a large ΔEBO. Reducing the administrative time does not bring extra costs with it and seems therefore an easy way to improve the system performance (the ΔEBO is even larger than a reduction in the order-and-ship times from Thales to shore). See Appendix L-1 for the results of the first iteration for this heuristic.

Appendix L-2 shows the results for the tactical decisions that are taken until at least the target availability level of 0.90 is reached. From the results we see that we have four iterations, in which SRUs are stocked for all LRUs for a weighted fill rate of 0.20, the order-and-ship times from Thales to shore are reduced for all LRUs to seven days, and one extra LRU is stocked. The *Total Costs* are then about €8,860 for an availability level of 0.901. Since the availability level is now equal to our target, we stop the optimisation procedure.

For this heuristic, there are in total 289 tactical decisions needed for all 96 different LRUs in the system. Since this heuristic also invests money in tactical decisions for LRUs for which no backorder reductions are attained, the costs become large. The costs are much higher than for the other two heuristics, but are still low compared to the INVENTRI solution (the costs are 18.9% compared to INVENTRI). Based on these case specific conclusions, we elaborate on some general findings in Section 7.5.2.

7.5.2. General Findings

From the ship backorder reductions (per invested euro per year) we also see for which LRUs in general a tactical decision has a large impact.

Order-and-ship times from shore to ship

The order-and-ship times from shore to ship have a large influence (marginal ΔEBO) on LRUs for which there are no spare parts on stock onboard and that cannot be repaired on the ship. This can be explained, because a failure of one of these LRUs will immediately lead to a downtime of (at least) the order-and-ship time from shore to ship. A large EBO reduction (not marginal) may be attained when these LRUs also have a large demand, because the onboard fill rate and ship repair probability are both zero for these kind of LRUs and the marginal ship EBO improvement is then equal to the ship demand. Compared to all tactical decisions, reducing these order-and-ship times contain the largest ΔEBO, but for the largest costs.

Order-and-ship times from Thales to shore
The order-and-ship times from Thales to shore have the largest impact (ΔEBO per invested euro per year) on LRUs for which there are no spare parts in the whole supply chain. Since these LRUs have a low demand (therefore no spares are needed), the costs per year are low. However, reducing these order-and-ship times only leads to a small reduction in the EBO. The LRUs, for which these order-and-ship times have the largest ΔEBO, are the LRUs that are in the top of the list of the availability killers. Compared to all tactical decisions, the smallest ΔEBO is attained when reducing these order-and-ship times, but also for the lowest costs.

Gross repair throughput times
The gross mean repair throughput time has a large influence on the system performance. It is hard to say for which LRUs in general stocking SRUs or using a fast repair has an impact, because it depends on the demand and the LRU prices (that vary from a few Euros to over €100,000). The LRUs, for which the gross repair throughput time has the largest ΔEBO, are those LRUs that are in the top of the list of the availability killers (just as for the order-and-ship times from Thales to shore). The two-week buffer in the net repair throughput time is also an important factor, since it has a small impact on the ship EBO for no extra costs.

7.6. Impact of Tactical Decisions on Availability Variability

In this section, we measure the impact of the tactical decisions (using the results of the three heuristics) on the variability of the availability. The availability variability will be expressed in the standard deviation (σ). In order to compare the influence of the different tactical decisions on the variability, we also show the probability that the availability is larger or equal to 88 percent (survival rate).

In the current situation we have a standard deviation of 0.077 and a survival rate of 60 percent (see also Section 7.3). Table 7-4 shows the results for all three heuristics and the INVENTRI solution. Based on these results, we see that there is no reasonably fixed relation between the average availability and the standard deviation. It seems that the standard deviation can be more than proportionally decreased by using a combination of reducing time parameters and stocking extra spare parts (SRUs and LRUs) as to only stocking extra spare parts.

	Annual Costs	Availability	σ	Survival Rate
Current Situation	**-**	**0.876**	**0.077**	**0.60**
INVENTRI	€ 47,000	0.902	0.066	0.74
Heuristic 1	€ 2,664	0.900	0.056	0.75
Heuristic 2	€ 2,955	0.900	0.056	0.74
Heuristic 3	€ 8,860	0.901	0.056	0.75

Table 7-4: Impact on Variability

We reduce a time parameter for *all LRUs together* in the system to investigate the impact of time parameters on the variability (see Table 7-5). The order-and-ship times from shore to ship have a large impact on the average availability, but the standard deviation remains the same. We do not know the reason for this, but it may be a case specific issue. For this, we recommend further research on more cases. For the other time parameters, there is a reasonably fixed relation between the average availability and the standard deviation. But lowering the gross mean repair throughput time has the largest effect on the availability, and therefore also on the variability.

Tactical Decision	Annual Costs	Availability	σ	Survival Rate
OS Times Shore to Ship	€ 278,000	0.910	0.077	0.74
OS Times Thales to Shore	€ 2,000	0.884	0.071	0.64
Stock SRUs (*k* = 0.10)	€ 730	0.887	0.068	0.66
Priority Rule	€ 41,000	0.899	0.057	0.74
2-Week Buffer	€ -	0.889	0.065	0.67

Table 7-5: Impact of Time Parameters on the Availability and Variability

In Section 7.5 we showed that stocking SRUs of the first availability killer is better than stocking spare parts as calculated with INVENTRI or stocking extra LRUs of the availability killer (see Appendix K-3). Appendix M shows that this is also valid for the variability in the availability.

From all results, we conclude that reducing time parameters has a larger effect on the variability than stocking extra spare parts (INVENTRI solution). But there is a reasonably fixed relation between the average availability and the variability when comparing the time parameters with each other. Reducing the mean repair throughput time is the best option for an improvement in both the availability and the variability and results in a less dispersed availability distribution.

7.7. Impact of Tactical Decisions on Initial Investment

In this section we investigate the impact on the initial investment (savings in initial investment) when taking a tactical decision and we optimise the spare part allocation with INVENTRI afterwards. To be able to compare all tactical decisions, the initial investment will be expressed in costs per year. For the total costs per year we sum the inventory holding costs per year (for the initial investment) and the extra costs per year for the tactical decision.

We will analyse the impact on the initial investment (see Table 7-6) when we reduce order-and-ship times for all LRUs, since in INVENTRI it is only possible to change these times for all LRUs together in the system. Besides this, we lower the gross mean repair throughput time for all LRUs with a ten percent reduction (k = 0.10) in the SRU waiting time, by using the priority rule for all LRUs (however this may not be feasible in practice, see Section 6.2), or by removing the two-week-buffer. In Section 7.5 we showed that stocking SRUs of the first availability killer has a large impact for low costs. Therefore, we analyse the impact on the initial investment when the SRUs of the first availability killer can be stocked (the extra costs per year are zero, since the costs of these SRUs are included in the initial investment).

Tactical Decision	Initial Investment	Annual Storage Costs	Annual Extra Costs	Annual Total Costs
Current Situation	**€ 2,760,000**	**€ 414,000**	€ -	**€ 414,000**
OS Time Shore to Ship	€ 2,486,000	€ 373,000	€ 278,000	€ 651,000
OS Time Thales to Shore	€ 2,659,000	€ 399,000	€ 2,000	€ 401,000
Stock SRUs (*k*=0.10)	€ 2,633,000	€ 395,000	€ 730	€ 395,730
Priority Rule	€ 2,421,000	€ 363,000	€ 41,000	€ 404,000
2-Week Buffer	€ 2,594,000	€ 389,000	€ -	€ 389,000
Stock SRUs Availability Killer	€ 1,800,000	€ 270,000	€ -	€ 270,000

Table 7-6: Impact of Tactical Decisions on Initial Investment

Reducing order-and-ship times from shore to ship results in a cost increase of 57 percent, because the costs of emergency shipments are very expensive. Reducing the order-and-ship times from Thales to shore results in a small reduction of 3 percent in the total costs per year.

Lowering the gross repair time by stocking SRUs (SRU waiting time reduction of 0.10) results in a 4.5 percent cost reduction per year, whereas using the priority rule leads to a decrease in the total costs per year of 2.5 percent. Removing the two-week buffer even results in a 6 percent cost reduction per year. When we include the SRUs of the first availability killer in INVENTRI, the total costs per year reduce with 35 percent. This is an absolute cost saving in the initial investment of €960,000 (€144,000 per year).

Overall, lowering the gross mean repair throughput time at Thales has a large impact on the initial investment. Compared to Sections 7.5 and 7.6, it has also a large impact on the availability and the variability.

7.8. Impact of Tactical Decisions on Robustness to Operating Hours

In this case we assume all ships are sent simultaneously on a mission for four months (2880 annual operating hours). Since in practice there is variability in the actual annual operating hours (AOH), we investigate to what extent the tactical decisions are robust to a change in the AOH. For this, we make the assumption that the AOH may change at most with 10 percent. [Ypma, 2010]. When a larger change occurs, Thales and the customer need to estimate the AOH more accurately. To be able to compare the tactical decisions, we show for each option the survival rate for a target availability of 88 percent (see the results in Table 7-7).

Tactical Decision	Availability Current AOH	Survival Rate {Pr(Av≥0.88)}		
		- 10 % AOH	Current AOH	+ 10 % AOH
Current Situation	**0.876**	**0.73**	**0.60**	**0.46**
INVENTRI Solution	0.902	0.84	0.74	0.60
Heuristic 1	0.900	0.83	0.75	0.64
Heuristic 2	0.900	0.80	0.74	0.66
Heuristic 3	0.901	0.82	0.75	0.65

Table 7-7: Impact of Heuristics on the Robustness to Changing AOH

From Table 7-7, we see that a combination of reducing time parameters and stocking extra spare parts (SRUs and LRUs) as we do in the three different heuristics, make the system more robust to changes in AOH as to only stocking spare parts (INVENTRI solution). To see which time parameter makes the system most robust, we investigate the impact of the time parameters when we change it for all LRUs together (see Table 7-8).

Tactical Decision	Availability Current AOH	Survival Rate {Pr(Av≥0.88)}		
		- 10 % AOH	Current AOH	+ 10 % AOH
OS Time Shore to Ship	0.910	0.83	0.74	0.61
OS Time Thales to Shore	0.884	0.75	0.64	0.51
Stock SRUs (k = 0.10)	0.887	0.76	0.66	0.53
Priority Rule	0.899	0.81	0.74	0.63
2-Week Buffer	0.889	0.78	0.67	0.55

Table 7-8: Impact of Time Parameters on the Robustness to Changing AOH

For this case, the current situation is very sensitive to a changing AOH. From Table 7-8, we see that decreasing order-and-ship times result in a small improvement in the robustness to changing AOH. Lowering the gross mean repair throughput time has a larger impact on the robustness. A reduction in the net repair throughput time of four weeks (priority rule) results already in a more robust system than reducing one of the order-and-ship times for all LRUs.

Therefore, lowering the gross mean repair throughput time is the best tactical decision to make the system more robust to changing AOH.

7.9. Conclusions

In our case study we focus on a 3-echelon, 2-indenture supply network. We consider six ships with 2880 annual operation hours (four months). The target performance level is 88 percent system supply availability, where in the current situation the survival rate (probability that the availability is at least the target) is 60 percent. We compared the results of the developed heuristics to the INVENTRI solution. Furthermore, we looked at the impact of tactical decisions on the availability variability, initial investments, and robustness to changing annual operating hours (AOH). Based on the results, we draw the following conclusions:

(1) Heuristic one (tactical decisions over all LRUs) results in the lowest costs

Heuristic one is the best option, since it results in the lowest annual costs (5.6% compared to INVENTRI). However, it takes many decisions for many different LRUs. Heuristic two takes only six tactical decisions for two availability killers and only has slightly larger annual costs (6.3% compared to INVENTRI).

(2) A combination of reducing time parameters and stocking extra spare parts (SRUs and LRUs) leads to lower costs, a better variability, and a better robustness to changing AOH than only stocking spare parts

Using the developed heuristics results in lower costs than the INVENTRI solution. Comparing the time parameters to each other, we see that there is a reasonable fixed relation between the average availability and the standard deviation. Besides, lowering the gross mean repair throughput time has the largest impact on the robustness of the system.

(3) Lowering the gross mean repair throughput time at Thales is the best option to improve service contract performance

Lowering the gross repair throughput times at Thales is done by stocking SRUs or lowering the net repair throughput time (priority rule). These options have the largest impact on the average availability (and therefore also on the variability), the largest impact on the robustness to changes in AOH, and it results in the largest reduction in costs per year of the initial investments. The initial investment may even be reduced with 35 percent when including the SRUs of the first availability killer in INVENTRI. However, compared to all tactical decisions, the largest EBO reduction can be attained when reducing order-and-ship times from shore to ship, but it also has the largest costs.

