THALES

The transition from operational availability to mission availability

Case study

Unclassified

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THALES

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Preface

The results of my graduation period at Thales Netherlands in Hengelo at the department ILS competence center are presented in this Master of Science thesis. The Master of Science thesis has been performed during the period September 2013 and May 2014.

I conducted an extension on a baseline study in the first three months to get an overview of the maintenance and logistics at Thales Nederland. The baseline study is the basis of my Master of Science thesis (Heida & Schmal, 2014). Some parts are cannibalized from this study for this research.

This Master of Science thesis was an informative assignment. I learned a lot during my graduation period. The logistic support environment was a new experience to me. Thanks to Thales I learned a lot from this industry. I consider this graduation as a valuable experience.

I am thankful to Thales Netherlands for giving me the opportunity to graduate for my Master of Science thesis. With this opportunity I could graduate with my study Industrial Engineering and Management with as specialization track: Production and Logistics. I would like to take this opportunity to thank the following people. Firstly, I would like to thank Rindert Ypma for his time to help and support me during my graduation period. I could perform this Master of Science thesis thanks to Rindert Ypma. Secondly, I would like to thank Mathieu Pivaut, who was my supervisor at Thales Nederland in the first three months. I would like to thank him for his time and effort to help me with my baseline study. I would also like to thank my colleagues at the department ILS competence center for the pleasant work environment. Thirdly, I would like to thank my supervisors Matthieu van der Heijden and Ahmad Al Hanbali of the University of Twente. They spend a lot of time reading and giving extensive feedback on my draft versions of my Master of Science thesis. I would also thank them for the general feedback during my graduation period.

Finally, I would like to thank my family and friends for supporting me during my graduation period.

Jaco Schmal

Hengelo, 4 June 2014

Management summary

Thales is planning to deliver systems with a Performance Based Logistic contract. Thales is responsible for the whole maintenance process against a fixed fee. The key performance indicator is the mission availability per ship over a certain time period. The mission availability is defined as the system uptime during the mission divided by the mission time (mission uptime + mission downtime). The downtime is measured by the supply availability. Within a performance based logistic contract, Thales will receive financial penalties when the mission availability drops below the agreed mission availability target. Thales receives a financial bonus when the system performed as agreed. It is of great importance for Thales to determine what the effects are of a performance based contract. Thales performed several studies to estimate the effects and costs of a performance based logistic contract. This research focuses on the transition from the key performance indicator 'supply availability' to the mission availability.

The objective of this research is to find an optimal spare parts allocation procedure for the antenna of the Smart-L ELR case. An optimal spare parts procedure involves minimizing the cost with as constraint a minimum mission availability target. Simultaneously it should take into account the mission's length, annual operational hours, repair lead-time, of the multi-indenture antenna. In addition Thales prefers an spare parts allocation procedure which is "robust". The solution of the optimized procedure are as less sensitive as possible for variations of the Mean Time Between Failure. In that case the solution may have slightly higher cost. With this objective the main research question is formulated:

What is the optimal spare parts allocation procedure of the antenna of the Smart-L ELR to ensure that the minimum mission availability constraint is satisfied, the cost are minimized, considering mission profiles, annual operational hours, and repair lead-time?

In this research there are four allocation procedures constructed, whereby the transfer point from Inventri to Simlox is different per procedure. The second procedure uses two types of ships, namely a mission ship and a short-mission ship. A mission ship goes on mission for several months and the short-mission ships will perform multiple short missions per year. The second procedure calculates the supply availability of the mission ships and the short-mission ships separately by Inventri. The mission ship allocation is combined with the ship spare parts of the short-mission ship allocations. Subsequently, Simlox is used to allocate the spare parts following a single-site METRIC allocation process, whereby the ships together are considered as single-site. Procedure 3 calculates the spare parts allocation to a supply availability level of 99.99% with Inventri. Afterwards checks the allocation list when the short-mission ship is allocated too. The spare parts allocation list, until the short-mission ship is allocated, is implemented in Simlox. Subsequently, Simlox is used to allocate the spare parts following a single-site METRIC allocation process, whereby the ships together are considered as single-site.

The case study consists of a 3-echelon, multi-indenture supply network with three ships, one shore stock location and one original equipment manufacturer (Thales).

From this case study, we can conclude:

The third procedure generates higher mission availability solutions which are less sensitive to MTBF variations, but costs slightly more

An experiment is conducted whereby it seems that the mission availability in procedure 3 is less sensitive to MTBF variations due to higher average mission availability solutions. The slightly more expensive procedure copes better to MTBF variations. Thales prefers a procedure which copes better to

MTBF variations, regardless it has slightly higher costs. The third procedure can cope for this case at least to 12.5% lower Smart-L antenna MTBF values, but costs maximal 11% more.

Procedure 2 generates overall the most cost-effective solutions

Procedure 2 generates overall the most cost-effective solutions. Compared to procedure 3 this is a more labor-intensive procedure (more iterations), but generates cheaper solutions.

The probability of backorders reduction is made plausible linearly proportional to the mission availability addition.

It is made plausible that the delta probability of backorders (PBO) is linearly proportional to the delta mission availability. This is made plausible for a 3-echelon structure whereby in all the stock locations the delta EBO is made plausible to be linearly proportional to the delta mission availability. This results in that the choices of the VARI-METRIC model can be used to allocate the spare parts.

The reduction of the repair lead-time can reduce the initial spare parts cost in this case with 39.76%, but it can only be realized by stocking component spare parts.

The largest total initial spare parts cost is achievable by reducing the repair lead-time. The reduction of the repair lead-time is only allowable when Thales stocks components as spare parts. The component spare parts cost is much lower than the Line Replaceable Unit (LRU) spare parts. The maximal initial spare parts cost reduction is for a steady state model in this Smart-L case 39.76%.

The reduction of the shipment cycle time reduces the initial spare parts costs, in this case 28.13%.

The one month shipment cycle time and two months shipment cycle time is studied and how it influences the initial spare parts costs. The total initial spare parts cost is higher for the shipment time of two months than the total initial spare parts cost of one month. The initial spare parts costs reduction is in this Smart-L case 28.13%.

The following recommendation can be presented based on this case study:

Use the third procedure to allocate the spare parts for requested minimum mission availability target, because it generates in general higher mission availability solutions which are less sensitive to MTBF variations

This procedure, which generates a solution with slightly higher costs, can cope better with the MTBF variations due to higher average mission availability solutions. Therefore the recommendation is to use the third procedure for allocating the spare parts to stock locations.

Reduce the repair lead-time, because it reduces the initial spare parts costs

In the systems of Thales there are a lot of printed circuit boards. These printed circuit boards are designed to be an LRU. In a PBL contract environment the inventory costs are at the expense of Thales. The recommendation is that costs can be saved by reducing the repair lead-time in a PBL contract environment. Reducing the repair lead-time can only be realized by stocking components as spare parts.

Reduce the shipment time between customer's site and the ships from two months to one month

The total initial spare parts cost is higher for the shipment time of two months then the total initial spare parts cost of one month. Therefore, the recommendation is to agree in terms of the PBL contract a one month shipment time. The initial spare parts costs reduction is in this Smart-L case 28.13%.

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List of abbreviations

AAW	Anti Air Warfare
ACE	Advanced Centre for Electronics
AOH	Annual operational hours
ASuW	Anti Surface Warfare
B2G	Business to Government
BIT	Built In Test
CMMS	Computerized Maintenance Management System
COTS	Commercial Off-The-Shelf
CSS	Customer Service Support
DFM	Design For Maintenance
EBO	Expected backorders
ELR	Extended Long Range
EWC	Early Warning Capability
ILS	Integrated Logistic Support
IVVQ	Integration, Verification, Validation and Qualification
KPI	Key Performance Indicator
LRU	Line Replaceable Unit
MaSeLMa	Integrated maintenance and service logistics concept for maritime and offshore
MDT	Mean Down Time
METRIC	Multi-Echelon Technique for Recoverable Inventory Control
MSD	Mean Supply Delay
MTBF	Mean Time Between Failure
MTBM	Mean Time Between Maintenance
MTTR	Mean Time To Repair
OEM	Original Equipment Manufacturer
PBL	Performance Based Logistics
PBO	Probability of backorders
PCB	Printed Circuit Board
PNBO	Probability of no backorders
PPM	Product Portfolio Management
SCC	Software Competence Centre
Smart-L	Signaal Multibeam Acquisition Radar for Targeting, L-band
SRU	Shop Replaceable Unit

1 Thales

This chapter introduces Thales (Thales Group). The company is responsible for the production of the Smart-L radar system and Smart-L ELR radar system.

Thales Nederland B.V. was established in 1922 under the name of "NV Hazemeyer's fabriek voor signaalapparaturen" in the city of Hengelo, since then the company has been known as: Hollandse Signaalapparaten, Thomson CSF signal and since 2000 Thales Nederland. The main expertise of Thales Nederland has been the development of fire control, radar systems and combat management for navies around the world. Thales Nederland is an expert in the field of radar technology, it produces radars as well as complete combat systems including radars. Thales Nederland is the original equipment manufacturer (OEM) and supplies initial products as well as spare parts and offers repairs for their products. A more detailed history description is discussed in paragraph 1.1, the internal organization of Thales in paragraph 1.2, the market wherein Thales performs in paragraph 1.3 and the system Smart-L in paragraph 1.4.

1.1 History

Hazemeyer started the company to produce fire control equipment for the Hr.Ms. Sumatra and Hr.Ms. Java ships of the Royal Netherlands Navy. Thereafter the company grew rapidly and started to supply to foreign navies like Sweden, Spain and Greece. In 1940 the German army captured the factory. Fortunately, a great part of the staff was able to escape to the United Kingdom and continued their work on radar and fire control systems in the UK. After the war the staff returned to find the factory deserted and pillaged. The Dutch government bought the factory in 1945 to establish a good defence industry, the company name changed to N.V. Hollandse Signaalapparten. With new facilities and staff a rapid development in radar and fire control for the army as well as computer and air traffic equipment was established. Philips bought a large part of the shares in 1956 and becoming main shareholder. The company kept growing and expended across several cities in the Netherlands. At the end of the eighties 5000 people were employed serving customers over 35 countries. The end of the Cold War changed the political view of governments and companies, high defence budgets were no longer needed. Philips discarded defence and control systems as part of its core business. In 1990 the already reorganised Hollandse Signaalapparaten was taken over by Thomson-CSF. The reorganisation and fusion of the company brought a change in the company's vision; from now on new systems were designed targeting defence equipment and combat management. In 2000 Thomson-CSF changed its name to Thales to carry out a clear corporate structure.

The originally French Thales Group is a global technology leader for defence & security and aerospace & transport markets. In 2011 Thales was located in 56 countries and employed 67000 people of whom 22500 were engineers and researchers. From the generated revenues in 2011 (12.9 billion euros) 20% was invested in research and development, giving Thales the unique possibility to design, develop and deploy systems and services which are highly complex. Nowadays the Thales Group has three core businesses: Defence, Aerospace & Space and Security.

As a member of the Thales group, Thales Netherlands employs about 2000 people in 5 locations, making Thales Netherlands the largest Dutch defence company. In 2013 sales, of which 75% due to export, generated approximately 500 million euros income. About 1700 employees are stationed at the Headquarters in Hengelo were Thales is specialized in naval technology.

1.2 Internal organization

Thales Nederland is divided in three industries (Figure 1).

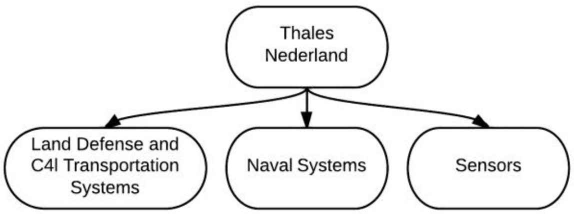


Figure 1: Major industries Thales Nederland

Land defense and C4l transportation systems

The development of land defence and transportation products and systems is executed by this industry. Products of the land defence department are the Sotas vehicle system (a navigation and communication system suitable for all vehicle types in missions) and the Squire (a hard to detect portable radar). A non-related, but notable product that the transportation department also developed is the OV-chipcard reader for the Dutch Railways (NS).

Naval systems

The support and development of naval product, except the physical hardware, is executed by this industry. Software development, logistics, support, acquisition, communication, etc. are accomplished by the departments of this industry.

Sensors

Development, production and maintenance of the hardware of the naval product takes place in this industry. Furthermore, this industry is responsible for the design, testing, production a repair of the physical products. The naval system and the sensor industry departments are responsible for the repairs, therefore these departments are further described. In Figure 2 the organization structure of the Naval Systems industry is shown.

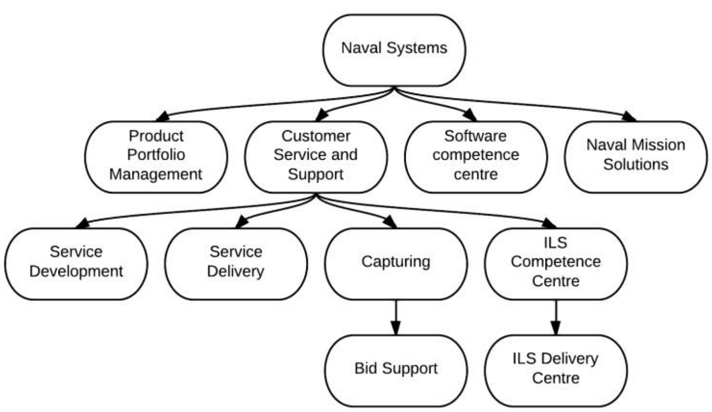


Figure 2: Organizational structure Naval Systems

Naval systems consist of more than ten departments, four of which are relevant in terms of the development and maintenance of radar systems. Below a short description of the activities and responsibilities of the departments is given. The department of customer service support is described in detail for a better insight.

- Product Portfolio Management (PPM): Develops new products
- Software Competence Centre (SCC): Develops software that controls the radar system
- Naval mission solutions: Combines software and hardware to a working system
- Customer Service Support (CSS): Develops and provides services and support for the radar systems.
    - Service development: Responsible for the development of new service, maintenance and logistic concepts based on customer demands.
    - Service delivery: Responsible for the service during the use phase. (helpdesk support, sending expert engineers/spare parts)
    - Capturing: Responsible for the sales of radars to customers
        - Bid support: Supports capturing
    - Integrated Logistic Support (ILS) competence centre: Responsible for the theoretical maintenance (Design For Maintenance (DFM)) and logistic design for the radar systems.
        - ILS Delivery centre: Responsible for documentation and training which are necessary to use the radar systems

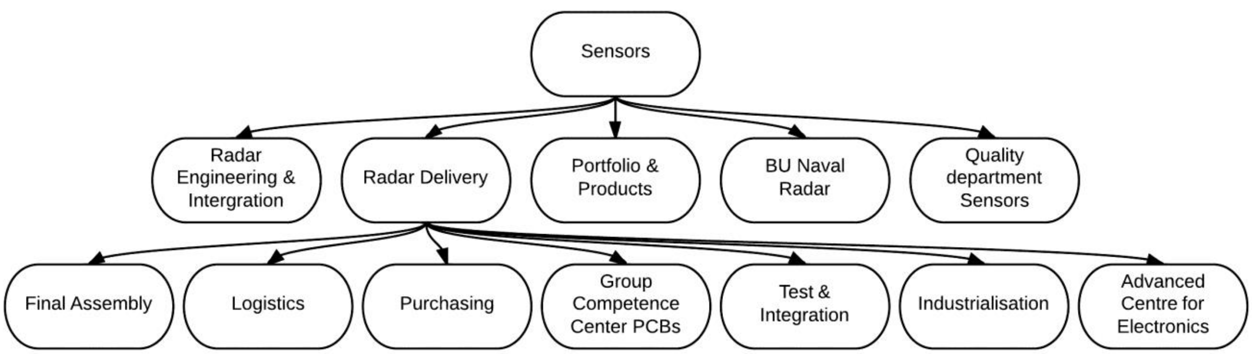


Figure 3: Organizational structure Sensors

Figure 3 shows the organizational structure of the Sensors industry. Below a short description of the activities and responsibilities of the departments is given. For insight the department is described in detail.

- Radar engineering & integration: Responsible for the specifications of the hardware
- Radar delivery: Responsible for the assembly of the product
    - Final assembly: Responsible for assembling all sub-systems into the final product
    - Logistics: Responsible for the logistics in the whole product chain. From documentation to orders for the demanded parts, to the delivery of all sub-systems to final assembly.
    - Purchasing: Responsible for purchasing modules of the sub-systems from external suppliers and for purchasing components and parts for Thales production department.
    - Group competence centre PCBs: responsible for the production of printed circuit boards (PCBs).

- Test & integration: Responsible for the integration, verification, validation and qualification (IVVQ) of the products. Parts are examined and tested in this department.
- Industrialisation: Responsible for the preparation of the system after the prototype is operational and before selling the product on the market.
- Advanced Centre for Electronics (ACE): Responsible for the assembly of components on the PCBs into a working electrical product.

- Portfolio & products: Responsible for the development of new products
- BU Naval radar: Responsible for bringing in new orders from (potential) customers.
- Quality department sensors: Independent department responsible for the quality control of the whole product chain from documentation to the final product.

1.3 Market of Thales

Thales has customers in over 55 countries. The company sells their products to the agencies of governments or directly to the governments and therefore performs in a Business-to-Government (B2G) market. Figure 4 shows Thales' worldwide presence; showing the number of employees per country.

Figure 4: Worldwide presence

Thales is the original equipment manufacturer of several radars. In Figure 5 radars are divided horizontally in three categories: Short range for self-defence of small ships, medium range for local area defence on medium ships/small frigates and long range for wide area defence on frigates. Vertically Figure 5 is divided into surveillance radars, electro-optical sensors, radar tracker and electro optical tracker. The surveillance radars detect conventional air targets and some of them could detect medium range stealth air targets. The electro-optical sensors detect super-sonic or stealth targets. Another category is the radar tracker. These radars are for gun and missile fire support against missiles, fighters and surface targets. Finally the electro-optical tracker could assists the ship's defense by tracking under radar silence for precise fire control of weapon systems against high maneuvering air and surface targets.

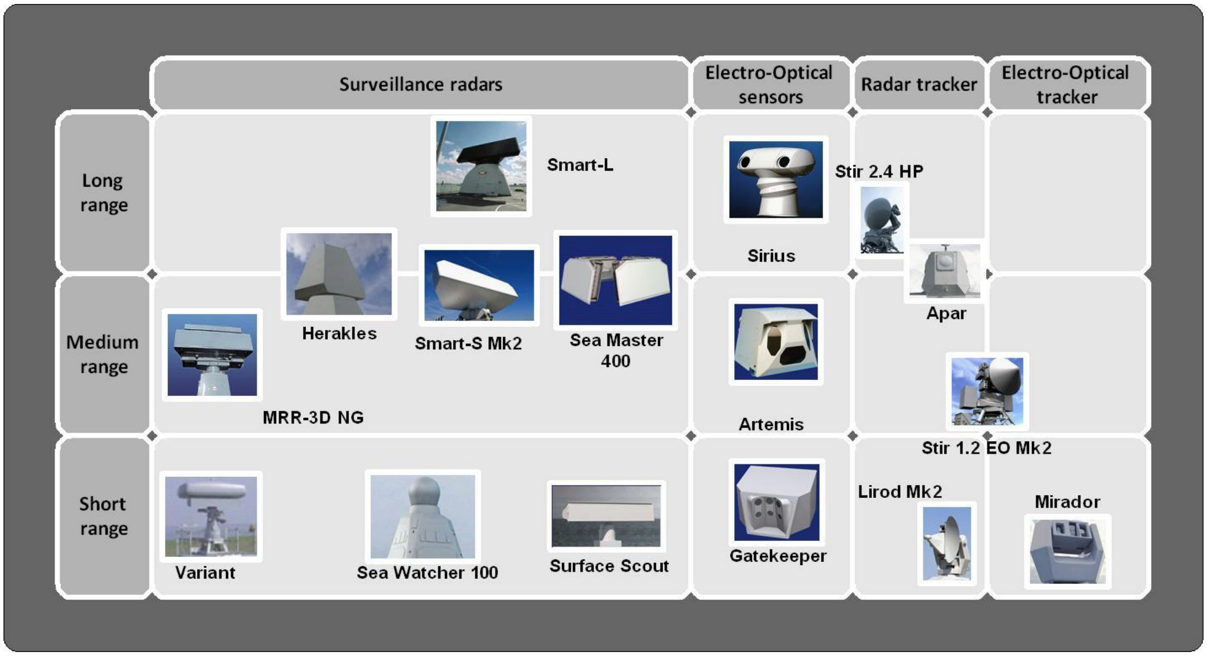


Figure 5: Short to long range radars

The latest innovation of Thales is the integrated mast family namely the I-Mast. The I-Mast is an all-in-one radar mast, which contains all the major radars, sensors and antennas for a naval ship. There are four types of I-mast: the I-mast 50, I-mast 100, I-mast 400 and the I-mast 500. Each I-mast is intended for a different class of naval vessels.

Using the classic radar equation (Wolff) the range of a radar can be determined, due to the 4th power in the equation; doubling the range a 16 times higher transmitted power is necessary. The radio power of a long range radar like the Smart-L increases rapidly when extending the range. The equation of Wolff is as followed:

$$R^4 = \frac{P_s * G^2 * \lambda^2 * \sigma}{P_E * (4\pi)^2}$$

R = range [m]
Ps= transmitted power [W]
PE = received power [W]
G = antenna gain [antenna's directivity and electrical efficiency]
λ = wavelength [m]
σ = Antenna cross section [m2]

Thales sold in 2013 over 1300 systems. These systems are installed all over the world. Table 2 provides an overview on the number of systems in each continent. Most systems are installed in Europe. The Netherlands has a 5.62% share of the systems. In Table 1 presents the top five most sold system types.

The radar systems in the top five are relatively old systems. It is therefore logical that Thales has sold most of these systems. Additionally, these systems are not that large and thus expensive as for example the Smart-L.

Table 1: Top five most sold systems

	Amount of systems sold	Percentage of systems sold
STIR 180 Base, I/K, 180/240 HP	150	10.96%
TACTICOS	143	10.45%
WM 22 - 28	122	8.91%
SCOUT-Mk1	113	8.25%
LW08	66	4.82%

Table 2: Amount of systems sold per continent

	Amount of systems sold worldwide	Percentage of systems sold worldwide
Europe	630	46.02%
Asia	364	26.59%
South-America	161	11.76%
Africa	140	10.23%
North-America	72	5.26%
Australia	2	0.15%
Grand Total	1369	100.00%

Stir

The Stir is a tracker for gun and missile fire control. The Stir has a long range to track the airborne missile. This radar guides the Semi Active Homing missiles to their targets.

Tacticos

Tacticos is a combat management system which combines the combat operations and the maritime security operations. The system controls the ship's radars and provides onboard missile guidance. Tacticos is also implemented with multiple mission profiles for a variety of ship types.

WM 22 – 28

The WM surveillance and tracking radar is an ancestor of the I-Mast. The WM family is over 40 years old. This system could surveillance and track missiles in the air. The last WM system is sold in 1990 and is only updated and supported by Thales.

Scout – MK1

The scout is a stand-alone mobile system which could also be operated remotely. This radar performs at a short-to-medium range. The Scout is a fully solid-state system with high reliability, low weight and small dimensions.

LW08

The LW08 is high-power radar which is designed for long-range surveillance and target indication for weapon control systems.

1.4 Smart-L

The Signal Multibeam Acquisition Radar for Tracking L band (SMART-L) is a three dimensional navel long-range search radar for air surveillance and surface surveillance. The Smart-L is developed and manufactured at the headquarters in Hengelo. The radar system provides two dimensional and three dimensional track/plot data about tactical threats and friendly forces in support of the ship's Anti Air Warfare (AAW) and Anti Surface Warfare (ASuW) tasks. The system is designed to have a maximum range of 400 km. (Data Sheet Thales Smart-L, 2012) The expectations are that the range of the radar can be improved to track ballistic missiles up to 2000 km in the future. (Schipper, 2014) Over 20 Smart-L systems are sold by Thales to navies from: The Netherlands, Germany, Italy, France, Denmark, Great Britain and South Korea. (Thales group, 2014) All the radars are adapted to the customer's wishes; all are Smart-L systems but every single one is uniquely tuned. In Table 3, general specifications of the Smart-L are presented.

Table 3: Specifications Smart-L (Data Sheet Thales Smart-L, 2012)

General specification Smart-L	
Dimensions	8.4 x 4 x 4.4 [m]
Weight	7800 [kg]
Antenna Rotations	12 [rpm]
Frequency	110-170 [GHz] (D-band), former 0.5 – 1.55 [GHz] (L-band)
Range (air)	400 [km]
Range (surface)	60 [km]
Elevation coverage	0-70 [°]
Capacity (air)	>1000 [tracks]
Capacity (surface)	>100 [tracks]

The Smart-L radar system contains 11 sub-systems, as can be seen in Figure 6. The Antenna is the only sub-system above deck and contains the bearing and the rotary joint unit, which are the main dynamic parts of the system. Below deck the other 10 sub-systems are located, these systems control and monitor the radar and mainly consist of electrical and electronic parts.