(4) Including subcomponents of expensive LRUs with a high failure rate in the spare part allocation optimisation results in large savings in initial investments

The first availability killer is in this case the most expensive LRU and has the highest failure rate. Including the SRUs of this availability killer in the spare part allocation optimisation, the initial investment decreases with €960,000 (35 percent decrease).

(5) Using a buffer in the net repair throughput time is disputable

Removing the two-week buffer has a small impact on the system performance (availability and variability). The system will be more robust to a change in AOH and cost savings of €27,000 per year in the initial investment may be made. Since it seems that in the order-handling and dispatching phase in the net repair throughput time a buffer is used already, it is disputable whether including an extra buffer of two weeks is necessary.

8. Conclusions and Recommendations

In this final chapter, we draw conclusions, give recommendations, point out some limitations of this research, and give opportunities for further research. In Section 8.1, we answer the research questions from Section 2.4 and answer the main research question. Based on these answers, we give recommendations to Thales in section 8.2. In Sections 8.3 and 8.4, we discuss limitations of our research and point out opportunities for further research.

8.1. Conclusions

The first research question we formulated in Section 2.4 is:

1) "What long-term service agreements are made at Thales, and how does Thales currently manage these service contracts?"

Thales distinguishes four different kinds of long-term service agreements. We focus on the performance-based contracts ("*contract for availability*"), where the average system supply availability on a ship is used as the key performance indicator. To fulfil the requirements of the contracts, Thales takes care of the maintenance, repair, and supply process. Because of the *repair-by-replacement policy*, spare parts are needed and the optimal allocation is calculated with INVENTRI (based on VARI-METRIC theory). To better understand the theories and concepts in this logistic area, and how system supply availability may be influenced, we stated the second research question:

2) "What literature about service contracts and the VARI-METRIC approach is applicable, and how do different parameters influence system performance?"

The "*contract for availability*" at Thales can be compared to the "*performance-based contract*" of Cohen et al. (2006). The service contract agreements at Thales correspond also to the generic agreements in literature from Verna (1999). The VARI-METRIC approach is an extension of METRIC that optimises the steady state supply availability (by minimising the expected ship backorders). Decreasing LRU backorders at the ships directly influence the average system supply availability. This can be done by increasing spare part stock levels, lowering mean repair throughput times and decreasing order-and-ship times. To investigate which parameters influence the availability the most, we posed the third research question:

3) "How can we determine the impact of the tactical decisions on the average availability?

We focus on five different tactical decisions: *Stocking LRUs*, *stocking SRUs* (such that the waiting time in the LRU gross mean repair throughput time at Thales decreases), *reducing order-and-ship times* (from shore to ship and from Thales to shore), and *reducing the net mean repair throughput times* (using a priority rule).

To be able to compare the tactical decisions, we calculate the impact (the expected ship backorder reduction (ΔEBO) per invested euro per year). For a reduction in a time parameter, the ΔEBO is equal to the product of the marginal ship backorder improvement per time unit reduction and the reduction in the time parameter. The marginal improvements (based on partial derivatives of the backorder function) are calculated using repair probabilities, demands, and fill rates. Besides the marginal backorder reductions, we defined general cost models to determine the costs per year for each tactical decision. The question is then how we can use these equations in the decision making process. This leaded to the fourth research question:

4) "In which general way can we determine which tactical decision Thales needs to take?"
We made a tool in Excel that calculates the impact of the different tactical decisions for each LRU in a system and supports the decision making process. The best heuristic to improve the average availability considers all LRUs in the system and takes each time a tactical decision for a specific LRU. To reduce the amount of combinations of LRUs and tactical decisions, it is also possible to only look at the so-called "availability killers" or take the same tactical decision for all LRUs together in the system. The optimisation procedure chooses the (combination of LRU and) tactical decision that has the largest impact. Since we want to know the impact of the heuristics and tactical decisions, we perform a case study. This resulted in the fifth research question:

5) "What is the impact of the tactical decisions on the average availability, the variability, initial investments, and the robustness to changing annual operating hours, and what general conclusions can be drawn?"
Using a combination of reducing time parameters and stocking extra spare parts leads to lower costs, a lower variability, and a better robustness to changing annual operating hours as to only stocking spare parts. The first heuristic contains the lowest costs, whereas focussing only at availability killers results in less tactical decisions for less LRUs but for slightly larger costs (6.3% versus 5.6% compared to INVENTRI). Taking each time the same tactical decisions for all LRUs has the largest costs (18.9% compared to INVENTRI).

Lowering the gross mean repair throughput time at Thales is the best option to improve the availability, the variability, the robustness to changing AOH, and it has also the largest impact on the initial investment. Besides this, including subcomponents of expensive LRUs with a high failure rate in the spare part allocation optimisation, results in large costs savings in the initial investment. Since it seems that in the order-handling and dispatching phase in the repair transaction process a buffer is used already, it is disputable whether having an extra buffer of two weeks in the net repair throughput time is necessary. Besides, reducing the buffer does not require an extra investment for Thales. Based on the answers on the research questions we will answer our main research question:

> ***"How can Thales use tactical decisions to improve the service contract performance at low costs, focusing on extra spare parts, decreasing order-and-ship times, and lowering mean repair throughput times?"***

We developed a method to improve the service contract performance that is based on calculating the backorder reductions (ΔEBO) per invested euro per year for each combination of tactical decision and LRU. The ΔEBO is approximated using marginal backorder reductions, whereas marginal backorder reductions are (based on METRIC) calculated using repair probabilities, demands, and fill rates. The first heuristic (tactical decisions over all LRUs) results in the lowest costs. However, the developed Excel tool may not be appropriate for this heuristic since there are many combinations of LRU and tactical decisions. This heuristic takes a lot of work and it may be difficult to use in practice. Therefore, the second heuristic (tactical decision over availability killers) is better and results only in slightly larger costs. Based on the results from the case study, lowering the gross repair throughput time has the largest impact on the availability, the variability, and the robustness of the system to changing AOH. Besides, optimising the spare part allocation with reduced gross repair throughput times (or including subcomponents of expensive LRUs with high failure rates) may result in large savings in the initial investment.

8.2. Recommendations

The goal of this research was to get insight into the impact of tactical decisions on the system performance (availability and its variability) for the different tactical decisions. Based on our conclusions from Section 8.1, we recommend the following:

(1) Consider reductions in time parameters besides stocking spare parts
Compared to stocking extra spare parts, using a combination of a reduction in time parameters and stocking extra spare is more cost effective, decreases the variability more than proportional, and makes the system more robust to changing annual operating hours.

(2) Analyse the impact of a tactical decision with the second heuristic
Using the marginal backorder reductions is a simple way to approximate the impact of a tactical decision for a certain LRU. The developed Excel tool uses these calculations. Although heuristic one (tactical decisions over all LRUs) results in the lowest costs, we recommend the second heuristic (tactical decisions over availability killers) since this requires less tactical decisions and is less difficult to use in practice.

(3) Better control the repair transaction process
We showed that lowering the gross repair throughput times at Thales is the best option to improve the system performance (large cost savings, large improvement in availability and variability, and more robust to changing annual operating hours). This should be an incentive for Thales to better control the repair transaction processes and to investigate the product structure and costs. This should then be included in INVENTRI. Besides, reducing the gross repair throughput time by stocking subcomponents (in this case of the availability killer) leads to a large improvement in the system performance for low costs.

(4) Decrease the buffer in the net repair throughput time
Since it seems that in the order-handling and dispatching phase a buffer already is used, it is disputable whether including an extra buffer of two weeks is necessary. Removing the buffer does not require any costs and has a small influence on the system performance.

(5) Do this analysis before contract agreements and spare part optimisation
In this case, large cost savings can be made in the initial spare part investment when investing in tactical decisions. Doing the analysis before a contract establishment, gives more awareness on the impact of time parameters. Thales may keep this in mind during contract negotiations and better contract agreements may be agreed upon.

(6) Always include subcomponents of expensive LRUs with a high failure rate in the spare part allocation optimisation
The first availability killer is in this case the most expensive LRU and has the highest failure rate. Including the subcomponents of this availability killer in the spare part allocation optimisation, results in a large savings in the initial investment. When subcomponents are cheap, place plenty of them on stock and set the waiting time for those SRUs in the gross repair throughput time to zero.

(7) Make customer more aware of the impact of order-and-ship times from shore to ship
When the attained availability is lower than agreed upon in the contract, and when the customer is more aware of the impact of the order-and-ship times from shore to ship, they may put more effort in trying to reduce these times. These order-and-ship times have

especially a large impact on LRUs for which there are no spare parts onboard and do not have a ship repair probability, since a failure of these LRUs immediately leads to a downtime of these order-and-ship times.

8.3. Research Limitations

The *first* limitation of this research is that we did not include different mission profiles in the simulations. In practice there will be different missions where the systems are active, alternated with periods where the radar systems are not in use. Different missions will affect the system availability, and probably also the variability.

The *second* limitation is that we only investigated the impact of the tactical decisions for one case. It is hard to make general conclusions from one case, because some results may be case specific (think of the impact of the order-and-ship times from shore to ship on the variability and that one item determines most of the system downtime).

The *third* limitation is that the simulations are based on the long-term behaviour of the system. We ignore the initial effect of a new installed base and a new set of spare parts, causing a higher availability early in the product life cycle. Developing a model based on transient behaviour and doing further research with this model is recommended.

The *fourth* limitation is that we assumed that the point in time to take a tactical decision is known. However, before comparing the tactical decisions we need to know the time it takes until the tactical decision affects the system availability. When deciding to stock extra spare parts for example, it may take a few months to over a year before the item is received at the stock location and affects the system availability. Optimising the point in time to take a tactical decision is further research.

8.4. Further Research

To better understand the influence of tactical decisions on the availability variability, we advise doing an analytical analysis of the availability variability. This will lead to better availability variability predictions and increase the service perception of the customer.

Different mission profiles influence the system performance. When ships are sent together on mission at the same time, this will lead to a high demand for spare parts in that period. The demand will be more stable when they are not sent on mission at the same time. Since each tactical decision has its lead-time before it affects the availability, different mission profiles will influence the choice of tactical decisions. When for example no ship will be sent on mission the coming few months, a long-term decision may be better than a short-term decision. Further research about this is recommended. The simulation model of Coenen (2009) can then be used, but needs some adjustments.

This research focused on the impact of the tactical decisions. However, research about determining and optimising the point in time to invest in the tactical decisions may also be done, because in practice it takes some time before a tactical decision affect the availability (ordering extra spare parts for example vary between a few months to over a year).

Finally, further research about the operational control of service contracts may be done. Operational decisions may be taken for specific actions (such as emergency repair or supply), based on the actual state of the service supply chain and current service contract performance.

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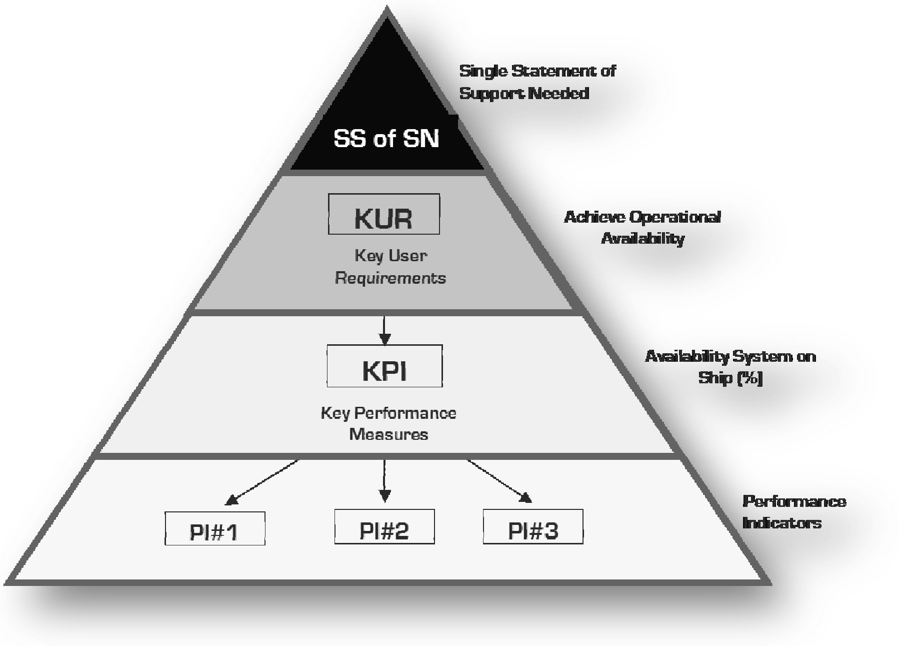
Appendices

Appendix A: Requirements Framework



Requirements Framework [Buijs, 2009]

Appendix B: After-Sales Business Models

Models of After-Sales Services

The value companies place on after-sales services will determine the business models that firms can use to deliver them. When services are all-important, manufacturers may choose to sell services rather than the products that generate them.