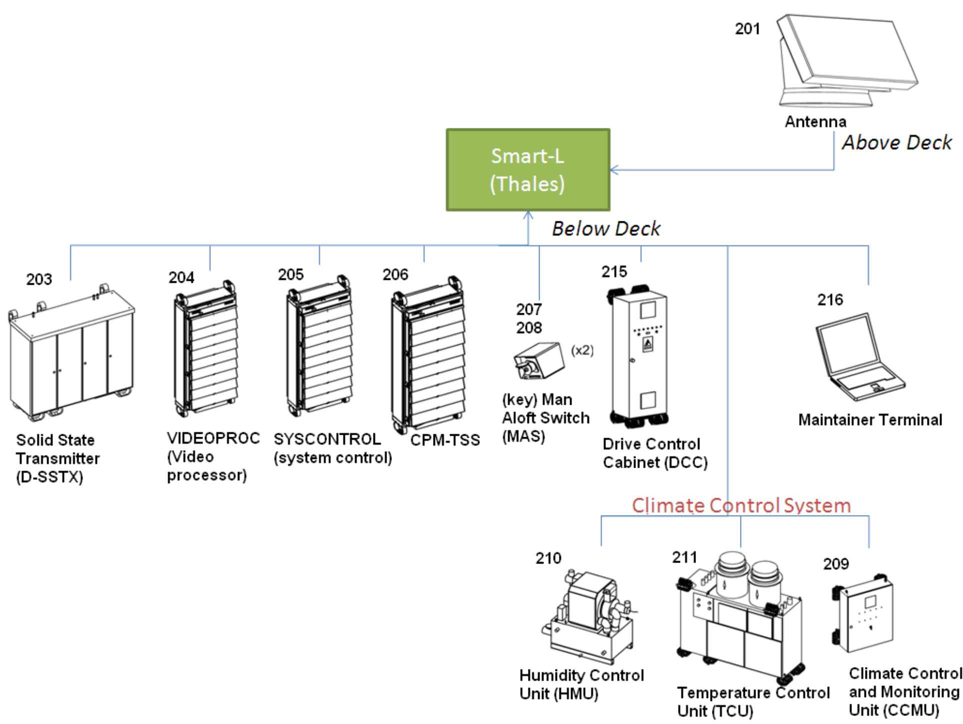


Figure 6: Smart-L system structure

In general every sub-system consists of Line Replaceable Units (LRUs), an LRU is an easy to replace unit to increase the availability of the system. LRUs are built from Shop Replaceable Units (SRUs) and SRUs consist of components.

2 Research design

Currently, Thales is developing a redesign of the Smart-L. This redesign (Smart-L ELR) contributes to the logistics of the availability contract: Performance Based Logistic (PBL) contract. This chapter will provide an outline for the research. In paragraph 2.1 the core problem will be discussed by giving a description about the Smart-L ELR antenna and the key performance indicator: availability. In paragraph 2.2 the research objectives will be defined with the research questions. In paragraph 2.3 the research approach is stated. In paragraph 2.4 the deliverables to Thales are explained and finally in paragraph 2.5 the research outline/plan is provided.

2.1 Core problem

Currently there is a service request shift from the traditional service contract to a Performance Based Logistic (PBL) contract. This means that the responsibility of the maintenance will shift from the customer to Thales. This changing customer demand lies at the root of this research. Thales must guarantee the system's availability to the customer by delivering the demanded service shift. Thales is currently redeveloping a system (Smart-L ELR) whereby this kind of service could be provided. This research will focus on the Smart-L ELR antenna. The scope of the product is defined in section 2.1.1 and the availability of the system in chapter 2.1.2.

2.1.1 Smart-L ELR antenna

The antenna system of the Smart-L ELR consists of five levels of parts. Each level consists of one or more parts. The first level is the antenna which will be referred to as the system in this research. The second level in the antenna is building blocks, which are virtual parts. In reality these are spaces on the antenna which consist of parts. The repair of the building blocks has to be conducted by replacement of Line Replaceable Units (LRUs). The third level is then subsequently the LRU level. This level consists of the parts which could be exchanged onboard the ship during missions to repair the antenna. The fourth level is the Shop Replaceable Units (SRUs) level. The LRUs consist of SRUs which could be exchanged to repair the LRU. The LRUs are repaired at Thales. The fifth level consists of components. The SRUs can be repaired by exchanging the components. The replacement of the components on the SRUs requires an environment where solder activities could take place thus Thales.

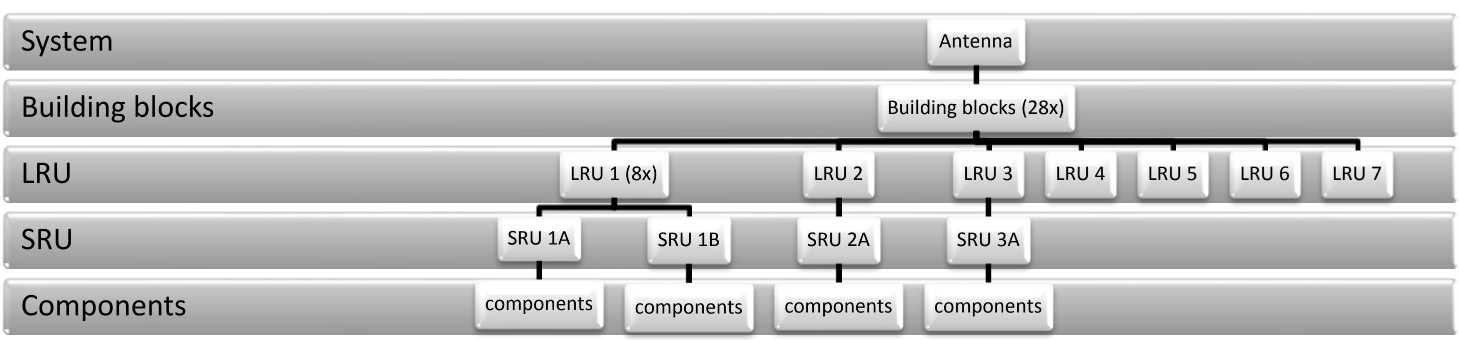


Figure 7: Product scope's breakdown

In the antenna of the Smart-L ELR are transmitters and receivers located. The Smart-L ELR has 28 building blocks which consist of parts who provide a transmit and receive function. The building blocks are 28 times mounted to the antenna and cannot be removed from the antenna. The building blocks consist of seven LRUs which are necessary to create a bundle of the transmit and receive function. See Figure 7 for a complete overview.

All parts are considered critical parts. When one of the parts fails than the higher indenture part (a building block) also fails.

The LRU 1 is placed eight times in one building block. Each LRU 1 is divided into two SRUs namely the SRU 1A and the SRU 1B. The LRU 1 is repairable by replacement of the SRU 1A or the SRU 1B and these SRUs are repairable by replacement of components. The complete breakdown structure of the antenna could be found in appendix A.

2.1.2 Availability

In a PBL contract, the Smart-L ELR has a minimum availability target per ship per calender year.

Operational availability

Currently, the availability is based on annual operational hours. The operational availability could be calculated by the up time divided by the uptime plus the down time. This equals to the Mean Time Between Maintenance (MTBM) divided by the Mean Time Between Maintenance plus Mean Down Time (MDT).

Operational availability $= \dfrac{\text{Uptime}}{\text{Uptime} + \text{Downtime}} * 100\% = \dfrac{\text{MTBM}}{\text{MTBM} + \text{MDT}} * 100\%$

Supply availability

Thales uses the Mean Down Time (MDT) as waiting time for spare parts. The downtime for the system repair by replacing LRUs should take a couple hours and could be neglected on yearly basis. The waiting time of the spare parts is the mearused variable. This kind of availability is defined by Sherbrooke as supply availability. (Sherbrooke, 2004) Whereby the Mean Supply Delay (MSD) is the delay on the spare parts. In this research the term operational availability refers to the supply availability.

Supply availability $= \dfrac{\text{Uptime}}{\text{Uptime} + \text{MSD}} * 100\%$

To achieve the availability obligation, several spare parts have to be stored in a multi-echelon supply chain. Thales receives a yearly fixed fee for maintenance on the sold systems. Depending on the contract Thales could get bonusses or penalties for the availability.

Smart-L ELR antenna availability

This case, the Smart-L ELR has an availability of 90%. This does not imply that the antenna of the smart-L ELR also has an availability of only 90%. In contrary the antenna of the Smart-L ELR has a higher availability necessary to ensure the 90% availability of the Smart-L ELR. In this case we use a Smart-L ELR MTBF of proximately of 450 hours. The availability of the antenna could easily be calculated with formula of the supply availability.

Supply availability Smart-L ELR $= \dfrac{450}{450 + \text{MSD}} = 90\%$

MSD = 50

Supply availability antenna $= \dfrac{700}{700+50} * 100\% = 93.3\%$

The availability of the antenna is approximately 93.3%. When the MTBF of the parts of the antenna is changed the availability of the antenna will also change. The basis is the availability of 93.3%.

Mission availability

The mission availability will be measured by the customer and Thales. Thales uses an internal clock in the systems. The captain of the ship measures for the customer. Every day the captain checks if the system is operational and documents it. The systems should be operational during missions. Therefore this case the system is 90% available during missions. The mission availability will be formulated like the operational availability, but the measurement will take place during missions.

Mission availability $= \dfrac{\text{Missionuptime}}{\text{Missionuptime} + \text{Missiondowntime}} * 100\%$

2.2 Research objective

The objective of this research is to find an optimal spare parts allocation procedure for the antenna of the Smart-L ELR. An optimal spare parts allocation procedure involves minimizing the cost and maximizes the mission availability constraint with a minimum availability target for the Smart-L ELR. Simultaneously it should take into account the mission length, annual operational hours, repair lead-time, of the multi-indenture antenna. In addition Thales prefers an allocation procedure which is "robust". The solutions of the procedure are as little as possible sensitive for variations of the Mean Time Between Failure. Thales prefers solutions which are less sensitive to variations to the Mean Time Between Failure, which may have slightly higher cost.

In order to tackle the problem multiple research question are generated. The research questions serve for a methodical way of answering the main research question. The main research question is:

What is the optimal spare parts allocation procedure of the antenna of the Smart-L ELR to ensure that the minimum mission availability constraint is satisfied, the cost are minimized, considering mission profiles, annual operational hours, and repair lead-time?

The following research questions are formulated as sub questions.

1. *How is the service supply chain of the Smart-L ELR structured? (chapter 3)*
   a. *What is a Performance Based Logistic (PBL) contract?*
   b. *What is the supply chain of the antenna of the Smart-L ELR?*
   c. *How is the repair process organized for the Smart-L ELR?*
2. *How is the literature of METRIC and VARI-METRIC applicable to the case study of the Smart-L ELR antenna? (chapter 4)*
3. *What are the optimal spare parts time parameters with Inventri (VARI-METRIC) and what influence has the repair lead-time on the spare parts inventory cost? (chapter 5)*
4. *How to step-by-step transform the VARI-METRIC (operational availability) solution to a mission availability solution? (chapter 6)*
5. *What is the impact of the allocation procedures in respect to MTBF variations? (chapter 7)*

Answering these sub questions eventually makes it possible to answer the main research question. This answer is stated in the conclusion in chapter 8.

2.3 Research approach

The baseline study for this research has already been carried out during the project MaSeLMa. For this study employees from Thales were interviewed and data files are evaluated. Parts of this baseline study will be used to answer the first research question.

A supply chain overview will be constructed for the first research question. This represents the work processes at Thales. This service supply chain includes the repair lead-time, shipment lead-times between stock locations. A flow diagram will be constructed for an overview.

Currently, Thales produces systems and sells most of their systems based on a traditional contract. This means that the system is sold with a warranty and for every service a new contract must be agreed. Mostly a system is sold with extra services like spare parts provisioning list, maintenance handbooks and training. Thales uses VARI-METRIC model variant of Rustenburg software called Inventri to calculate the spare parts provisioning. To answer the second research question a research of the VARI-METRIC model is required. Some assumptions are made to calculate the spare part stock per echelon in function of the availability of the spare parts against minimal cost. These assumptions, the parameters which the environment provides and the decision variable of this model should be defined. To research this mode the books of Sherbrooke and Rustenburg are used. (Sherbrooke, 2004) (Rustenburg, 2000).

Inventri could maybe be used for a first number of iterations of the initial spare part stock level calculation per echelon.

Thales uses at this moment Inventri to calculate the spare part list for their customers. To calculate their spare parts Thales uses standard repair lead-time and a procurement lead-time for a traditional “On Demand” contract. This is not beneficial for a PBL contract. M.C. van Zwam and T. Groener concluded that shorter repair lead-times create less initial spare parts cost. In addition, M.C. van Zwam concluded that short time parameters will create robustness to annual operational hours (AOH) variations. The failure demand is directly related to the MTBF and AOH. The failure demand is the MTBF divided by the AOH. Therefore it is expected that short time parameters will also create a less sensitivity to MTBF variations.