SERVICE PRIORITY	BUSINESS MODEL	TERMS	EXAMPLE	PRODUCT OWNER
None	Disposal	Dispose of products when they fail or need to be upgraded	Razor blades	Consumer
Low	Ad hoc	Pay for support as needed	TVs	Consumer
Medium-high	Warranty	Pay fixed price as needed	PCs	Consumer
Medium-high	Lease	Pay fixed price for a fixed time; option to buy product	Vehicles	Manufacturer; leasing company
High	Cost-plus	Pay fixed price based on cost and prenegotiated margin	Construction	Customer
Very high	Performance based	Pay based on product's performance	Aircraft	Customer
Very high	Power by the hour	Pay for services used	Aircraft engines	Manufacturer; service provider

After Sales Business Models [Cohen et al, 2006]

Appendix C: Statistical Inventory Control

For cheap items the focus is to manage these items as less as possible. Stocking spare parts is generally done for these items. Managing this stock, methods based on statistical data are used, also called Statistical Inventory Control (SIC) (e.g. Silver et al., 1998). SIC models are divided in periodic and continuous review models, cost versus cost/service models, and single and multi-echelon models. Cost models focus on minimizing the sum of the ordering costs, holding costs (of inventory), and penalty costs (when having shortage of stock). Cost/service models focus on minimizing the sum of ordering and holding costs subject to a target service level. Most of these models assume stationary demand processes, and focus on satisfying the demand of consumer products. Disadvantages of these SIC models are that they focus on single items instead of a system approach where the performance indicator is system availability (i.e. invest in spare part inventories such that the overall system supply availability is maximized given a limited budget). The models also assume that every item that is stocked is used (or sold) and there are no budget limits for stocking items (and costs are not optimised). Moreover, the models do not say anything about the availability of a system based on the system's components and available spare parts at several locations. From the standpoint of SIC, there is a low demand for a specific item. One-for-one replenishment (s-1, s) policy is the policy that best fits the characteristics and seems relevant in the spare part management problem. Appendix D elaborates on the item versus system approach and the one-by-one ordering policy. [Sherbrooke, 2004] [Rustenburg, 2000].

Appendix D: (VARI-) METRIC Theory

Appendix D-1: Assumptions METRIC

The assumptions of the METRIC theory are based on the assumptions of the one-echelon system. Understanding the single site model is needed to understand the Metric and VARI-Metric approach. The decision variable of the model is the stock level s_i of item *i* (this is the total amount in the repair- and distribution cycle). In the single-site model of Sherbrooke (2004) the following assumptions are made:

- The demand is Poisson distributed; this means that the time of a demand does not influence the time of the next demand and there is a continuous demand such that items will continue failing, even if the radar system is down.
- All demand that is not filled is backordered
- All backorders are equally important
- A (s_i-1,s_i) inventory model for item *i* is used (one-for-one replenishment)
- There are no capacity effects of repair shops (*M/G/∞* queuing model)
- There is no cannibalisation (obtaining a spare part for an device by removing the needed items from a similar device and replace them)

Where	m_i	= Mean demand per year for item *i*	(*i*=1..I)
	T_i	= Mean repair shop throughput time for item *i*	(*i*=1..I)
	c_i	= Price of item *i*	(*i*=1..I)

The METRIC theory calculates the optimal stock level for every ship, shore organisation and depot, where item demand and other item characteristics can be different, for every item in a system. As we know we want to maximise the availability and therefore minimize the expected backorders across all ships. The assumptions that are used by the METRIC theory are the assumptions of the singe site model in addition with the following assumptions:

- The decision of the location where an item will be repaired is not dependent on stock levels or repair shop workload, but only on technical factors
- Only the depot resupplies the bases, there is no lateral supply (pooling flexibility)
- A (*s*-1,*s*) inventory model is used for all items at every location
- The optimal steady state stock levels are determined (the number of ships and the operating hours will remain constant)
- The number of demand in two non-overlapping time periods is independent [Sherbrooke, 2004], [REMM, 2008]

Appendix D-2: VARI-METRIC calculations

The VARI-METRIC theory combines the multi-echelon and multi-indenture theory. The multi-echelon, multi-indenture problem is separable per LRU. We first will explain the single site, multi-indenture model and then we derive the demand per location per item and derive the mean and variance of the number of items in the pipeline per location per item. For complete proofs of the equations we refer to Sherbrooke (2004).

Single Site, Multi-Indenture Model

In the single item, multi-indenture model we assume that a failure of an LRU (module) at a base is always caused by exactly one SRU *i* (component) with probability q_i where the sum of all probabilities is less or equal to one. [REMM, 2008] If the mean base demand for an LRU is Poisson distributed the mean base demand for an SRU must also be Poisson distributed. Where

$$m_0 = \sum_{i=1}^{I} m_i \quad \text{and} \quad m_i = q_i m_0 \qquad (i\text{=0: LRU; } i\text{=1..I: SRU})$$

When the repair times T_i are constant, the expected LRU pipeline (X_0) equals the demand during the repair time plus the sum of the backorders of all SRUs. This can be written as Equation 4.23, where the expected backorders of an LRU are EBO(s_i| X_0).

$$E[X_o] = m_0 T_0 + \sum_{i=1}^{I} EBO(s_i \mid m_i T_i) = \mu_0$$

The variance of the LRU pipeline can be defined as:

$$Var[X_o] = m_0 T_0 + \sum_{i=1}^{I} VBO(s_i \mid m_i T_i)$$

Where $VBO(s_i) = E[BO^2(s_i)] - [EBO(s_i)]^2$,

$$\text{and } [EBO(s_i)] = \sum_{n=s_i+1}^{\infty} (n - s_i) \cdot \frac{(m_i T_i)^n e^{-m_i T_i}}{n!},$$

$$\text{and } E[BO^2(s_i)] = \sum_{n=s_i+1}^{\infty} (n - s_i)^2 \cdot \frac{(m_i T_i)^n e^{-m_i T_i}}{n!}$$

$$= (m_i T_i)^2 \cdot \sum_{n=\max\{s_i-1,0\}}^{\infty} \left(\frac{(m_i T_i)^n e^{-m_i T_i}}{n!} \right) - (2s_i - 1) m_i T \cdot \sum_{n=s_i}^{\infty} \left(\frac{(m_i T_i)^n e^{-m_i T_i}}{n!} \right) + s_i^{\,2} \cdot \sum_{n=s_i+1}^{\infty} \left(\frac{(m_i T_i)^n e^{-m_i T_i}}{n!} \right)$$

Multi-Echelon, Multi-Indenture Model

Sherbrooke (2004) proofs that for a multi-echelon structure the expected number of items and the expected variance in the pipeline for base *j* can be formulated as:

$$E[X_j] = E[E(X_j \mid X_0)] = m_j \left\{ r_j T_j + (1 - r_j) \left(O_j + \frac{EBO[s_0]}{m_0} \right) \right\}$$

and

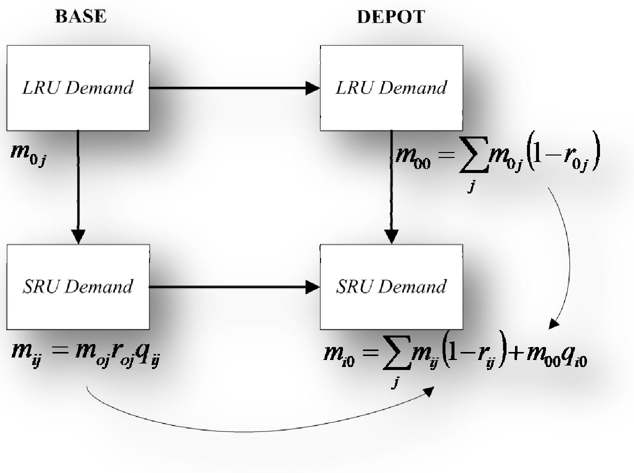
$$Var[X_j] = E[Var(X_j \mid X_0)] + Var[E(X_j \mid X_0)]$$

$$= m_j \{ r_j T_j + (1 - r_j) O_j \} + f_j \{ (1 - f_j) EBO(s_0) + f_j VBO(s_0) \}$$

Where the fraction (f_j) of the depot demand due to resupply to base j is:

$$f_j = \frac{m_j(1 - r_j)}{m_0}$$

Now we can combine the multi-indenture and multi echelon structure. The problem is separable per LRU. We will first derive the demand rates, based on the demand for an item per location (m_{ij}), the repair probability for an item per location (r_{ij}) and the probability that a failure of a LRU is caused by a certain SRU (q_{ij}). Sherbrooke uses a certain calculation sequence to calculate the demand rates (as a function of LRU base demand). The Figure below displays this sequence including the demand calculations.



Demand Calculation Sequence [REMM, 2008]

To calculate the expected number of items in the pipeline and the expected variance in the pipeline we use the previous calculation sequence in opposite direction. We start with the SRUs in repair at the depot, because other items and locations do not have any influence on it. The pipeline of SRUs in repair at the depot has a Poisson distribution with mean $m_{i0}T_{i0}$ and we are able to calculate the $\text{EBO}_{i0}(s_{i0})$ and the $\text{VBO}_{i0}(s_{i0})$. After this we can calculate the LRU depot pipeline, the SRU base pipeline and finally the LRU base pipeline. [Sherbrooke, 2004]

LRU Depot Pipeline calculations:

The fraction of the depot demand m_{i0} for a SRU caused by depot LRU repairs is formulated as:

$$f_{i0} = \frac{m_{00} q_{i0}}{m_{i0}}$$

The mean and variance of the LRU pipeline depends on the SRU backorders at the depot. A SRU backorder has a probability f_{i0} that it delays a LRU repair at the depot and a probability of 1- f_{i0} that it delays a resupply to some base.

$$E[X_{00}] = m_{00}T_{00} + \sum_{i=1}^{I} f_{i0} EBO_{i0}(s_{i0})$$

$$Var[X_{00}] = m_{00}T_{00} + \sum_{i=1}^{I} f_{i0}(1 - f_{i0}) EBO_{i0}(s_{i0}) + \sum_{i=1}^{I} f_{i0}^{\,2} VBO_{i0}(s_{i0})$$

SRU Base Pipeline calculations:

The fraction of all depot demand m_{i0} for a SRU that is resupplied to base *j* is formulated as:

$$f_{ij} = \frac{m_{ij}(1-r_{ij})}{m_{i0}}$$

The mean and variance of the SRU base pipeline depends also on the SRU backorders at the depot.

$$E[X_{ij}] = m_{ij}\left[r_{ij}T_{ij} + (1-r_{ij})O_i\right] + f_{ij}EBO_{i0}(s_{i0})$$

$$Var[X_{ij}] = m_{ij}\left[r_{ij}T_{ij} + (1-r_{ij})O_i\right] + f_{ij}(1-f_{ij})EBO_{i0}(s_{i0}) + f_{ij}^2 VBO_{i0}(s_{i0})$$

LRU Base Pipeline calculations:

The fraction of the depot demand m_{00} for a LRU that comes from base *j* is formulated as:

$$f_{0j} = \frac{m_{0j}(1-r_{0j})}{m_{00}}$$

The mean and variance of the LRU base pipeline depends on LRU depot backorders and SRU base backorders. All SRU base backorders arise from LRU demand at that base.

$$E[X_{0j}] = m_{0j}\left[r_{0j}T_{0j} + (1-r_{0j})O_0\right] + f_{0j}EBO_{00}(s_{00}) + \sum_{i=1}^{I} EBO_{ij}(s_{ij})$$

$$E[X_{0j}] = m_{0j}\left[r_{0j}T_{0j} + (1-r_{0j})O_0\right] + f_{0j}(1-f_{0j})EBO_{00}(s_{00}) + f_{0j}^2 VBO_{00}(s_{00}) + \sum_{i=1}^{I} VBO(s_{ij})$$

From these calculations we can calculate availability per base, because that depends on the expected LRU base backorders EBO(s_{0j}). [Sherbrooke, 2004]

Appendix E: Detailed Calculations of the Impact of Tactical Decisions

Appendix E-1: Parameter Influence

<u>The influence of the EBO of location j-1 on the pipeline of location j:</u>

$$\frac{\partial \mu_j}{\partial EBO_{j-1}(\mu_{j-1}; s_{j-1})} = \frac{m_j(1-r_j)}{m_{j-1}}$$

<u>The influence of the order-and-ship time on the pipeline of location j:</u>

$$\frac{\partial \mu_j}{\partial O_j} = m_j(1-r_j)$$

<u>The influence of the depot mean repair throughput time on the depot pipeline:</u>

$$\frac{\partial \mu_0}{\partial T_0} = m_0 r_0$$

<u>The influence of the pipeline of location j on the EBO of location j:</u>

Before we determine the influence, we first define:

$$g(u_j; s_j) = \sum_{n=s_j}^{\infty} \frac{\mu_j^n e^{-\mu_j}}{n!}$$

Where for $s_j \geq 1$,

$$\frac{\partial g(\mu_j; s_j)}{\partial \mu_j} = \sum_{n=s_j}^{\infty} \frac{n_j \mu_j{}^{n-1} e^{-\mu_j} - \mu_j{}^n e^{-\mu_j}}{n!} = \sum_{n=s_j}^{\infty} \frac{\mu_j{}^{n-1} e^{-\mu_j}}{(n-1)!} - \sum_{n=s_j}^{\infty} \frac{\mu_j{}^n e^{-\mu_j}}{n!}$$

$$= \sum_{n=s_j-1}^{\infty} \frac{\mu_j{}^n e^{-\mu_j}}{n!} - \sum_{n=s_j}^{\infty} \frac{\mu_j{}^n e^{-\mu_j}}{n!}$$

And by the “Harmonicareeks”: $\frac{\partial g(\mu_j; s_j)}{\partial \mu_j} = \frac{\mu_j{}^{s_j-1} e^{-\mu_j}}{(s_j-1)!}$

And for $s_j = 0$,

$$g(u_j; 0) = \sum_{n=0}^{\infty} \frac{\mu_j^n e^{-\mu_j}}{n!} = \mu_j \quad \text{and} \quad \frac{\partial g(\mu_j; 0)}{\partial \mu_j} = 1$$

The influence of the pipeline of location j on the EBO of location j is now approximated as follows:

$$\frac{\partial EBO_j(\mu_j;s_j)}{\partial \mu_j} = \sum_{n=s_j}^{\infty}\frac{\mu_j{}^n e^{-\mu_j}}{n!} + \mu_j \frac{\partial g(\mu_j;s_j)}{\partial \mu_j} - s_j \frac{\partial g(\mu_j;s_j+1)}{\partial \mu_j}$$

$$= \sum_{n=s_j}^{\infty}\frac{\mu_j{}^n e^{-\mu_j}}{n!} + \mu_j \frac{\mu_j{}^{s_j-1} e^{-\mu_j}}{(s_j-1)!} - s_j \frac{\mu_j{}^{s_j} e^{-\mu_j}}{s_j!}$$

$$= \sum_{n=s_j}^{\infty}\frac{\mu_j{}^n e^{-\mu_j}}{n!} + \frac{\mu_j{}^{s_j} e^{-\mu_j}}{(s_j-1)!} - \frac{\mu_j{}^{s_j} e^{-\mu_j}}{(s_j-1)!} = \sum_{n=s_j}^{\infty}\frac{\mu_j{}^n e^{-\mu_j}}{n!}$$

Because $\sum_{n=0}^{\infty}\frac{\mu_j{}^n e^{-\mu_j}}{n!} = 1$, we state that for all s we have that

$$\frac{\partial EBO_j(\mu_j;s_j)}{\partial \mu_j} = \sum_{n=s_j}^{\infty}\frac{\mu_j{}^n e^{-\mu_j}}{n!} = 1 - f_{LRU,j}$$

Appendix E-2: Marginal Backorder Reductions for Reducing a Time Parameter

Using the Equations from Section 5.2.2 we are able to approximate the marginal ship backorder reduction for reducing a time parameter. The marginal improvements are calculated using the derivatives of the ship backorder function. Using the sequence in which different parameters influence each other (see Figure 5.1) and using the differentiation chain rule, the marginal backorder reductions (influence of a time parameter on the expected ship backorders) are defined as follows:

The influence of extra stock at location j:

The decision of adding extra stock is already done in INVENTRI. The equation that is used for calculating the influence (marginal ship backorder reduction) of adding one extra spare part on stock at location *j* is as follows:

$$EBO_2(\mu_2;s_j) - EBO_2(\mu_2;s_j+1)$$

The influence of the order-and-ship time from shore to ship:

$$\frac{\partial EBO_2(\mu_2;s_2)}{\partial O_2} = \frac{\partial \mu_2}{\partial O_2}\cdot\frac{\partial EBO_2(\mu_2;s_2)}{\partial \mu_2}$$
$$= (1-r_2)m_2 \cdot (1 - Fill\,rate_2)$$

<u>*The influence of the order-and-ship time from Thales to shore:*</u>

$$\frac{\partial EBO_2(\mu_2;s_2)}{O_1} = \frac{\partial \mu_1}{\partial O_1} \cdot \frac{\partial EBO_1(\mu_1;s_1)}{\partial \mu_1} \cdot \frac{\partial \mu_2}{\partial EBO_1(\mu_1;s_1)} \cdot \frac{\partial EBO_2(\mu_2;s_2)}{\partial \mu_2}$$
$$= m_1(1-r_1)\cdot(1-Fill\,rate_1)\cdot \frac{m_2(1-r_2)}{m_1}\cdot(1-Fill\,rate_2)$$
$$= (1-r_1)(1-r_2)m_2 \cdot (1-Fill\,rate_1)(1-Fill\,rate_2)$$

<u>*The influence of the mean repair throughput time at Thales:*</u>

$$\frac{\partial EBO_2(\mu_2;s_2)}{\partial T_0} = \frac{\partial \mu_0}{\partial T_0} \cdot \frac{\partial EBO_0(\mu_0;s_0)}{\partial \mu_0} \cdot \frac{\partial \mu_1}{\partial EBO_0(\mu_0;s_0)} \cdot \frac{\partial EBO_1(\mu_1;s_1)}{\partial \mu_1} \cdot \frac{\partial \mu_2}{\partial EBO_1(\mu_1;s_1)} \cdot \frac{\partial EBO_2(\mu_2;s_2)}{\partial \mu_2}$$
$$= m_0 r_0 \cdot (1-Fill\,rate_0)\cdot \frac{m_1(1-r_1)}{m_0}\cdot(1-Fill\,rate_1)\cdot \frac{m_2(1-r_2)}{m_1}\cdot(1-Fill\,rate_2)$$
$$= r_0(1-r_1)(1-r_2)m_2 \cdot (1-Fill\,rate_0)(1-Fill\,rate_1)(1-Fill\,rate_2)$$

Appendix E-3: Backorder Reductions per invested Euro per Year

Since we know the marginal improvements of each tactical decision and the corresponding costs, the approximated impact (ΔEBO) per invested euro per year for each tactical decision is calculated as follows:

Extra Stock

<u>*Impact Stocking LRU*</u>*:* $\Delta EBO / C_{LRU} = \dfrac{EBO_2(\mu_2;s_j) - EBO_2(\mu_2;s_j+1)}{h \cdot c}$

<u>*Impact Stocking SRU:*</u> $\Delta EBO / I_{SRU} = \dfrac{r_0(1-r_1)(1-r_2)m_2 \cdot (1-f_{LRU,0})(1-f_{LRU,1})(1-f_{LRU,2})\cdot \Delta T_0}{\{(k+s)^2 \cdot h \cdot p \cdot c\} - \{k^2 \cdot h \cdot p \cdot c\}}$

Order-and-Ship Times

<u>*Impact Shore to ship:*</u> $\Delta EBO / C_{O_2} = \dfrac{(1-r_2)m_2 \cdot (1-f_{LRU,2})\cdot \Delta O_2}{C_{EmergencyShipment} \cdot m_1}$

<u>*Impact Thales to shore:*</u> $\Delta EBO / C_{O_1} = \dfrac{(1-r_1)(1-r_2)m_2 \cdot (1-f_{LRU,1})(1-f_{LRU,2})\cdot \Delta O_1}{C_{Transport} \cdot m_0}$

Repair Throughput Time

<u>Impact Priority Rule:</u> $\Delta EBO / C_{Priority} = \dfrac{r_0(1-r_1)(1-r_2)m_2 \cdot (1-f_{LRU,0})(1-f_{LRU,1})(1-f_{LRU,2})\cdot \Delta T_0}{(D+MH)\cdot m_0}$

Appendix F: Overview Excel Tool

This model should be used after the INVENTRI optimisation and when one wants to know to what extent different parameters influence (per invested euro) the availability. All calculations are based on the METRIC approach (Sherbrooke, 2004) for a multi-echelon, single-indenture model.

Input

In the excel sheet "*Input*" characteristics per LRU have to be filled in (see the Figure below for a screenshot of the first part of the input data). It is divided in item specific, time parameters, repair probabilities and stock level input. This data should be available, since it is the same input INVENTRI uses. The only difference with INVENTRI is the repair probability. This should be collected from both the "*SMRCODHG*" (source, maintenance, and recoverability code) and "*REPSURHG*" code (Repair Survival Rate). The spare part stock allocation (output) from INVENTRI is used as input for this tool.

			Item			Time Parameters (Hrs)				Repair Probability			Stock (INVENTRI)		
Nr.	LRU Name	Reference Nr.	Price	MTBF (hrs)	# in Sytem	OS SS	OS TS	Repair	Purchase	Ship	Shore	Thales	Ship	Shore	Thales
1	Confidential	Confidential	€ 5,609	176000	1	120	336	2160	8640	0.95	0.00	0.00	1	1	0
2	-	-	€ 238	11200000	5	120	336	0	5760	0.00	0.00	0.00	0	1	0
3	-	-	€ 5,073	127000	5	120	336	2160	7200	0.00	0.00	0.95	0	1	1
4	-	-	€ 5,073	108000	2	120	336	2160	7200	0.00	0.00	0.95	0	1	1
5	-	-	€ 5,073	106000	4	120	336	2160	6480	0.00	0.00	0.95	0	1	1
6	-	-	€ 4,999	1110000	3	120	336	2160	7920	0.00	0.00	0.95	0	1	0
7	-	-	€ 3,426	617000	1	120	336	2160	6480	0.00	0.00	0.95	0	1	0
8	-	-	€ 3,602	2750000	1	120	336	4320	6480	0.00	0.00	0.95	0	1	0
9	-	-	€ 3,751	1130000	1	120	336	2160	6480	0.00	0.00	0.95	0	1	0
10	-	-	€ 2,685	3650000	1	120	336	2160	7920	0.00	0.00	0.95	0	0	0
11	-	-	€ 3,711	934000	1	120	336	2160	6480	0.00	0.00	0.95	0	1	0
12	-	-	€ 3,101	2420000	1	120	336	2160	5040	0.00	0.00	0.95	0	1	0
13	-	-	€ 11,366	138000	2	120	336	2160	7920	0.00	0.00	0.95	0	1	0
14	-	-	€ 2,736	746000	1	120	336	2160	5760	0.00	0.00	0.95	0	1	0
15	-	-	€ 3,405	961000	1	120	336	2160	5760	0.00	0.00	0.95	0	1	0
16	-	-	€ 2,917	653000	1	120	336	2160	7200	0.00	0.00	0.95	0	1	0
17	-	-	€ 4,725	1160000	1	120	336	2160	7200	0.00	0.00	0.95	0	1	0
18	-	-	€ 33,020	188000	1	120	336	4320	7920	0.95	0.00	0.00	0	0	0

Screen-Shot of "Input" sheet

Network Structure:

Besides the LRU data, some general data about the network structure has to be filled in, and data for calculating the impact of tactical decisions is needed. Data about the network structure is already known since this is also input for INVENTRI (number of ships and shore locations, annual operating hours, and the total hours a year). Data about order-and-ship times, repair times, and stock have to be filled in such that the impact of parameters on the availability per invested euro can be calculated.