For research question three, the consequences of modifying these lead-times to the costs are investigated. The goal is to find an optimal steady state solution.

Research question four computes a spare parts allocation procedure. This procedure defines the spare part stock level at each supply chain location. The emphasis in this research question lies on transition from the operational availability of Inventri to the mission availability. The mission availability is calculated in the software Simlox. Simlox is a commercial off-the-shelf simulation software package that can simulate the missions and with this software a mission availability of a ship or multiple ships can be calculated. Simlox gives among others as output the operational availability, the mission availability and the probability of backorders per item per location.

Shipment times, repair lead-time and spare parts inventory influences each other. The question is which procedure Thales should use to have a robust system, that has the least influences towards parts MTBFs. It is unclear if the MTBF are correctly, because they are not tested in practice. If Thales has a robust spare parts allocation procedure then a small variation in the MTBF is allowed. For research question five the robustness of the spare parts inventory towards the shipment times and the repair lead-time are examined.

2.4 Deliverables

This research results in two deliverables for Thales. Firstly, Thales will receive a copy of this master thesis report. In this report Thales will find a foundation for the maintenance procedure and the underlying choices which are made during the research. Secondly, Thales will receive Simlox simulation input files with the optimal configuration based on this research.

2.5 Research outline/plan

In this paragraph, the outline of the master thesis is discussed. The sub research questions divide the report in chapters.

In chapter 3 the baseline of this research will be described (research question 1). Within the baseline the service contract, the supply chain, the repair of the system and LRU are described. In chapter 3 Inventri is introduced to calculate the spare parts allocations. In this research Inventri will be used to calculate the spare parts Inventory over the supply chain.

Inventri is introduced to calculate the spare parts allocations in chapter 3. This research will use Inventri to calculate the spare parts Inventory over the supply chain. Literature research is performed in chapter 4 in order to understand how Inventri calculates the spare parts allocation. Inventri calculates the spare parts allocation following the VARI-METRIC model variant of Rustenburg. Firstly, the model METRIC has to be investigated to understand the VARI-METRIC model. Secondly, the VARI-METRIC model will be discussed. Finally, the depot repair of Inventri is investigated. At the end of this chapter research question two will be answered and will be clear whether Inventri could be used.

In chapter 5 is discussed what the spare part stock level should be for the Smart-L ELR antenna in a steady state model (research question 3). Firstly, to determine what the spare part stock levels should be at Thales a calculation of the repair lead-time versus the investment cost of the lower indenture spare parts (components) is performed and analyzed. Secondly, the inventory of the LRU over the supply chain has to be calculated and investigated. The repair lead-time and the investment of the lower indenture have influence on the investment on LRU spare part stock levels. At the end of this chapter a balanced steady state solution will be provided.

The consequences of the steady state solution for the mission availability are investigated in chapter 6. From one Key Performance Indicator (KPI) of Inventri the transitions must be made to Simlox, which has KPI per system. A procedure is designed, which transforms step-by-step the operational availability solution to a mission availability solution. In this chapter research question 4 is answered and will be clear, how the transition could be made to the mission availability allocation.

The MTBF variation is the most important criterion of this research. In chapter 7 the criteria are defined and evaluated per solution. Then sensitivity of the solution in respect to MTBF variations is discussed. Subsequently, the procedures for the mission availability solutions are compared. The MTBFs will be varied and the spare part stock levels are calculated according to the procedure of research question 4. These results will be analyzed and conclusions of the quality of the procedures could be drawn in this chapter.

3 Service of the antenna

Currently there is a service request shift from the traditional service contract to a Performance Based Logistic (PBL) contract. This means that the responsibility of the maintenance will shift from the customer to Thales. This is a new approach of maintenance for Thales. We will discuss the properties of the PBL contract in paragraph 3.1.

Due to the service responsibility change from the customer to Thales there will be also a change in the service supply chain. We will discuss the differences in paragraph 3.2.

The system repair onboard the ship is conducted by exchanging LRUs. Therefore the ship has a stock of ready-for-use LRUs. An LRU has the soft restriction that it must be exchangeable onboard the ship. For this research the assumption is that only the LRUs could be exchanged onboard the ship. The system repair will be more elaborated in paragraph 3.3.

Within Thales there are multiple repair flows. The LRUs are repaired by exchanging SRUs and the SRUs are repaired by exchanging components. Beside the repair process there is also an incoming flow from the suppliers of new LRU, SRU and components. It dependents on the part whether it is repaired or ordered from the supplier. There is also a possibility that the parts cannot successfully be repaired anymore and a new part should be ordered by the supplier. We will discuss the part repair process in paragraph 3.4.

The key findings of this chapter are given in paragraph 3.5.

3.1 Performance Based Logistic contract

Thales delivers their systems with a service contract. The terms of responsibility per actor are given in the service contract. Currently, Thales has three kinds of fundamental contracts namely, “On Demand” (traditional) contract, Service Level Agreement and Contract for Availability (PBL contract).

Currently, Thales sells mostly “On Demand” contracts which are similar to a traditional service contract. An “On Demand” contract is sold with a warranty and for each additional service a separate contract has to be agreed. This also means that when the system fails and the ship is on a mission the customer is responsible for whether the required spare parts stock is available. With the “On Demand” contract the customer is final responsible for the system and their spare parts availability.

Within the PBL contract an agreed performance level for a fixed price is offered. This service contract is based on the availability of the systems also known as “Contract for Availability”. The customer provides indicator performances and based on these performances Thales provides the spare parts, which should assure the agreed availability of the system. A typical availability of a system like the Smart-L is 90% to 95%. This service contract is in general more efficient and effective for the customer than the “On Demand” and “Service Level Agreement”. The benefits for the customer by choosing for a PBL contact are:

- Continuous investments in an In-Service support organisation are no longer needed;
- A fixed annual In-Service support fee ensures the agreed operational availability by Thales;
- Financial planning by the customer is better feasible as a result of the fixed fee;
- Periodic reports by Thales that show the achieved performance based upon Key Performance Indicators;
- Thales provide continuous monitoring of customer's products, services and processes with a view on improvement;
- Risks will be externalized. Risks relating to system availability are handled by Thales.

In short a PBL contract means that the customer owns the system and Thales performs all the service which the system requires. The services are planned, controlled and executed by Thales.

Thales does not have a lot of experience with PBL contracts. Currently there are only a view contracts sold of this format.

3.2 Service supply chain

Thales advices their customers which spare parts should be procured when they buy an "On Demand" contract. In the context of the service part supply system (Verrijdt, 1997) Thales recommends a flexible option namely the allocation flexibility. Thales uses Inventri which is based on a VARI-METRIC model variant of Rustenburg (2000) to calculate the spare part stock level per spare part stock location (echelon). The calculation is executed by the software Inventri. Inventri is custom made and special developed by the company ORTEC. Thales is the single owner of this software. The relation among the availability, spare parts allocation, repair lead-time and the shipment times of VARI-METRIC are more in depth discussed in chapter 5. Furthermore the VARI-METRIC model will be reviewed in chapter 4. In this paragraph we will discuss the service supply chain of Thales. Firstly, we will discuss the traditional contract service supply chain in section 3.2.1. Secondly we will discuss the PBL contract service supply chain in section 3.2.2. Finally we will discuss the case supply chain in section 3.2.3.

3.2.1 Traditional contract service supply chain

Inventri basically calculates the spare parts allocation under restriction of a minimum availability and/or maximum budget. Inventri allocates every iteration a spare part which gains the highest possible system availability per invested value. The customer requests typically two types of procurement recommendations with a traditional contract.

- First advice of Thales is: the customer has a budget to invest in their spare parts and requests Thales which items should be procured to get the best possible system availability.
- Second advice of Thales is: the customer demands certain system availability and Thales provides a list of spare parts that the customer should procure regardless of a budget.

The typically spare part stock locations for the customer are the ship and on shore. The customer could also request a spare part stock location at Thales, which is also possible and will be met in the terms of the service contract. Figure 8 gives an overview of possible spare part stock locations.

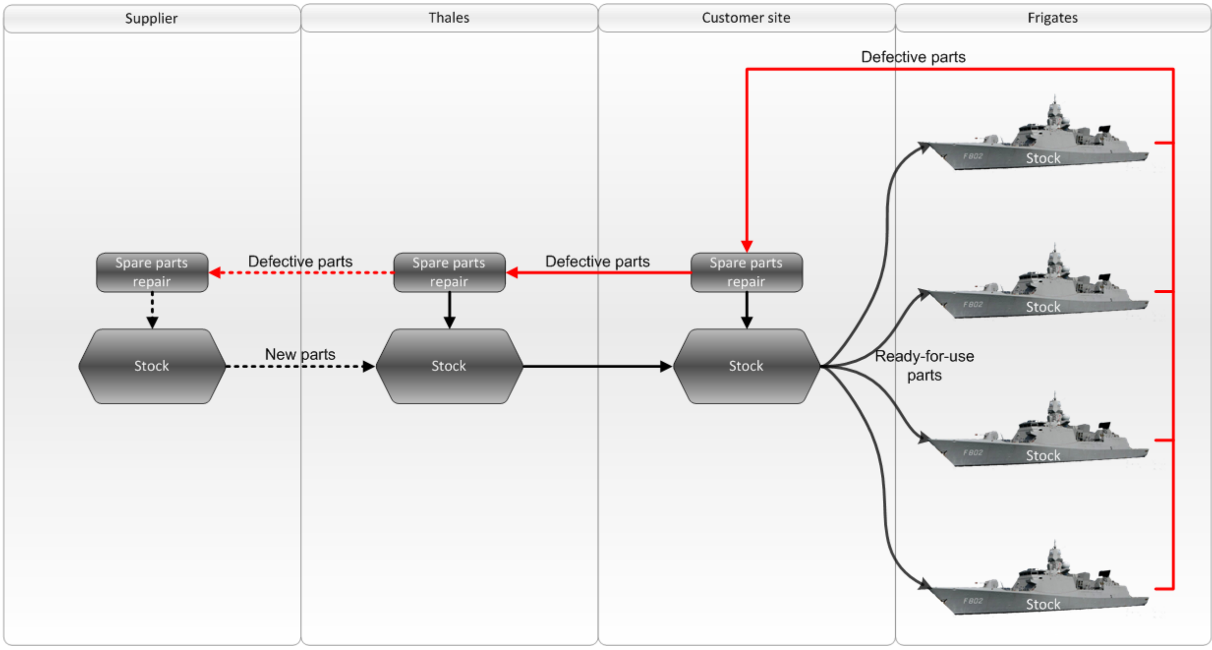


Figure 8: Service supply chain for a traditional service contract

In special cases like the Dutch navy, some repairs could be done at the customer's site as it is displayed in Figure 8. For example, the Dutch navy invested in a lot of repair equipment. If the depot could not repair the spare parts, the repair will be executed a level higher. Commonly the costumer's site does not have a depot to repair the spare parts. Then spare parts repair will also be executed by a higher level, thus Thales.

3.2.2 Performance Based Logistic contract service supply chain

The traditional service contract procedures are described in the previous paragraph. With a PBL contract Thales has full responsibility for maintaining the systems. In addition the spare part repairs will only be executed by Thales. A new supply chain is modelled to give an overview of the supply chain that is used in this research. In Figure 9 is only the LRU part flow indicated. The LRUs are repaired at Thales or a supplier of Thales. There must be a spare part stock of SRUs and components at Thales to ensure short repair lead-time of the LRU.

Figure 9 provides an overview of the part flow and which spare parts could be stocked at a location. The SRUs and components could only be stocked at Thales. The LRUs could be stocked onboard the ship, at the customer site or at Thales. When the failed part is not repairable then Thales orders a new part at the supplier.