Order-and-Ship Times:

For both the order-and-ship times from Thales to shore and from shore to ship, the minimum amount of hours has be filled in (the amount of time for an emergency supply ($O_{2(Emergency)}$) and for sending an LRU using the one-by-one policy instead of the batching policy ($O_{1(One-by-One\,Policy)}$)). Besides this, the costs for the emergency supply and transport costs for a LRU have to be determined.

Repair Times:

Based on the different phases in the repair throughput time (order-handling, repair, dispatch, and buffer) the data about the repair times can be filled in. When a *Fast Repair* is done, the mean repair throughput time of an LRU excluding the waiting time for subcomponents (is equal to the administrative time plus net repair time) decreases with a certain percentage p.

This percentage is currently set at 50 percent. Then, for each different phase in the repair throughput time the amount of time they take has to be filled in. The *Total Repair Time* (without the waiting time for subcomponents) is the sum of the different phases. Besides this, the cost for using a fast repair (priority rule) has to be filled in. This is the sum of the material handling department costs and the average direct repair costs.

Stock:

Since the cost per year for extra stock are calculated as the *Inventory Holding Costs* (*h*) and the waiting time for subcomponents is reduced stepwise (with step size *k*), this data needs also to be filled in. The Figure below shows a screenshot of the second part of the input data.

Network Structure		
# Ships	6	
# Shore Locations	1	
AOH	2880	
Hours/Year	8640	
Order-and-Ship Times		
Minimum Time from Shore to Ship	48	Hrs
Minimum Time from Thales to Shore	168	Hrs
Costs (per LRU) Shore to Ship Time	€ 10,000	per (Emergency) Shipment
Costs (Per LRU) Thales to Shore Time	€ 75	per Shipment (One-By-One Policy)
Repair Times		
Fast Repair Time (Priority Rule) (*p*)	50%	of Total Repair Time
Total Repair Time (No Waiting Time for Subcomponents)	56	Days
- Order Handling	14	Days
- Net Repair Time	14	Days
- Dispatch Time	14	Days
- Buffer Time	14	Days
Costs Fast Repair	€ 1,500	per Repair
- Costs Material Handling Department	€ 500	per Repair
- Costs Direct Repair (on Average)	€ 1,000	per Repair
Stock		
Inventory Holding Cost Percentage (*h*)	15%	of item Price
Stepsize (*s*) for Reduction Waiting Time SRUs	10%	

Screen-Shot of "Input" sheet

Output

In the excel sheet *"Output"* the output data is given and is based on the equations from Sherbrooke (2004). Per location (ship, shore, Thales) the *Demand*, *Pipeline*, *Expected Backorders (EBO)*, *Variance of the EBO (VBO)*, *Fill Rate*, and the *Average Waiting Time* for an LRU are automatically calculated. Besides this, the average supply availability per LRU and the total weighted average system supply availability are calculated. The number one Availability Killer (LRU with largest ship EBO) is automatically coloured red and bold. The Figure below shows a screenshot of the output sheet.

			Demand / Year			Availability
Nr.	LRU	Reference Nr	Ship	Shore	Thales	0.8959
1	Confidential	Confidential	0.0164	0.0049	0.0049	1.0000
2	-	-	0.0013	0.0077	0.0077	1.0000
3	-	-	0.1134	0.6803	0.6803	0.9983
4	-	-	0.0533	0.3200	0.3200	0.9992
5	-	-	0.1087	0.6521	0.6521	0.9984
6	-	-	0.0078	0.0467	0.0467	0.9999
7	-	-	0.0047	0.0280	0.0280	0.9999
8	-	-	0.0010	0.0063	0.0063	1.0000
9	-	-	0.0025	0.0153	0.0153	1.0000
10	-	-	0.0008	0.0047	0.0047	0.9997
11	-	-	0.0031	0.0185	0.0185	1.0000
12	-	-	0.0012	0.0071	0.0071	1.0000
13	-	-	0.0417	0.2504	0.2504	0.9989
14	-	-	0.0039	0.0232	0.0232	0.9999
15	-	-	0.0030	0.0180	0.0180	1.0000
16	-	-	0.0044	0.0265	0.0265	0.9999
17	-	-	0.0025	0.0149	0.0149	1.0000
18	-	-	0.0153	0.0046	0.0046	0.9920

	SHIP				
Nr.	Pipeline	EBO	VBO	Fill Rate	Avg WaitTime
1	0.0039	0.0000	0.0000	0.996	4.01
2	0.0000	0.0000	0.0000	0.000	136.56
3	0.0017	0.0017	0.0017	0.000	131.79
4	0.0008	0.0008	0.0008	0.000	123.58
5	0.0016	0.0016	0.0016	0.000	130.73
6	0.0001	0.0001	0.0001	0.000	140.84
7	0.0001	0.0001	0.0001	0.000	131.89
8	0.0000	0.0000	0.0000	0.000	128.24
9	0.0000	0.0000	0.0000	0.000	126.50
10	0.0003	0.0003	0.0003	0.000	2904.00
11	0.0000	0.0000	0.0000	0.000	127.86
12	0.0000	0.0000	0.0000	0.000	122.88
13	0.0011	0.0011	0.0011	0.000	229.37
14	0.0001	0.0001	0.0001	0.000	129.58
15	0.0000	0.0000	0.0000	0.000	127.44
16	0.0001	0.0001	0.0001	0.000	131.53
17	0.0000	0.0000	0.0000	0.000	126.50
18	0.0080	0.0080	0.0080	0.000	4522.80

	SHORE				
Nr.	Pipeline	EBO	VBO	Fill Rate	Avg WaitTime
1	0.0051	0.0000	0.0000	0.9949	22.85
2	0.0054	0.0000	0.0000	0.9946	16.56
3	0.0434	0.0009	0.0010	0.9575	11.79
4	0.0163	0.0001	0.0001	0.9838	3.58
5	0.0405	0.0008	0.0008	0.9603	10.73
6	0.0150	0.0001	0.0001	0.9851	20.84
7	0.0088	0.0000	0.0000	0.9912	11.89
8	0.0035	0.0000	0.0000	0.9965	8.24
9	0.0048	0.0000	0.0000	0.9952	6.50
10	0.0015	0.0015	0.0015	0.0000	2784.00
11	0.0058	0.0000	0.0000	0.9942	7.86
12	0.0022	0.0000	0.0000	0.9978	2.88
13	0.0807	0.0032	0.0033	0.9225	109.37
14	0.0072	0.0000	0.0000	0.9929	9.58
15	0.0056	0.0000	0.0000	0.9944	7.44
16	0.0084	0.0000	0.0000	0.9916	11.53
17	0.0047	0.0000	0.0000	0.9953	6.50
18	0.0044	0.0044	0.0044	0.0000	8256.00

	THALES				
Nr.	Pipeline	EBO	VBO	Fill Rate	Avg WaitTime
1	0.0049	0.0049	0.0049	0.000	8640.00
2	0.0051	0.0051	0.0051	0.000	5760.00
3	0.1899	0.0169	0.0188	0.827	215.21
4	0.0893	0.0039	0.0041	0.915	104.60
5	0.1793	0.0152	0.0168	0.836	200.85
6	0.0132	0.0132	0.0132	0.000	2448.00
7	0.0077	0.0077	0.0077	0.000	2376.00
8	0.0032	0.0032	0.0032	0.000	4428.00
9	0.0042	0.0042	0.0042	0.000	2376.00
10	0.0013	0.0013	0.0013	0.000	2448.00
11	0.0051	0.0051	0.0051	0.000	2376.00
12	0.0019	0.0019	0.0019	0.000	2304.00
13	0.0710	0.0710	0.0710	0.000	2448.00
14	0.0063	0.0063	0.0063	0.000	2340.00
15	0.0049	0.0049	0.0049	0.000	2340.00
16	0.0074	0.0074	0.0074	0.000	2412.00
17	0.0042	0.0042	0.0042	0.000	2412.00
18	0.0042	0.0042	0.0042	0.000	7920.00

Screen-Shot of "Output" sheet

Impact Tactical Decisions

In the excel sheet *"Impact Tactical Decisions"*, one of the three developed optimisation procedures should be followed. The combination of tactical decision and LRU that contains the largest impact (Δ*EBO* per invested euro per year) is shaded green. Per iteration of the optimisation procedure, the new value of the parameter (stock, order-and-ship time, or repair time) should be set in the input sheet. Next, we elaborate on the calculations that are made for each tactical decision.

Order-and-Ship Times:

For both order-and-ship times, the reduction (ΔO_i) in hours and the corresponding costs per year (C_{O_i}) are calculated. Besides this, the marginal backorder reduction (per hour) is calculated, but is a hidden column. The absolute *ship* backorder reduction (Δ*EBO*) is calculated by multiplying the marginal backorder reduction with the reduction in order-and-ship times. Finally, the impact ($\Delta EBO \,/\, C_{O_i}$) is calculated and these values are used in the optimisation method.

			OS Time Shore-Ship					OS Time Thales-Shore				
Nr.	LRU	Reference Nr.	Δ OS Time	ΔEBO (for Δ OS Time)	Annual Costs		Impact	Δ OS Time	ΔEBO (for Δ OS Time)	Annual Costs		Impact
1	Confidential	Confidential	72	0.0000	€	49	5.41E-10	168	0.0000	€	0.37	8.56E-10
2	-	-	72	0.0000	€	77	1.39E-07	168	0.0000	€	0.58	2.35E-07
3	-	-	72	0.0009	€	6,803	1.39E-07	168	0.0001	€	51.02	1.84E-06
4	-	-	72	0.0004	€	3,200	1.39E-07	168	0.0000	€	24.00	6.99E-07
5	-	-	72	0.0009	€	6,521	1.39E-07	168	0.0001	€	48.91	1.72E-06
6	-	-	72	0.0001	€	467	1.39E-07	168	0.0000	€	3.50	6.45E-07
7	-	-	72	0.0000	€	280	1.39E-07	168	0.0000	€	2.10	3.78E-07
8	-	-	72	0.0000	€	63	1.39E-07	168	0.0000	€	0.47	1.49E-07
9	-	-	72	0.0000	€	153	1.39E-07	168	0.0000	€	1.15	2.07E-07
10	-	-	72	0.0000	€	47	1.39E-07	168	0.0000	€	0.36	4.32E-05
11	-	-	72	0.0000	€	185	1.39E-07	168	0.0000	€	1.39	2.50E-07
12	-	-	72	0.0000	€	71	1.39E-07	168	0.0000	€	0.54	9.42E-08
13	-	-	72	0.0003	€	2,504	1.39E-07	168	0.0001	€	18.78	3.35E-06
14	-	-	72	0.0000	€	232	1.39E-07	168	0.0000	€	1.74	3.09E-07
15	-	-	72	0.0000	€	180	1.39E-07	168	0.0000	€	1.35	2.40E-07
16	-	-	72	0.0000	€	265	1.39E-07	168	0.0000	€	1.98	3.62E-07
17	-	-	72	0.0000	€	149	1.39E-07	168	0.0000	€	1.12	2.04E-07
18	-	-	72	0.0000	€	46	1.39E-07	168	0.0000	€	0.34	4.32E-05

Screen-Shot of "Impact Tactical Decisions" sheet for both the Order-and-Ship Times

Gross Repair Throughput Time:

Lowering the gross repair throughput time is done in three different ways. For the both the options of having *no buffer* or using a fast repair (*priority rule*) the same calculations are made as for the order-and-ship times. There is one extra column that indicates the *new repair time* when taking that tactical decision. The third option is to stock subcomponents of an LRU, which will reduce the waiting time for the subcomponents. Besides the same calculations as for the other two options, we added two extra columns. One column shows the *percentage reduction in the SRU waiting time* (for the next iteration). Since per iteration the data in the input sheet is changed, a column is added that shows the *original repair time*. This column (shaded yellow) has to be copied from the start solution from the input data.

Gross Repair Throughput Time (Stock SUBCOMP)							Gross Repair Throughput Time (Priority Rule)					Gross Repair Throughput Time (No Buffer)				
Original Repair Time	% Reduction Waiting Time	Δ Repair Time	New Repair Time	ΔEBO (for Δ Repair Time)	Annual Costs	Impact	Δ Repair Time	New Repair Time	ΔEBO (for Δ Repair Time)	Annual Costs	Impact	Δ Repair Time	New Repair Time	ΔEBO (for Δ Repair Time)	Annual Costs	Impact
2160																
2160	0.10	82	2078	0.0000	€ 4	1.96E-06	672	1488	0.0001	€ 1,020	6.03E-08	336	1824	0.0000	€ -	∞
2160	0.10	82	2078	0.0000	€ 4	1.74E-07	672	1488	0.0000	€ 480	1.14E-08	336	1824	0.0000	€ -	∞
2160	0.10	82	2078	0.0000	€ 4	1.67E-06	672	1488	0.0001	€ 978	5.35E-08	336	1824	0.0000	€ -	∞
2160	0.10	82	2078	0.0000	€ 4	2.78E-07	672	1488	0.0000	€ 70	1.23E-07	336	1824	0.0000	€ -	∞
2160	0.10	82	2078	0.0000	€ 3	1.43E-07	672	1488	0.0000	€ 42	7.19E-08	336	1824	0.0000	€ -	∞
4320	0.10	298	4022	0.0000	€ 3	4.39E-08	672	3648	0.0000	€ 9	2.84E-08	336	3984	0.0000	€ -	∞
2160	0.10	82	2078	0.0000	€ 3	3.89E-08	672	1488	0.0000	€ 23	3.93E-08	336	1824	0.0000	€ -	∞
2160	0.10	82	2078	0.0000	€ 2	3.52E-06	672	1488	0.0001	€ 7	8.21E-06	336	1824	0.0000	€ -	∞
2160	0.10	82	2078	0.0000	€ 3	5.76E-08	672	1488	0.0000	€ 28	4.75E-08	336	1824	0.0000	€ -	∞
2160	0.10	82	2078	0.0000	€ 2	1.00E-08	672	1488	0.0000	€ 11	1.79E-08	336	1824	0.0000	€ -	∞
2160	0.10	82	2078	0.0000	€ 9	3.41E-06	672	1488	0.0002	€ 376	6.36E-07	336	1824	0.0001	€ -	∞
2160	0.10	82	2078	0.0000	€ 2	1.21E-07	672	1488	0.0000	€ 35	5.87E-08	336	1824	0.0000	€ -	∞
2160	0.10	82	2078	0.0000	€ 3	5.85E-08	672	1488	0.0000	€ 27	4.56E-08	336	1824	0.0000	€ -	∞
2160	0.10	82	2078	0.0000	€ 2	1.52E-07	672	1488	0.0000	€ 40	6.88E-08	336	1824	0.0000	€ -	∞
2160	0.10	82	2078	0.0000	€ 4	2.97E-08	672	1488	0.0000	€ 22	3.88E-08	336	1824	0.0000	€ -	∞

Screen-Shot of "Impact Tactical Decisions" sheet for the Repair Throughput Time

Stock LRUs:

For each location (ship, shore, Thales) the same information is given as for the order-and-ship times. The reduction in the expected ship backorder is calculated (using the same calculations as in the output sheet) for a stock level of s+1. The costs per year are the inventory holding costs for an extra LRU. For an extra LRU at the ships, the inventory holding costs are multiplied with the amount of ships in the network.

Extra STOCK (s+1)								
ΔEBO (Stock Ship)	Annual Costs	Impact	ΔEBO (Stock Shore)	Annual Costs	Impact	ΔEBO (Stock Thales)	Annual Costs	Impact
0.0000	€ 5,048	1.503E-09	0.0000	€ 841	9.991E-12	0.0000	€ 841	9.992E-12
0.0000	€ 214	9.504E-08	0.0000	€ 36	6.902E-08	0.0000	€ 36	6.892E-08
0.0017	€ 4,566	3.785E-07	0.0002	€ 761	2.004E-07	0.0001	€ 761	1.213E-07
0.0008	€ 4,566	1.670E-07	0.0000	€ 761	2.885E-08	0.0000	€ 761	1.181E-08
0.0016	€ 4,566	3.599E-07	0.0001	€ 761	1.750E-07	0.0001	€ 761	1.026E-07
0.0001	€ 4,499	2.820E-08	0.0000	€ 750	2.492E-08	0.0000	€ 750	2.464E-08
0.0001	€ 3,083	2.311E-08	0.0000	€ 514	1.246E-08	0.0000	€ 514	1.229E-08
0.0000	€ 3,242	4.795E-09	0.0000	€ 540	1.847E-09	0.0000	€ 540	1.840E-09
0.0000	€ 3,376	1.105E-08	0.0000	€ 563	3.402E-09	0.0000	€ 563	3.353E-09
0.0003	€ 2,416	1.097E-07	0.0003	€ 403	6.309E-07	0.0002	€ 403	5.548E-07
0.0000	€ 3,340	1.366E-08	0.0000	€ 557	5.030E-09	0.0000	€ 557	4.959E-09
0.0000	€ 2,791	6.065E-09	0.0000	€ 465	8.516E-10	0.0000	€ 465	8.383E-10
0.0011	€ 10,229	1.083E-07	0.0005	€ 1,705	3.017E-07	0.0005	€ 1,705	3.027E-07
0.0001	€ 2,462	2.351E-08	0.0000	€ 410	1.040E-08	0.0000	€ 410	1.025E-08
0.0000	€ 3,065	1.442E-08	0.0000	€ 511	5.041E-09	0.0000	€ 511	4.968E-09
0.0001	€ 2,626	2.557E-08	0.0000	€ 438	1.341E-08	0.0000	€ 438	1.324E-08
0.0000	€ 4,253	8.547E-09	0.0000	€ 709	2.631E-09	0.0000	€ 709	2.594E-09
0.0080	€ 29,718	2.688E-07	0.0007	€ 4,953	1.474E-07	0.0007	€ 4,953	1.415E-07

Screen-Shot of “Impact Tactical Decisions" sheet for Stocking an Extra Spare LRU

Overview All LRUs:

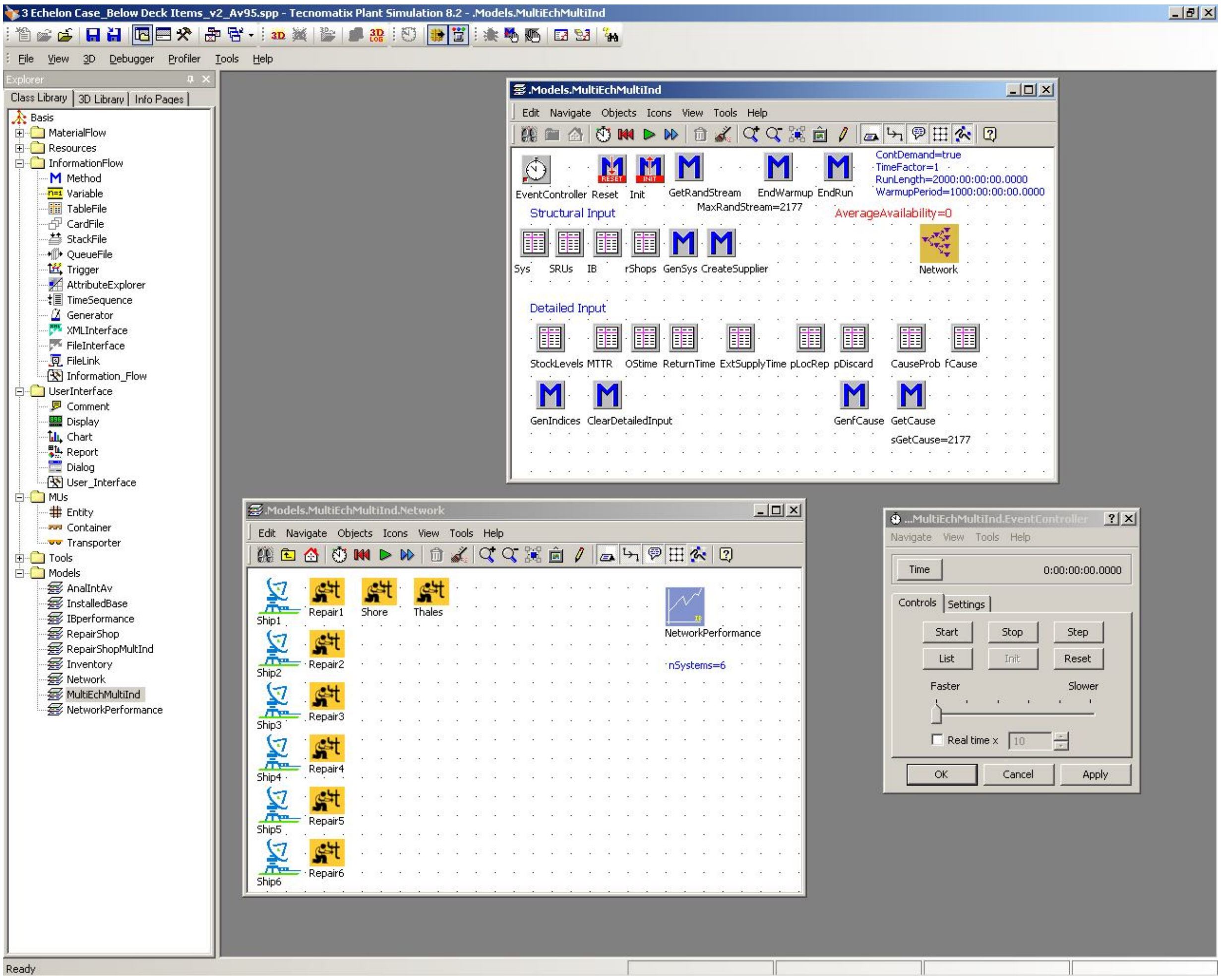
Since one of the heuristics is to take a tactical decision for all LRUs together, the total results for each tactical decision are shown in a table. The total yearly costs and the total backorder reductions are the sum over all LRUs. The best tactical decision is shaded green.

Overview (for all items)			
Tactical Decision	Total Annual Costs	Sum ΔEBO	Impact
Shore to Ship	€ 277,955.65	0.03833	1.38E-07
Thales to Shore	€ 2,084.67	0.00725	3.48E-06
Subcomponents	€ 732.72	0.00544	7.42E-06
Priority Rule	€ 41,071.57	0.01541	3.75E-07
+1 LRU (best option)		0.01125	7.45E-07
Buffer Time	€ -	0.00771	∞

Screen-Shot of "Impact Tactical Decisions” sheet per Tactical Decision for all LRUs Together

Appendix G: Simulation Model Characteristics

The main model, as we can see in the Figure below**,** contains the input (*structural* input about the product and network structure and the installed base and *detailed* input about item specific parameters) and the simulation control.



Screen-Shot of the Simulation Model

Input

The input is specified in two parts: A *structural* part (service network structure, product structure, installed base) and a *detailed* part in which all the detailed parameters should be set. The reason is that the detailed part depends on the structural part. For example, the matrix of repair times depends on the number of parts and the number of locations that has been specified in the structural part.

<u>*Structural Input*</u>

The product and system structure consists of four tables where we define the LRUs, the SRUs, the installed base, and the repair shops.

1. LRUs are specified in the table *Sys*. An LRU is given by an item number, multiplicity, the mean time between failure (taking into account the average operating hours), and a label to identify the LRU.
2. SRUs are specified in the table *SRUs*. An SRU is given by an item number and a label to identify the SRU.

3. The installed base is specified in the table *IB*. The installed base is specified with the location where a system is installed (ships), the number of systems per location, the most downstream repair shop in the supply chain where an item can be repaired, and the fraction of time the system is operational and generates failures. The output field *availability* gives the average supply availability for that location (ship).
4. The relation between the repair shops, where parts can be kept on stock and where repair can take place, are specified in the table *rShops*. It is given by the name of the repair shop and the direct predecessor in the supply chain.

Detailed Input

1. The stock levels per item and location are specified in the table *StockLevels*. We use the initial spare part allocation calculated by INVENTRI, as input for this table.
2. The mean repair throughout times (mean time to repair) per item and location are specified in the table *MTTR*. The model assumes exponential distributed repair times.
3. The order-and-ship times per item and location are specified in the table *OStime*. The model assumes deterministic order-and-ship times.
4. The time to return a failed item one stage upstream in the supply chain (return time) per item and location is specified in the table *ReturnTime*. It is also possible to include these times in the repair throughput times, the return times have then to be set to zero.
5. The time needed to receive a new item if the failed item is discarded per item and location (resupply time) is specified in the table *ExtSupplyTime*. The model assumes exponential distributed resupply times.
6. The probability that an item can be repaired at a location (r_{ij} in terms of Sherbrooke (2004)) is specified in the table *pLocRepair*.
7. The probability that an item will be discarded at a location is specified in the table *pDiscard*. If an item is not repaired and not discarded it will be send one stage upstream in the supply chain to consider repair.
8. The probability that a failure of a LRU is caused by a failure of a SRU (parent-child relations) is specified in the table *CauseProb*. The values are the q_{ij} in terms of Sherbrooke (2004). This table can become very large. Therefore the table *fCause* is generated automatically in the model. This table gives per item a sub-table specifying which SRU causes the failure with which probability.