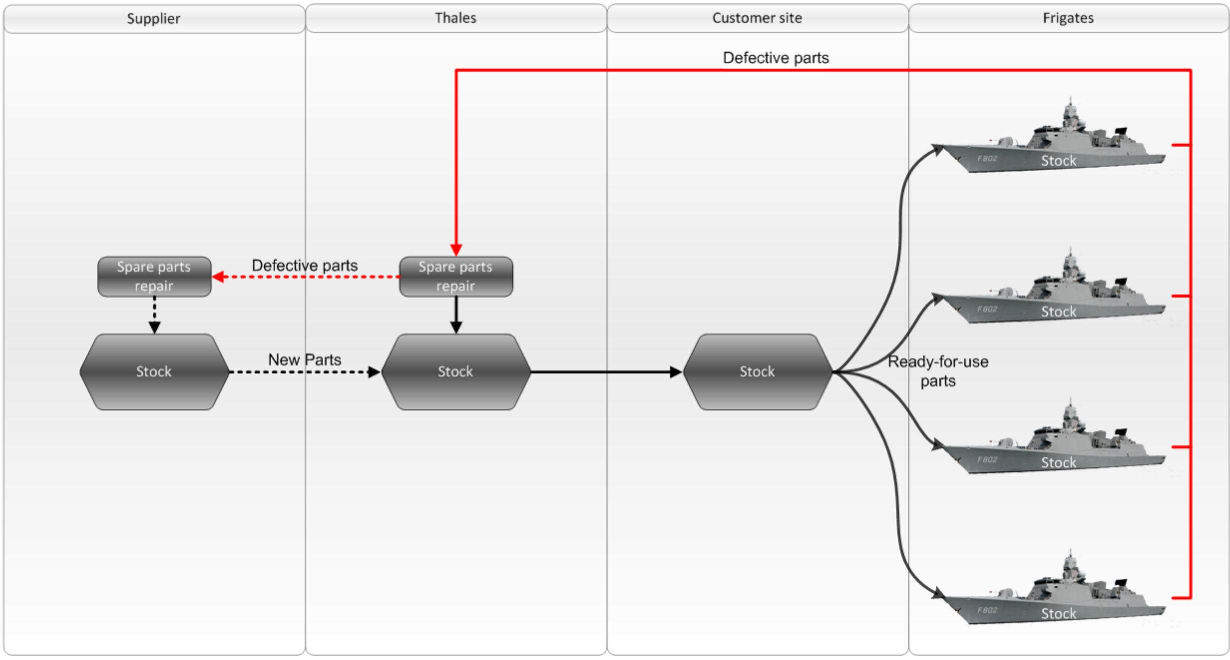


Figure 9: Service supply chain in terms performance based logistic contract

Within a service supply chain there are multiple environment parameters and decision variables. The environment parameters are dependent on the customer and system. The Dutch navy has different environment parameters compared with for example Brazil and each system has parts with their own specifications. The decision variables are the variables which Thales could influence to improve the availability and reduce the costs. The following environment parameters will be used in this research:

Input parameters:

- Annual Operating Hours
- Echelon structure
- Mission profiles
- Part MTBF
- Shipment times (replenishment time)

Annual Operating Hours

The systems are in general bought with the ship's purpose. The Smart-L is bought for long missions. This means that the annual operating hours for the Smart-L is typically large. The annual operating hours are per fleet of systems.

Echelon structure

The echelon structure is also dependent on the customer. One customer has one harbor and five ships, while another customer could have two harbors and six ships.

Mission profiles

For the customer it is important that the system is functioning during the missions. The length of these missions varies over time. Short missions will take about 3 to 7 days and long missions will take 3 to 7 months. The sum of the mission length may not exceed the total annual operating hours. These mission profiles are dependent of the ship type. These types will be discussed in section 3.2.3.

Part MTBF

Each system contains out of parts and each part has Mean Time Between Failure (MTBF). A MTBF is a typically failure rate for parts. The failure rate could be calculated with MTBF formula:

$$\text{Failure rate } \lambda = \frac{1}{\text{MTBF}}$$

MTBF is calculated by the reliability engineers to predict failure from the system. The MTBF is the amount of operational hours between two failures.

$$\text{MTBF} = \frac{\text{Total operating hours}}{\text{Total number of failures}}$$

Shipment times (replenishment time)

The shipment of parts from Thales to the customer's site and from the customer's site to the ship is called: Shipment time **from** mother station. The shipment from the ship to the customer's site and from the customer's site to Thales is called: Shipment time **to** mother station. This way the variable could be used in multiple levels in the supply chain. Simlox uses the same terms. It is advisable to create many variables, because each software will use the data in a different way. For example Inventri uses only the shipment time from mother station and the shipment time to the mother station is part of the repair lead-time.

The following decision variables are used to influence the supply chain to optimize the availability and minimize the cost:

- Spare parts allocation per echelon level
- Repair lead-time

Spare parts allocation per echelon level

The spare parts could be stored at different levels, namely Thales, at the customer's site or onboard the ship. The position of the spare parts is a tactical decision. It could be possible that it is cheaper to store one LRU at the customer's site instead of storing an LRU on each ship. Unfortunately some parts need to be stored onboard the ship, because they have a high failure rate.

Repair lead-time

Failed parts are sent to Thales. The repair lead-time of Thales could influence the LRU spare parts inventory. The repair lead-time is dependent on the spare parts of the lower indenture parts like the SRUs and the components. The inventory levels of the lower indenture are important for the repair lead-time. More about this topic in paragraph 3.4.

3.2.3 Case study service supply chain

We will discuss the case study supply chain in this section. All the input parameters, which are known, will be discussed. This case study will have three ships, whereby two ships are mission ships, one ship is a short-mission ship.

Annual Operating Hours

The ships will have X annual operational hours together. The mission ship will go on large missions. Large missions have mission duration from three to seven months. We will use proportions to provide the division between the mission ships and the short-mission ships. In this case study the mission ships will have the proportion 9/20X hours operational for long missions and the short-mission ships will have the proportion 1/10X hours operational divided over multiple small missions. Small mission has mission duration from three to seven days.

Mission profiles

The missions are typical per ship per year. Therefore a classification of ship types could be made. This research has two types of ships, a mission ship and a short-mission ship. A mission ship goes on mission for several months and the short-mission ships will be close to the harbour for practices and tests. The short-mission ships will perform multiple short missions per year for several days. In Table 4 a short overview is presented.

Table 4: Specifications of the ship type

Mission ship type	Length mission
Mission ship	3 to 7 months
Short-mission ship	3 to 7 days

Naturally, the ships will annually cycle on mission ship type. Simlox will require mission profiles. The profiles will be programmed as Table 5. Simlox is modelled with one year warm-up period. This year will be deleted. For this reason there is a year zero in Table 5. Thus there will be an average over five years.

Table 5: Operational hours per year, per ship

Year	Operational hours per ship	Description mission
0	Ship: 9/20X hours Ship: 9/20X hours Ship: 1/10X hours	mission ship mission ship short-mission ship
1	Ship: 9/20X hours Ship: 9/20X hours Ship: 1/10X hours	mission ship mission ship short-mission ship
2	Ship: 9/20X hours Ship: 9/20X hours Ship: 1/10X hours	mission ship mission ship short-mission ship
3	Ship: 9/20X hours Ship: 9/20X hours Ship: 1/10X hours	mission ship mission ship short-mission ship
4	Ship: 9/20X hours Ship: 9/20X hours Ship: 1/10X hours	mission ship mission ship short-mission ship
5	Ship: 9/20X hours Ship: 9/20X hours Ship: 1/10X hours	mission ship mission ship short-mission ship

Resupply cycle

The ships are on mission for months, but there could be a monthly or every other month resupply. These resupply options are possible for Thales. The parts have an average waiting time of 15 days for a monthly resupply. The parts have an average waiting time of 30 days for an every other month resupply. The spare parts will be stored as much as at the customer's site instead of Thales. Thales could use the seven workdays of the customer. Thales gets eventually the call if the part should be replenished. The shipment times from the customer's site to the mission ship will be summed with additional five days, because this will include administrational delay. The delay is determined in Table 6.

Table 6: Determination of the additional five days

Spare parts shipment decision time	Time
Captain will contact shore for a spare parts	One day
The shore will contact Thales	One day
Thales finds the responsible employee who decides the spare parts are replenishment	One day
Thales gives green light to shore for spare parts replenishment	One day
Shore includes the spare parts to the replenishment cycle	One day
Total	**Five days**

Forward shipment time will be 20 days for the mission ships and three days for the short-mission ships. Figure 10 shows a total overview.

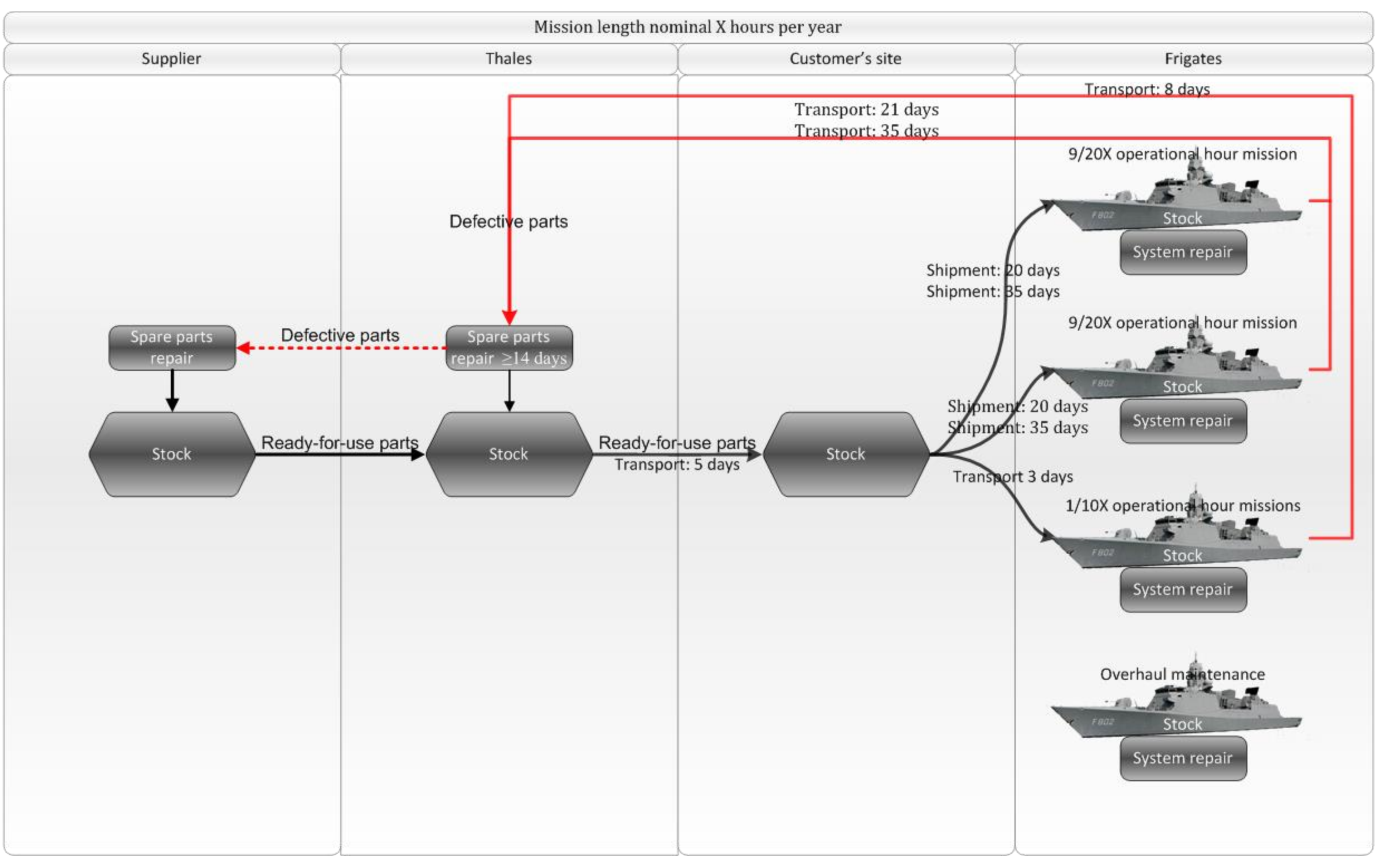


Figure 10: Case service supply chain in terms performance based logistic contract

Return shipment time

The return shipment times from the mission ships to Thales will take about the same time as the forward shipment time. This means that the 5 days from shore to Thales plus the 15 or 30 days from the mission ships to shore. This will be 21 days (three calendar weeks) or 35 days (five calendar weeks). The shipment time is modified to 21 days due to calendar weeks notation. For the small mission ships it will be five days from shore to Thales plus the three days from small mission ship to shore. In total eight days for the return shipment.

The shipment times will vary between ships and shore stock locations. Shipment time from Thales to the customer’s site will be the same for all the ships. In this research the shipment between Thales and the customer’s site will be five days.

The repair lead-time at Thales will be defined in chapter 5.

3.3 Repair of the Smart-L ELR

Thales created the original maintenance concept for the Smart-L ELR. Within this research several principles will be used. The Smart-L ELR is a redesign on the Smart-L. Hereby it is well known that a ship could be on mission for large part of the year. A failure during a mission when there is no spare part stock will have consequences in terms of availability. Penalties are imposed when the system availability will descend below the agreed level of the contract. To prevent penalties the Smart-L ELR is built in such a way that the downtime is minimized. This is achieved by decomposing the functionality into parallel units, and decomposing the system into as much as possible LRUs. In this chapter the useful part of the current maintenance concept is described.

The Smart-L ELR is decomposed into as much as possible LRUs. The decomposition enables quick repairs onboard the ship if spare parts are available. Exchanging LRUs could be performed during missions and takes a few hours. LRU exchange must be possible to achieve the agreed availability target.

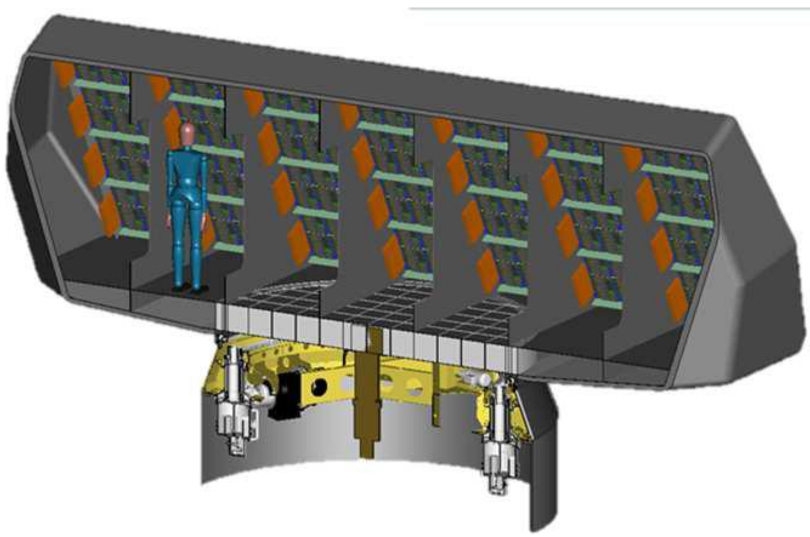


Figure 11: The accessibility of Smart-L ELR above deck

The maintainer onboard the ship could enter the smart-L ELR by a hatch when the system is shutdown. The LRUs are exchangeable from inside the antenna (Figure 11). The maintainer knows which LRU has failed by the Built In Test (BIT), which is implemented into the software of the radar. In Figure 11 a maintainer is displayed to give an overview of how the LRUs are accessible. To exchange LRUs there has to be a spare part stock onboard the ship. The spare part stock level could be calculated by Inventri. This is calculated by systems operational hour per year and the replenishment time of the ships stock, but cannot consider mission profiles. The software Simlox is used to calculate the mission profiles of the ships. To manage the spare part stock onboard the ship the following requirements are necessary.

Spare part stock on shore

The spare parts onboard the ship will run out over time. When the ship is on mission and LRUs fail, these will be exchanged by the spare parts. The failed LRUs should be replenished by ready-for-use spare parts. Therefore a shore stock is necessary to ensure short replenishment lead-time of the ship. Especially after long missions the ship has a relatively large stock of failed LRUs that should be replenished by the shore stock.

Replenishment procedure for the failed LRUs

When the failed LRUs are on shore, then these LRUs should also be replenished by ready-for-use LRUs. This could be accomplished by repair or replacement by new ones. This is dependent on the repair abilities of the LRUs. When it is cheaper to buy a new LRU the failed LRU will be replaced by a new LRU. Otherwise the LRU should be repaired by Thales.

Monitoring of the stock levels and location of spare parts

Monitoring of the stock levels and location of the spare parts are necessary. This is executed by a Computerized Maintenance Management System (CMMS). It tracks and traces the position and levels of the spare parts to ensure the stock levels are sufficient.

A maintainer as part of the ship's crew is needed for these exchanges. This maintainer needs to be trained and certified by Thales to a basic maintenance skill level. When an LRU fails the maintainer should be able to exchange the LRU with manuals which serve as a guide for the maintenance procedure.

3.4 Spare parts repair

Thales repairs the LRUs. Due to few acquisitions per year and few commonalities among systems of the parts, the repairs are performed in a one-for-one process. Thales repairs parts by repair & return or replacement & repair. Most parts (>90%) are processed by the repair & return procedure. Due to the amount of sold "On Demand" contracts it was no debatable to change the repair process into a replacement & repair process.

- Repair & return (>=90%)

  The failed part is sent to Thales. Thales repairs the failed part and afterwards the repaired part is returned to customer.

- Replacement & repair (<10%)

  The customer contacts Thales when the part failed. Thales sends immediately a functional part. The customer replaces the part and sends the failed part to Thales, who repairs the part and stores the repaired part.

Both repair processes have their pros and cons. A quick overview is give of the differences in Table 7.

Table 7: Pros & cons between the repair processes

Process	Repair lead-time	Inventory cost
Repair & return	Long	Low
Replacement & repair	Short	High

The goal of this research is to minimize the initial spare parts inventory costs. Therefore, it is important to research this repair process in more detail. We will solely discuss the repair & return process.

Repair & return process (Zwam, 2010)

In this section we will elaborate the repair & return process, because this is the general repair procedure of Thales. Reducing the repair lead-time could benefit the spare parts provision cost.

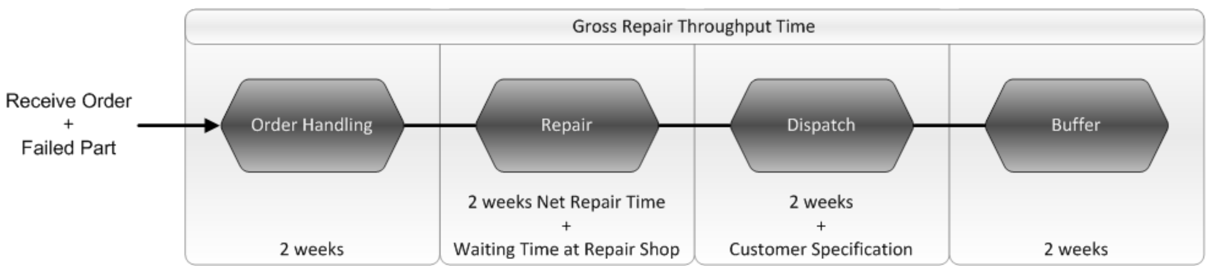


Figure 12: Repair Throughput Time (Donderwinkel, 2005)

The repair process of Thales consist of four phases: Quotation phase, order-handling phase, repair phase and the dispatch phase. Only the repair phase will be used, because only this phase is applicable for a PBL contract, which is the subject of this research. This means that there will be no negotiations for the repair quotation. This quotation phase is meant for other service contracts like the "On Demand" contract. The assumption in this research is that the parts with PBL contract gets the highest priority and therefore the Order handling phase and Dispatch phase could be set to zero weeks. The different phases will be described shortly.

Order-handling

The order-handling phase will start with the incoming failed part. In this phase the part will be examined and the defects will be reported. The part will be examined visually to check part's conditions when enters the repair process. The examination will be reported into the system. The order-handling phase will take 14 days.

Standard repair

The repair phase consists of the standard repair. The net repair lead-time within Thales is two weeks. Besides the two weeks standard repair, it consists of waiting time for the lower indenture spare parts to repair the LRU or SRU. In the "On Demand" contract the customer procures the LRU spare parts. Then the LRU repair was the responsibility of the customer. With the PBL contract the responsibility shifts to Thales and the repair lead-time is important for Thales. The repair phase consists of the net repair lead-time of two weeks and the waiting time of the lower indenture parts.

To minimize the repair lead-time Thales have to stock lower indenture parts. How many parts and what costs are engaged will be determined in chapter 5.

Dispatch

The dispatch phase is the end of the repair process within Thales. The repaired parts are accepted, approved and packed by the Material Handling department. They perform some administrational tasks until the part is actually sent the material department. This is the bottleneck within the dispatch stage. Some delay is caused due that customers demand that all the repairs are sent in one batch. This is cheaper than one-for-one shipment. Furthermore the shipment dependents on the shipment licence which is sent by the customer. The receipt could take some days to a week. In total, the dispatch phase will take at least two weeks.

Buffer

Thales suffers from all the variations in the repair phases. In addition, the shipment between departments will take some time. To ensure on time delivery Thales uses two weeks as a buffer period.

The typical net repair lead-time of each LRU is eight weeks. Including the waiting times of the lower indenture spare parts and customer specific time, the gross repair lead-time is at least eight weeks.

In order to guarantee the contractual repair lead-time of eight weeks, it is important to stock lower indenture spare parts. This rapidly benefits the total initial spare parts costs. Fast repair lead-time could create lower LRU stock. The cost reduction is calculated in chapter 5.

3.5 Conclusion

In this chapter, the PBL contract is discussed. With such a contract Thales is responsible for the performance of the system

The availability of the system is determined by the annual operational time. The availability depends also on the type of mission. Thales defines two mission types, namely short and long missions. Long missions could take three to seven months and short missions could take three to seven days. These types are typically per ship per year. Therefore a mission ship and a short-mission ship are introduced. The mission ship will perform long missions and the short-mission ships will perform multiple short missions per year.

The LRU spare parts will be stored either at customer’s site and/or onboard the ship. The system is designed to repair the system in a couple of hours. For this repair spare parts have to be available.

The LRUs are stored onboard the ship or at the customer’s site. The stock levels have to be determined for the customer’s site and onboard the ships. When the LRU fails it will be sent to Thales for repair. This repair will be conducted by ordering a new one if it is a vendor part, otherwise it will repaired by exchanging SRUs or components. Thales has a minimal repair lead-time of 14 days. Most of the repair are performed following the repair and return process. To minimize the total cost it is important to research the stock level of the components versus the SRUs. This will be studied in chapter 5.

4 Literature

The literature which Thales uses to calculate the spare parts lists is discussed in this chapter. Thales uses the software tool Inventri to calculate in the spare parts allocation to a target availability or budget. This calculation is based on the VARI-METRIC model (Sherbrooke, 2004). VARI-METRIC is an extension of the METRIC model (Sherbrooke, 1968). For this literature review we will only refer to (Sherbrooke, 2004) and (Rustenburg, 2000), because this literature is comprehensive. Therefore a review will conducted of METRIC in paragraph 4.1. In addition, METRIC uses an allocation procedure which could be used for the transition of the operational availability to mission availability.

After METRIC is reviewed we will continue by reviewing the VARI-METRIC model in paragraph 4.2. The greatest difference between METRIC and VARI-METRIC is that the number of items in the pipeline distribution is calculated. This will be done by a variance-to-mean ratio, hence VARI-METRIC.

In paragraph 4.3 we discuss the depot repair model. Depot repair calculates the amount of inventory of components per LRU for a depot in respect to delivery reliability. This review is conducted, because this model will be used to find an optimal steady-state scenario.

Finally, the key findings of this chapter are given in paragraph 4.4.

4.1 Multi-Echelon Technique for Recoverable Inventory Control (METRIC)

Sherbrooke developed the METRIC approach (Sherbrooke, 1968) to calculate the inventory level of the spare parts to ensure a system availability. He used for his calculation the system availabilty and the cost for his decision. The output of METRIC is an availability-cost curve. This curve is an effecient frontier.

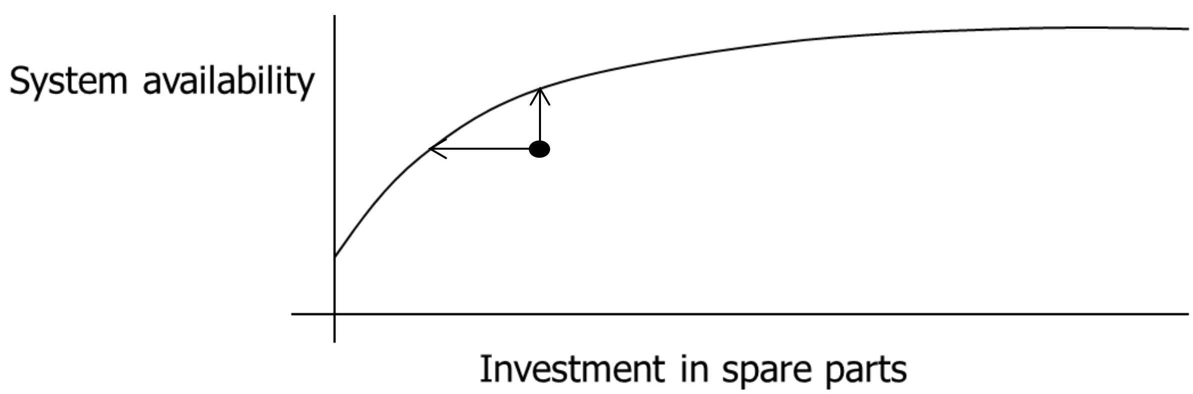


Figure 13: Cost-Availability curve efficient frontier

For example, a solution like the point in Figure 13 can be improved. With the same investment there is a higher availability possible (arrow pointing up). When the request is the availability then the costs could be reduced (arrow pointing left). The points above the convex curve are unfeasible. Some parameters influence the initial spare parts costs and availability. This research will investigate the transition from operational availability (Inventri) to mission availability (Simlox). Therefore it is necessary to know how the availability is calculated and what decisions are made to allocate spare parts. METRIC uses several of assumptions. These assumptions will be discussed in section 4.1.1.