Simulation Control

To control the simulation, four global variables can be set: Continuous demand, Time factor, Run length, and Warm-up period.

1. *ContDemand* is a Boolean variable that indicates whether item failures continue when a system is down or not. METRIC assumes continuous demand, so item failures occur even when the system is down.
2. *TimeFactor* is a variable that scales (divides) all times by a certain factor. This prevents the simulation clock reaches its limit.
3. *Runlength* is a variable that indicates the length of the simulation run (excluding warm-up period).
4. *WarmUpPeriod* is a variable that sets the length of the warm-up period. The performance measurement starts after this period has passed.

Network

When the model is initialised (click in the *EventController* on Reset and Init), it generates the system structure in the object *Network*. The nodes at the left-hand side represent the installed base, the others the suppliers (repair shops). Another object is for performance measurement at network level.

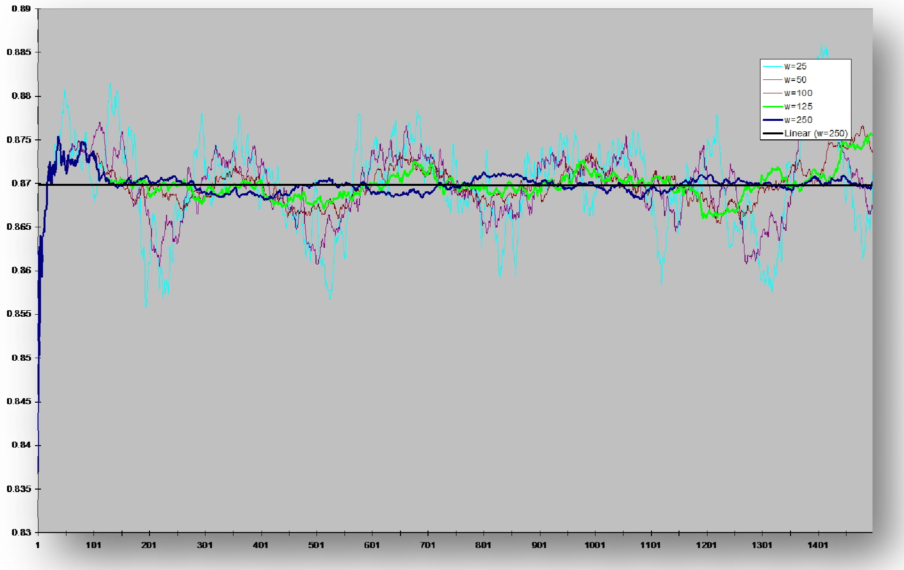
1. The *installed base* contains several methods for generation of failures (the first failures are generated upon initialisation and updated when the item has failed) and an object for performance measurement for this location (ship).
2. The *repair shops* represent the repair shops and their stock point. The stock point receives items from its own repair shop, repaired items form the next upstream stock point, and new items from an external supplier. Several methods handle failed items.
3. The object *Network Performance* measures the total network performance.
    a. The table *Results* keeps track of the up- and downtimes in the installed bases. It is specified in the number of systems that are operational and the length of the period during which this number of system has been working. This is used for detailed performance measurement (probability density function of the availability during a period).
    b. The global variable *Availability* gives the average network availability (same as in the main frame)
    c. The object *AnalIntAv* generates the probability distribution function of the interval availability. The results are given in survival probabilities and density function.

Output

There are three important outputs (performance measurements): average availability, availability distribution, and pipelines and backorders.

1. The *Average Availability* is measured for each part of the installed base and over all systems in the network.
2. The *Distribution* over the availability in a certain interval length is measured for each part of the installed base and over all systems in the network.
3. Detailed characteristics of the pipelines and backorders (expected and variance) are measured for all repair shops.

Appendix H: Resulting Graph of Welch's Method



Determining Warm-Up Period with Welch's Method

We use the *batch means method* and have one long run consisting of 5 batches of all 1500 years. The correlation between the batches is low (about 0.02). We use Welch's method to determine the warm-up period. From this point in time the system is in its steady state and the performance measurement starts after this period has passed. From Welch's method (Figure above) we see that after about 150 years the system is in its steady state. However, we currently use a warm-up period of 10.000 years, because situations that occur only on rare occasions (because of some very long MTBF values) will then probably be included in this long period and it takes almost no extra runtime. We further use a simulation run length of almost 20.000 years. This long simulation run length allows us to obtain accurate probability distributions of the availability.

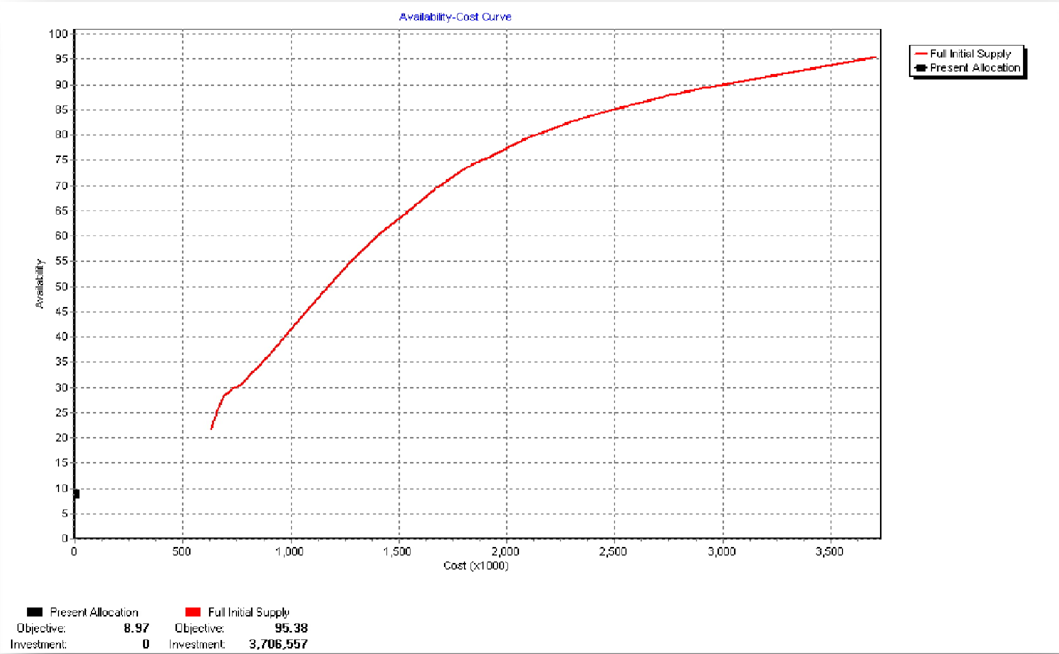
Appendix I: Model Verification

Appendix I-1: Ship Availability Levels from Simulation

	Target Availability	Simulation
Ship 1	0.88	0.876
Ship 2	0.88	0.875
Ship 3	0.88	0.876
Ship 4	0.88	0.878
Ship 5	0.88	0.876
Ship 6	0.88	0.875
Total Network	0.88	0.876

Simulation Results per Ship

Appendix I-2: Availability versus Costs Curve (INVENTRI)



Availability versus Cost Curve from INVENTRI

Appendix I-3: Availability Comparison Between INVENTRI and Simulation

Investment	Target Availability	INVENTRI	Simulation
€ -	-	0.090	0.092
€ 633,441.00	0.20	0.217	0.225
€ 748,835.92	0.30	0.301	0.300
€ 1,022,464.42	0.40	0.425	0.419
€ 1,407,755.92	0.60	0.604	0.592
€ 1,681,755.19	0.70	0.697	0.686
€ 2,127,244.59	0.80	0.799	0.793
€ 2,759,824.51	0.88	0.880	0.876
€ 3,706,557.25	0.95	0.954	0.952

Steady State Availability Comparison

Appendix J: Heuristic 1

	Tactical Decision	Costs / Year	Δ *EBO*	Cumulative Costs	Total Δ *EBO*	Availability
1.	25 Items Thales to shore	€ 17.99	0.00080	€ 17.99	0.00080	-
2.	Stock SRUs Item 54 (*k*=0.10)	€ 95.02	0.00360	€ 113.01	0.00440	-
3.	Stock SRUs Item 55 (*k*=0.10)	€ 75.54	0.00130	€ 188.55	0.00570	-
4.	Stock SRUs Item 90 (*k*=0.10)	€ 0.67	0.00001	€ 189.22	0.00571	-
5.	Thales to shore Item 55	€ 53.66	0.00070	€ 242.88	0.00641	0.887
6.	Priority Rule Items 20.28.29.33.67.70.73.83	€ 327.11	0.00270	€ 569.99	0.00911	0.890
7.	Priority Rule Items 10.27.50.51	€ 19.07	0.00020	€ 589.06	0.00931	0.890
8.	Stock SRUs Item 54 (*k*=0.20)	€ 285.05	0.00170	€ 874.11	0.01101	0.896
9.	Stock SRUs Item 55 (*k*=0.20)	€ 226.62	0.00120	€ 1.100.73	0.01221	0.897
10.	Stock SRUs Item 90 (*k*=0.20)	€ 2.03	0.00001	€ 1.102.76	0.01222	-
11.	Stock SRUs Item 56 (*k*=0.10)	€ 8.02	0.00003	€ 1.110.78	0.01225	-
12.	Stock SRUs Item 13 (*k*=0.10)	€ 8.52	0.00003	€ 1.119.30	0.01228	-
13.	Thales to shore Item 56	€ 19.06	0.00010	€ 1.138.36	0.01238	-
14.	Thales to shore Item 13	€ 18.78	0.00010	€ 1.157.14	0.01248	-
15.	Stock SRUs item 55 (*k*=0.30)	€ 377.69	0.00110	€ 1.534.83	0.01358	0.898
16.	Stock SRUs item 90 (*k*=0.30)	€ 3.38	0.00001	€ 1.538.21	0.01359	-
17.	Thales to shore Item 19	€ 14.00	0.00004	€ 1.552.21	0.01363	-
18.	Thales to shore Item 74	€ 7.82	0.00002	€ 1.560.03	0.01365	-
19.	Stock SRUs Item 77 (*k*=0.10)	€ 3.19	0.00001	€ 1.563.22	0.01366	-
20.	Stock SRUs Item 58 (*k*=0.10)	€ 3.80	0.00001	€ 1.567.02	0.01367	-
21.	Thales to shore Item 63	€ 11.68	0.00003	€ 1.578.70	0.01370	-
22.	Thales to shore Item 78	€ 11.71	0.00003	€ 1.590.41	0.01373	-
23.	Priority Rule Item 55	€1.073.29	0.00240	€ 2.663.70	0.01613	0.900

Results of Iterations for Heuristic 1

Appendix K: Heuristic 2

Appendix K-1: Breakdown Structure of the first Availability Killer

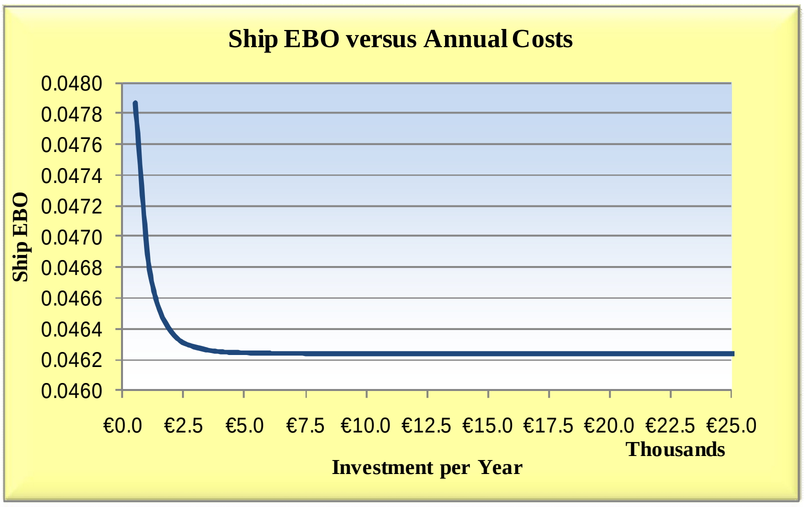
LRU/ SRU	Item Name	Multi-plicity	Item Costs	MTBF (Hours)
LRU	**Availability Killer 1**	**22**	**€ 126,688.20**	**19,129**
SRU	**1**	1	€ 1,400.00	33,333,333
SRU	**2**	1	€ 1,295.00	33,333,333
SRU	**3**	1	€ 3,355.00	1,026,821
SRU	**4**	1	€ 1,960.00	6,666,667
SRU	**5**	1	€ 2,585.00	6,250,000
SRU	**6**	1	€ 8,490.00	1,387,232
SRU	**7**	1	€ 5,310.00	126,455
SRU	**8**	1	€ 2,075.00	14,705,882
SRU	**9**	1	€ 2,230.00	181,270
SRU	**10**	1	€ 3,115.00	215,974
SRU	**11**	1	€ 2,420.00	1,173,709
SRU	**12**	5	€ 3,330.00	209,767
SRU	**13**	1	€ 2,670.00	179,287

First Availability Killer and its Subcomponents

Appendix K-2: Results of Marginal Analysis

Total Costs	Extra Investment	Added Item	Reduction SRU Waiting Time	Ship EBO	ΔEBO
		Current Situation	**0.000**	**0.0510**	**-**
€ 499.5	€ 499.50	13	0.145	0.0479	0.0031
€ 999.0	€ 499.50	13	0.269	0.0469	0.0041
€ 1,333.5	€ 334.50	10	0.346	0.0466	0.0044
€ 1,734.0	€ 400.50	14	0.425	0.0464	0.0045
€ 2,233.5	€ 499.50	13	0.516	0.0463	0.0047
€ 2,700.8	€ 467.25	11	0.585	0.0463	0.0047
€ 3,497.3	€ 796.50	8	0.683	0.0463	0.0047
€ 3,996.8	€ 499.50	13	0.740	0.0462	0.0047
€ 4,331.3	€ 334.50	10	0.765	0.0462	0.0047
€ 4,731.8	€ 400.50	14	0.790	0.0462	0.0047
€ 5,231.3	€ 499.50	13	0.821	0.0462	0.0047
€ 6,027.8	€ 796.50	8	0.863	0.0462	0.0047
€ 6,390.8	€ 363.00	12	0.879	0.0462	0.0047
€ 6,858.0	€ 467.25	11	0.898	0.0462	0.0047
€ 7,361.3	€ 503.25	4	0.916	0.0462	0.0047
€ 7,860.8	€ 499.50	13	0.931	0.0462	0.0047
€ 8,195.3	€ 334.50	10	0.936	0.0462	0.0047
€ 8,991.8	€ 796.50	8	0.949	0.0462	0.0047
€ 9,392.3	€ 400.50	14	0.955	0.0462	0.0047
€ 9,891.8	€ 499.50	13	0.961	0.0462	0.0047
€ 11,165.3	€ 1,273.50	7	0.975	0.0462	0.0047
€ 11,459.3	€ 294.00	5	0.978	0.0462	0.0047
€ 11,847.0	€ 387.75	6	0.981	0.0462	0.0047
€ 12,314.3	€ 467.25	11	0.985	0.0462	0.0047
€ 12,813.8	€ 499.50	13	0.987	0.0462	0.0047
€ 13,125.0	€ 311.25	9	0.988	0.0462	0.0047
€ 13,921.5	€ 796.50	8	0.991	0.0462	0.0047
€ 14,115.8	€ 194.25	3	0.992	0.0462	0.0047
€ 14,450.3	€ 334.50	10	0.993	0.0462	0.0047
€ 14,660.3	€ 210.00	2	0.993	0.0462	0.0047
€ 15,060.8	€ 400.50	14	0.994	0.0462	0.0047
€ 15,423.8	€ 363.00	12	0.995	0.0462	0.0047
€ 15,927.0	€ 503.25	4	0.996	0.0462	0.0047

Partial Marginal Analysis Results for Subcomponents of the first Availability Killer



Ship EBO versus Annual Costs Curve

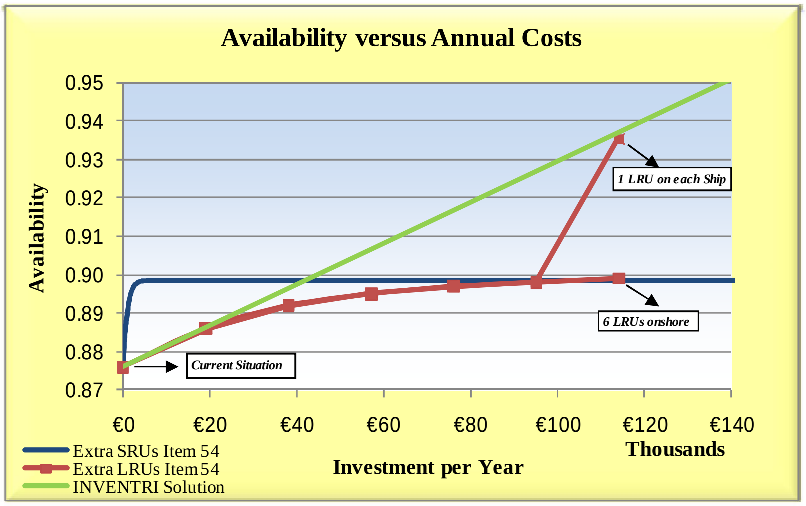
Appendix K-3: Results of Stocking the Availability Killer

In the figure below, we show that stocking SRUs of the first availability killer is a better decision than stocking the LRUs. The figure shows the availability versus cost curve for the two possibilities of adding extra stock (LRUs or SRUs) compared to the INVENTRI solution. Since we assume the stock allocation on each ship is the same (and in this case we have six ships), we need an LRU in multiplicities of six when we want to stock it onboard. So for the first five times we stock one extra LRU, we determine whether to stock the item onshore or at Thales. Using the Excel tool, we see that we stock the first five times item 54 onshore. However, the average availability is larger when we stock one LRU on each ship and do not stock six LRUs onshore. The table below shows the results of investing in item 54.

	Total Investment	Availability	Standard Deviation	Coefficient of Variation
Current Situation	€ 2,759,824	0.876	0.077	0.088
+ 1 LRU onshore	€ 2,886,513	0.886	0.068	0.077
+ 2 LRU onshore	€ 3,013,201	0.892	0.062	0.070
+ 3 LRU onshore	€ 3,139,889	0.895	0.058	0.065
+ 4 LRU onshore	€ 3,266,577	0.897	0.057	0.064
+ 5 LRU onshore	€ 3,393,266	0.898	0.056	0.062
+ 6 LRU onshore	€ 3,519,954	0.899	0.055	0.061
∞ LRU onshore	∞	0.899	0.055	0.061
+ 1 LRU on ships	€ 3,519,954	0.935	0.060	0.064

Simulation Results of Stocking Extra Spares of the first Availability Killer

From the figure we see that instead of investing about €45,000 per year in spare parts (from the INVENTRI solution) or €114,000 per year in extra LRUs of item 54, an investment of €4,000 per year for extra subcomponents of the item 54 leads to the same average availability (0.898). From this, we conclude that investing in the subcomponents of item 54 is better than when we invest in spare parts as calculated with INVENTRI or invest in extra LRUs of item 54.



Availability versus Cost Curve

Appendix K-4: Iterations Heuristic 2

Tactical Decision	Costs per Year		Δ EBO	Δ EBO / Costs per Year
OS Time Shore to Ship	€	199,000	0.0276	1.39 E-07
OS Time Thales to Shore	€	1,500	0.0049	32.93 E-07
Stock SRUs (*k*=0.10)	**€**	**1,000**	**0.0036**	**35.60 E-07**
Priority Rule	€	29,800	0.0080	2.69 E-07
Stock LRU onboard	€	114,000	0.0497	4.36 E-07
Stock LRU onshore	€	19,000	0.0038	1.99 E-07
Stock LRU at Thales	€	19,000	0.0029	1.51 E-07

Results Tactical Decisions of First Iteration for the First Availability Killer

	Tactical Decision	Costs / Year		*Δ EBO*	Cumulative Costs		Total *Δ EBO*	Availability
1.	**Stock SRUs Item 54 (*k*=0.10)**	€	999.00	0.0036	€	999.00	0.0036	-
2.	**Stock SRUs Item 54 (*k*=0.20)**	€	735.00	0.0017	€	1,734.00	0.0053	-
3.	**Stock SRUs Item 54 (*k*=0.30)**	€	499.50	0.0008	€	2,233.50	0.0061	-
4.	**Thales to shore Item 54**	€	1,490.51	0.0012	€	3,724.01	0.0073	0.898
5.	**Stock SRUs Item 55 (*k*=0.10)**	€	75.54	0.0013	€	3,799.55	0.0086	-
6.	**Thales to shore Item 55**	€	53.66	0.0017	€	3,853.21	0.0103	0.900

Results of all the Iterations for Heuristic 2

Appendix L: Heuristic 3

Appendix L-1: First Iteration of Heuristic 3

Overview (all items)			
Tactical Decision	**Costs / Year**	**Δ EBO**	**Impact**
OS Times Shore to Ship	€ 278,000	0.0383	1.38 E-07
OS Times Thales to Shore	€ 2,000	0.0073	34.80 E-07
Stock SRUs (*k*=0.10)	**€ 730**	**0.0054**	**74.18 E-07**
Priority Rule	€ 41,000	0.0154	3.75 E-07
Stock LRU (item 55, onshore)	€ 15,000	0.0113	7.45 E-07
2-Week Buffer	€ -	0.0077	∞

Results of First Iteration for Tactical Decisions for all Items Together

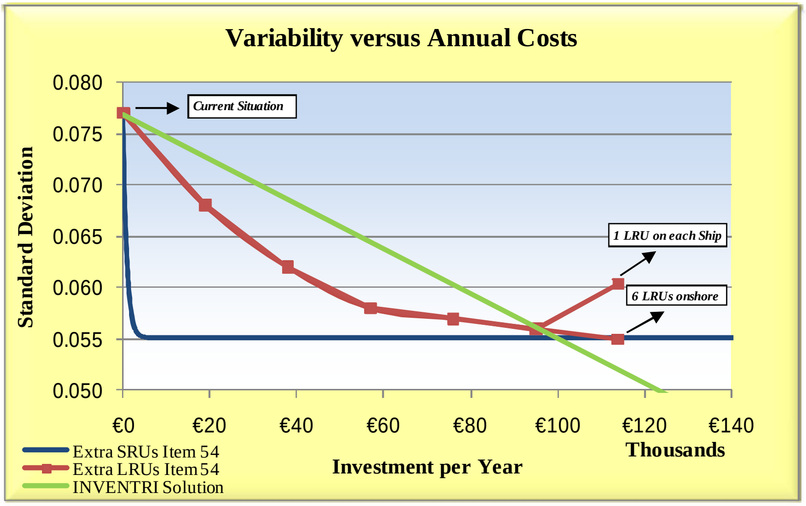
Appendix L-2: All Iterations of Heuristic 3

	Tactical Decision	**Costs / Year**	***Δ EBO***	**Cumulative Costs**	**Total *Δ EBO***	**Availability**
1.	**Stock SRUs (*k*=0.10)**	€ 733	0.0054	€ 733	0.0054	0.887
2.	**OS Times from Thales to shore**	€ 2,085	0.0053	€ 2,817	0.0107	0.892
3.	**Stock SRUs (*k*=0.20)**	€ 2,198	0.0023	€ 5,016	0.0130	0.899
4.	**Stock LRU (Item 73, onshore)**	€ 3,842	0.0024	€ 8,857	0.0154	0.901

Results from the Optimisation Procedure

Appendix M: Impact SRUs of Availability Killer on the Availability Variability

A nice example can be given for the first availability killer, where we compare the impact of lowering the gross mean repair throughput time (by stocking SRUs) to the impact of stocking LRUs and the INVENTRI solution. The figure below shows the variability versus costs curve, where we see that stocking extra LRUs of item 54 results in a better variability than investing in spare parts as optimised with INVENTRI. Furthermore, we see that for investing €4,000 per year in extra subcomponents of item 54, an extra investment of €115,00 per year in extra LRUs of item 54 or an extra investment of €100,000 per year in spare parts (from INVENTRI solution) is needed to attain the same standard deviation.



Variability versus Cost Curve