Secondly, the operational availability will be discussed in section 4.1.2 and finally the spare parts allocation will be discussed in section 4.1.3.

4.1.1 Assumptions

The METRIC theory needs some assumptions to calculate the spare part inventory level in the supply chain. The following assumptions are made:

Assumption 1: Demands occur according to a Poisson process

One of the properties of the Poisson failure process is that the variance-to-mean ratio is one. This also means that the demand is independent of the previous failure. The Poisson demand process is without memory. This means the parts of the antenna could fail even when the antenna is down.

Assumption 2: No lateral supply

Bases could not supply each other within METRIC. The bases have to be supplied by the higher echelon base. Bases which could supply each other have a pooling flexibility following (Verrijdt, 1997).

Assumption 3: No condemnation

METRIC does not account condemnation. Instead a repair success rate is introduced whereby a fixed amount of parts should be procured.

Assumption 4: Independent repair lead-times

Every part has its own independent repair lead-time. The parts are taken into repair directly. This means the repair capacity is also infinite. The repair shop is modelled as an M/G/∞ queue and is based on theory provided by Palm. (Palm, 1938)

Assumption 5: (S-1, S)-policy on every echelon

METRIC uses a (S-1, S)-policy. This is the most optimal policy systems with parts which are high-cost and have a low demand repairs.

Assumption 6: Backorders for different items are equally important

METRIC does not uses priority rules within repair lead-times and backorders of parts. All parts are equally important.

Assumption 7: Order and ship times are deterministic variables

The order and ship times are deterministic variables: “Often, the order and ship times are relatively small compared to the total repair lead-times.” (Rustenburg, 2000, p. 25)

Assumption 8: “Infinite source”

The amount of backorders influences the demand rate. When the amount back orders increases then the amount of parts that may fail decreases. The demand rate will slow down, but will never be zero. (Rustenburg, 2000)

4.1.2 Operational availability

The system is operationally unavailable when the system is repaired by a maintenance activity. This activity could be a preventive or a corrective maintenance activity. Operational unavailability can be caused by the delay of supply. A delay of spare parts therefore results in system downtime. The operational availability is the Mean Time Between Maintenance (MTBM) divided by the Mean Time Between Maintenance plus the Mean Time To Repair (MTTR). The overall formula is:

$$\text{Operational Availability} = \frac{MTBM}{MTBM + MTTR} * 100$$

The operational availability could be divided in two kinds of availabilities namely: Maintenance availability and supply availability.

Maintenance availability

The system is unavailable during a maintenance activity. The maintenance availability depends on the MTBF of the system and does not include the stock levels thus stock policy.

Supply availability

The supply availability does not consider the maintenance unavailability. This availability assumes that the largest unavailability is the delay on spare parts and thus the stock policy. The maintenance unavailability should take few hours whereas the supply unavailability could take days or weeks. Thales only uses the supply availability, because the impact maintenance unavailability is minimal. The variables for the supply availability are explained briefly in Table 8.

Table 8: Explanation of variables for the supply availability

Variable	*Meaning variable*
i*=1,…,*I	Number of LRU
j*=1,…,*J	Number of ships
***EBO*$_{ij}$(*s*$_{ij}$)**	Expected backorders for LRU *i* at ship *j* if the stock level equals s for LRU *i* at ship *j*
***Z*$_i$**	Number of LRUs of type *i* in a single radar
***N*$_j$**	Number of radar systems at ship *j*

The supply availability of the ship is:

$$\text{Ship's supply availability} = \prod_{i=1}^{I} \left[1 - \frac{EBO_{ij}(s_{ij})}{N_j Z_i} \right]^{Z_i}$$

Commonly, the systems are sold in small series e.g. three ships. The supply availability over all the ships is the average of the ship's supply availability. The overall supply availability will be:

$$\text{Supply availability} = \frac{\sum_{j=1}^{J} \prod_{i=1}^{I} \left[1 - \frac{EBO_{ij}(s_{ij})}{N_j Z_i} \right]^{Z_i} * N_J}{\sum_{j=1}^{J} N_j}$$

The objective of METRIC is to maximize the availability and minimize the total spare parts costs. Maximizing the supply availability is approximately equivalent to minimizing the expected backorders.

4.1.3 Spare parts allocation

The allocation procedure of METRIC uses the invested euro and the network availability. The objective is to maximize the supply availability given the limited budget C. The non-linear programming problem variables are briefly explained in Table 9.

Table 9: Explanation of variable for the non-linear programming problem Sherbrooke

Variable	*Meaning variable*
i*=1,…,*I	Number of LRU
A(s)	Supply availability with stock s
c_i	Cost of LRU *i*
s_i	Stock level of LRU *i*
C	Initial Budget

The difference between the non-linear programming problems is that Sherbrooke works with expected backorders and Rustenburg uses the probability of a backorder. In a non-linear programming problem it is formulated like:

Table 10: Comparison of non-linear programming problem between Sherbrooke and Rustenburg

(Sherbrooke, 2004)	(Rustenburg, 2000)
$\underset{s_i, i=1..I}{Min} \sum_{i=1}^{I} EBO_i(s_i)$	Min $\sum_{i=1}^{I} PBO_i(s_i)$
Subjected to:	**Subjected to:**
$\sum_{i=1}^{I} c_i s_i \leq C$	$\sum_{i=1}^{I} c_i s_i \leq C$
$s_i \in N_0$ for all $i = 1,..., I$	$s_i \in N_0$ for all $i = 1,..., I$
Where $N_0 = \{0, 1, 2, ...\}$	Where $N_0 = \{0, 1, 2, ...\}$

The pipeline must be calculated before the EBO or the PBO can be calculated. The pipeline is the number of items in repair or being resupplied from a higher echelon. To calculate the stock(*s*) with a (*s*-1, *s*) is holds that Stock (*s*) = On Hand (*OH*) + Due In (*DI*) – Backorders (*BO*), where either the *OH* or *BO* is zero. The pipeline could be seen as the Due In and following the Palm's Theorem it holds that the Due In or pipeline could be formulated as:

$$\Pr\{n \text{ items of type} i \text{ in repair}\} = \frac{(m_i T_i)^n e^{-m_i T_i}}{n!}$$ *Pipeline or Due in*

The EBO and the PBO could be calculated with the pipeline as derived in Table 12. The variables for these formulas are briefly explained in Table 11.

Table 11: Explanation of variable for difference between EBO and PBO

Variable	*Meaning variable*
i=1,…,I	Number of LRU
J=1,…,J	Number of ships
EBO$_i$(s$_j$)	Expected backorders for LRU *i* if the stock level equals s_i
PBO$_i$(s$_i$)	Probability of backorders of LRU *i* if the stock level equals s_i
s$_i$	Stock of LRU *i*
m$_i$	Failure demand of LRU *i*
T$_i$	Repair lead-time of LRU *i*

Table 12: The difference between EBO and PBO

(Sherbrooke, 2004)	(Rustenburg, 2000)
$EBO_i(s_i) = 1 * \Pr\{DI_i = s_i + 1\} +$ $2 * \Pr\{DI_i = s_i + 2\} + 3 * \Pr\{DI_i = s_i + 3\} \ldots$	$PBO_i(s_i) = P(BO_i > 0)$ $PBO_i(s_i) = P(BO_i > s_i)$
$EBO_i(s_i) = \sum_{x=S_i+1}^{\infty} (n - s_i) * \Pr(DI_i = n)$	$PBO_i(s_i) = \sum_{x=s_i+1}^{\infty} P(DI_i = x)$
$EBO_i(s_i) = \sum_{x=S_i+1}^{\infty} (n - s_i) * \frac{(m_i T_i)^n}{n!} * e^{-m_i T_i}$	$PBO_i(s_i) = 1 - \sum_{x=0}^{s_i} P(DI_i = x)$
$EBO_i(s_i) = m_i T_i \sum_{n=s_i}^{\infty} \frac{(m_i T_i)^n}{n!} * e^{-m_i T_i} - s_i \sum_{n=s_i+1}^{\infty} \frac{(m_i T_i)^n}{n!} * e^{-m_i T_i}$	$PBO_i(s_i) = 1 - \sum_{x=0}^{s_i} \frac{(m_i T_i)^x}{x!} * e^{-m_i T_i}$

Following the discussion in section 4.1.2 maximizing the availability is approximately equivalent to minimizing the EBO. Inventri is based on Rustenburg's equation, (Rustenburg, 2000) and has a small difference in calculating the item availability.

Table 13: Item availability comparison between Sherbrooke and Rustenburg

(Sherbrooke, 2004)	(Rustenburg, 2000)
$\text{Item availability} = \left[1 - \frac{EBO_i(s_i)}{NZ_i}\right]^{Z_i}$	$\text{Item availability} = \left[1 - PBO_i(s_i)\right]$

The allocation procedures of Sherbrooke and Rustenburg have their similarities, but, as discussed before, Rustenburg uses the probability of a backorder instead the expected back order like Sherbrooke. They both invest in the part which gives the largest availability for per invested euro. An investigation to the single-site one indenture is conducted to compare the procedures. Sherbrooke starts his procedure with setting all the location with a stock level of zero. Subsequently, the procedure checks whether with which item at which location has the maximal expected backorder reduction per invested euro. Then he selects the maximal delta and adds the part to the spare part stock. In the last step Sherbrook checks if the total spare part investment is exceeding the budget. If not, starts with selecting a new spare part otherwise stop the procedure.

Rustenburg uses more or less the same procedure. The difference is that Rustenburg does not use absolute zero spare parts as a starting point. Rustenburg starts with two formulas whereby in all cases the cost-availability curves are convex or almost convex. "For a realistic case, the available budget must be significantly larger than this initial value." (Rustenburg, 2000, p. 64) In step two the same procedure is calculated as Sherbrooke suggested, however Rustenburg uses the probability of the backorder. The base delta is separately calculated from the ship delta, however in step three the maximal delta is chosen. The spare part is added to the spare parts list until the available budget is reached after which the procedure stops. Step three and step four are more or less the same as Sherbrooke. Both the procedures are described in Table 14. In Table 15 the variables are explained briefly.

Table 14: Allocation procedure comparison between Sherbrooke and Rustenburg

Step	Marginal Approach for the model M(1,1) (Sherbrooke, 2004)	Allocation process for the model M(1,1) (Rustenburg, 2000)
1	Set $s_i = 0$ for all *i*	Set $s_i := \max\{\lceil m_i \mathrm{E}T_i - 2 \rceil, 0\}$ for all *i* $\hat{C} = \sum_{i=1}^{I} c_i s_i$
2	Calculate the marginal expected backorder reduction per invested euro for each item: $\Delta_i := \frac{EBO_i(s_i) - EBO_i(s_i+1)}{c_i}$ for all *i*	Calculate the probability of a backorder reduction per invested euro for each item: $\Delta_i := \frac{PBO_i(s_i) - PBO_i(s_i+1)}{c_i}$ for all *i*
3	Select the item *i** for which Δ_i is maximal	$k := \arg\max\{\Delta_i \mid i = 1,\ldots, I\}$
4	If $c_{i*} + \sum_{i=1}^{I} c_i s_i \le C$ Then $c_{i*} := c_{i*} + c_i$ $s_{i*} := s_{i*} + 1$ Goto step 2 Else stop	If $\hat{C} + c_k \le C$ Then $\hat{C} := \hat{C} + c_k$ $s_k := s_k + 1$ Goto step 2 Else stop

Table 15: Explanation of variables for the allocation procedures

Variable	*Meaning variable*
i=1,…,I	Number of LRU
s_i	Stock level of LRU i
m_i	Demand of LRU i
T_i	Repair lead-time of LRU i
C	Initial available budget
c_i	Cost of LRU i
$EBO_i(s_i)$	Expected backorders for LRU i if the stock level equals s
$PBO_i(s_i)$	Probability of a backorder for LRU i if the stock level equals s of LRU i

The marginal approach of the single-site model of Sherbrooke is optimal. (Sherbrooke, 2004) For general multi-echelon, multi-item and multi-indenture it is reasonably good and simple heuristic approach. Rustenburg claims that: All vectors $S=S_1,..,S_I$ that satisfy the condition $\frac{\Delta \mathrm{E}[BO_i(s_i)]}{c_i} \leq \lambda \leq \frac{\Delta \mathrm{E}[BO_i(s_i+1)]}{c_i}$ constitute the so-called 'efficient frontier'. When the items are on the 'efficient frontier' then the solution is optimal. The multi-echelon, multi-indenture of Rustenburg could generate convex solutions, because of the initial stock level in the beginning of the allocation procedure.

4.2 VARI-METRIC

Like it is stated in assumption 6 in section 4.1.1, the METRIC method minimizes the expected backorders, because the assumption is that item importance among items is equally. In practice there is a structure of items. This structure is recognized by Muckstadt. (Muckstadt, 1973) Muckstadt solely uses the end-items in a multi-echelon supply chain. This method is called MOD-METRIC.

Sherbrooke responses that the MOD-METRIC is underestimating the total backorders. Muckstadt used a Poisson distribution to calculate the number of items in the pipeline. This is true for the number of items in the de depot pipeline. The pipelines of the bases however could have a different distribution. Sherbrooke showed in (Sherbrooke, 2004) that the pipelines of the depot are indeed Poisson distributed, but the base pipeline is not always Poisson distributed. The distribution of the base pipeline is depending on the backorders of the depot. When the Variance-to-mean ration is exactly one then the pipeline is Poisson distributed, but most of the times the variance-to-mean is larger than one. Therefore Sherbrooke responded with VARI-METRIC. This method checks what kind of distribution the pipeline needs to calculate the backorders. The following distributions are used in Inventri for the pipelines. Whereby the E[X] is the mean of random variable X and V_x is the variance-to-mean.

Table 16: Four types of distributions related to V_x and E[X] (Rustenburg, 2000, p. 58)

Combinations of E[X] and V_x	Type of distribution
$1 - E[X] \leq V_x < 1$	Mixture of two binominal distribution
$V_x = 1$	Poisson distribution
$1 < V_x \leq 1 + E[X]$	Negative binominal distribution
$V_x > 1 + E[X]$	Mixture of two geometric distributions

The VARI-METRIC model uses the multi-echelon and multi-indenture structure. A review is made of a single-site, multi-indenture model to keep the theory understandable. Most of the derivations can be found in appendix C, the complete derivations can be found (Rustenburg, 2000) and (Sherbrooke, 2004).

Single-site, multi-indenture model

When an LRU fails then this is caused by an SRU *i* with a probability q_i. The LRU could only be defect by one of the SRUs so the sum of all the probabilities q_i must be equal to one. An LRU could be in three states, namely: Operational, in repair or on stock. Figure 14 shows the steady state model. The assumption in this model is that the repair success rate is 100%.

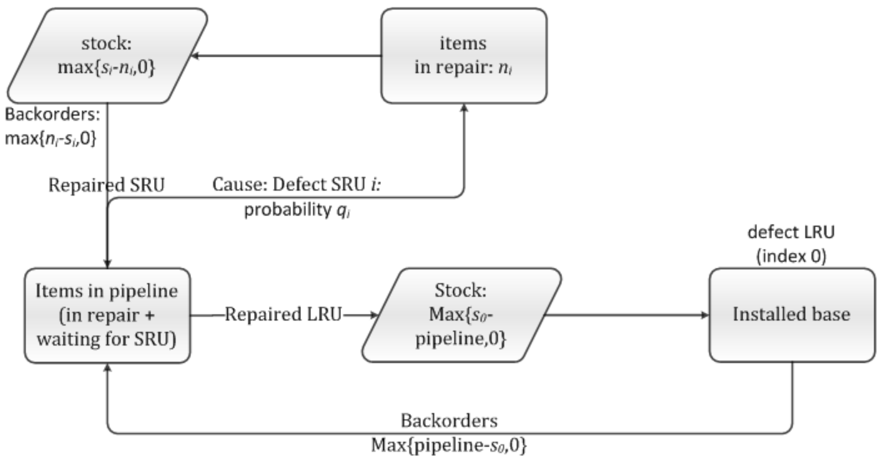


Figure 14: Steady state single-site, multi-indenture model

The single LRU demand is the sum of the demand of the SRUs. The expected pipeline of the LRU is the demand of the LRU multiplied by the repair lead-time of the LRU plus the summation of the expected backorders of the SRUs. This is also true for the variance of the LRU's pipeline, but the summation is over the variance in backorders of the SRUs. The formulas are as followed:

$$E[X_0] = m_0 T_0 + \sum_{i=1}^{I} EBO(s_i)$$

$$Var[X_0] = m_0 T_0 + \sum_{i=1}^{I} VBO(s_i)$$

Multi-echelon, multi-indenture model

Sherbrooke uses multiple demand calculations for the multi-echelon, multi-indenture model. Each demand calculation depends on the location and the indenture. Sherbrooke also takes into account that the base could repair the system, otherwise the depot repairs the LRUs. The probability whether the base could repair the LRU is r_{ij}. Figure 15 shows how the formula is adjusted to fit each location and indenture.

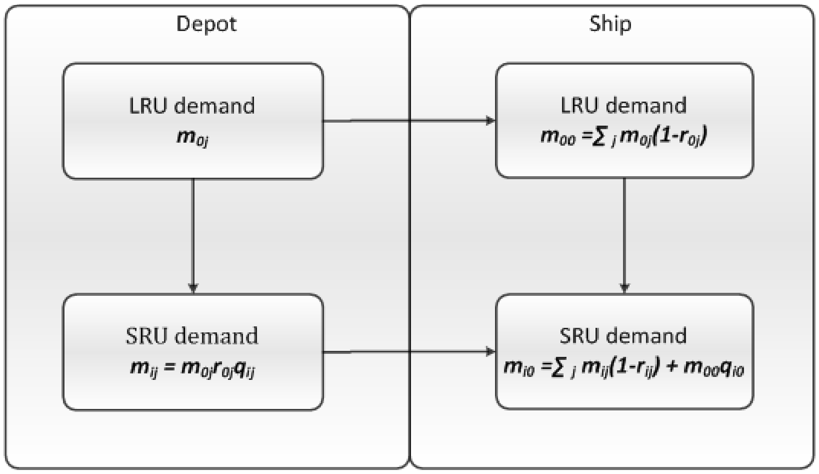


Figure 15: Demand formulas per location per indenture (Sherbrooke, 2004)

The demands of the LRU at the depot and the SRU at the depot can be calculated from the demand of the LRU at base. From the demand of the SRU at base and the demand of the LRU at depot the demand of the SRU at the depot can be calculated.

Now the demands are explained the pipelines could be explained. The calculations of the pipelines are made in the opposite direction of Figure 15. The pipeline variance is among other dependent on the variance of backorders (VBO). The VBO can be calculated with the following formula:

$$VBO(s_0) = E\left[BO^2(s_0)\right] - E^2\left[BO(s_0)\right]$$

The pipeline for the LRU can be calculated as followed: Start with the calculations of the SRUs in the depot repair. The SRUs in the depot repair have no influences from other items and locations. The numbers of the SRUs in the pipeline have a Poisson distribution with a mean $m_{i0}T_{i0}$. The calculations of the mean and the variance of the SRU *i* at the depot could be done by $EBO_{i0}(s_{i0})$, $VBO_{i0}(s_{i0})$. The following step is the calculations of the depot pipeline of the LRUs. This pipeline is dependent on the SRU pipeline. The third step is the SRU pipeline at the base. The SRU pipeline at the base is dependent on the SRU backorders of the depot. The final step is to calculate the pipeline of the LRUs at the base. The numbers of the LRUs in the base pipeline are dependent on the LRU backorders at the depot and the SRU backorders at the base. All the SRU backorders at base *j* arise from the LRU demand at base *j.*

4.3 Depot repair

The customer returns the defective part and agrees upon a certain repair lead-time with Thales. The standard repair process is exactly the same as in the VARI-METRIC model. Thus, in this case Thales only keeps stock of subassemblies and components. The LRU repair should be completed within the repair lead-time. The Depot repair of Inventri calculates per LRU the stock level of the SRUs or components. The depot repair calculates with the breakdown of each LRU and the supply chain of the LRU the required SRU/component stock levels. This stock level is calculated with an input variable repair lead-time and the probability target. The outcome of a depot repair calculation is that Thales could repair the LRU within the repair lead-time with the probability target, but therefore it needs the calculated inventory stock of the SRUs or components.

The variables to calculate the Depot repair probability are briefly explained in Table 17.

Table 17: Explanation of variables for the calculation of the depot repair probability

Variable	*Meaning variable*
i*=1,…,*I	LRU
j*=1,…, *J(i)	LRU_i has *J(i)* children (SRU or component)
T_i	the standard repair lead time
T_i^{agreed}	repair lead-time which is agreed with the customer
m_i	Demand of LRU *i per year*
DDR_i	due date reliability of LRU *i*

Essential to know in this situation is the probability that an LRU_i is repaired within the repair lead-time.

The repair lead time of LRU_i, T_i^{real} will be equal to the standard repair lead time T_i (whereby all SRUs and components are available) + slack (whereby the SRU *j* could be made available for repair). The realized repair lead-time should be smaller than the repair lead-time agreed with the customer. The Depot repair calculates per LRU_i the Due Date Reliability (DDR_i) depending on the repair/procurement lead-time of the SRUs or the procurement lead-time of components. This means that the reliability could be defined as a probability that the LRU_i is repaired within the repair lead-time agreed to the customer (which is implemented as input variable for each LRU_i). The DDR_i could be formulated as:

$$DDR_i = P\left(T_i^{real} \le T_i^{agreed}\right)$$

We determine a Weighted Due Date Reliability (WDDR) with the DDR per LRU. The WDDR is dependent on the demand of the LRU_i (m_i) with respect to the total LRU_i demand. The WDDR formula is as follows:

$$WDDR = \sum_{i=1}^{I} \frac{m_i}{\sum^{I} m_i} P\left(T_i^{real} \le T_i^{agreed}\right)$$

The algorithm will use the greedy algorithms of Rustenburg to add spare parts until the requested WDDR is satisfied. This model could be linked to the single-site system approach, whereby the weighted probability is used.

4.4 Conclusion

In this chapter we discussed three types of spare part management models. Thales uses Inventri to calculate the spare parts. These lists are calculated with Inventri which uses VARI-METRIC model variant of Rustenburg, an extension of the METRIC procedure. It is also possible to do a Depot repair calculation with Inventri.

METRIC is a spare parts allocation heuristic. Metric allocates spare parts which has the highest expected backorder reduction per invested euro per location. The marginal approach of the single-site model of Sherbrooke is optimal. (Sherbrooke, 2004) For general multi-echelon, multi-item and multi-indenture it is reasonably good and simple heuristic approach.

The marginal approach of the single-site model of Rustenburg (Rustenburg, 2000) is optimal when all vectors $S=S_1,..,S_I$ that satisfy the condition $\frac{\Delta \mathrm{E}\left[BO_i(s_i)\right]}{c_i} \leq \lambda \leq \frac{\Delta \mathrm{E}\left[BO_i(s_i+1)\right]}{c_i}$ shape the 'efficient frontier'. The multi-echelon, multi-indenture of Rustenburg could generate convex solutions, by modifying the initial stock level in the beginning of the allocation procedure.

METRIC assumes that the number of items in the pipelines is Poisson distributed. VARI-METRIC is an extension on METRIC which calculates, based on the mean-to-variance ratio of the number of items in the pipeline, what kind of distribution the pipeline needs. With this distribution fit of the pipeline, Inventri calculates following Rustenburg the spare part stock levels in the supply chain. With Inventri, which uses the VARI-METRIC approach, Thales calculates optimal spare parts allocation solutions with this VARI-METRIC model variant of Rustenburg.

Inventri has, beside the VARI-METRIC procedure, a depot repair model. This model calculates per LRU or SRU what the inventory levels are of the components. The inventory levels are based on weighted delivery reliability. Thales calculates for certain delivery reliability and a repair lead-time the stock levels of the components. This model could be linked to the single-site system approach, whereby the weighted probability is used.

5 Steady state spare parts allocation (Inventri)

In 2010 M.C. van Zwam concluded: "A combination of reducing time parameters and stocking extra spare parts leads to lower costs, a better variability, and a better robustness to changing Annual Operating Hours than only stocking spare parts." (Zwam, 2010) The Annual Operating Hours is directly related to the MTBF. Therefore the assumption is made that reducing the time parameters will also give better robustness to changing MTBF.

This chapter will answer the research question:

What are the optimal spare parts time parameters with Inventri (VARI-METRIC) and what influence has the repair lead-time on the spare parts inventory cost?

Research has been performed to determine what parameters are the most optimal for Thales in Smart-L ELR antenna case. The supply chain of Thales could be divided into the inventory in the supply chain (LRUs and SRUs) and the component spare parts at Thales for repair. The inventory of the supply chain is dependent on the repair lead-time of Thales.

1. The inventory of components at Thales
2. The inventory in the supply chain.
    - Repair lead-time of Thales

In Inventri there is only one repair lead-time. This repair lead-time is divided into three stages. However, Inventri does not encounter these three stages. Simlox on the other hand needs these time parameters to calculate the availability. The repair lead-time consists out of the shipment from ship-to-shore, shipment from shore-to-Thales and the repair lead-time, displayed in Figure 16.

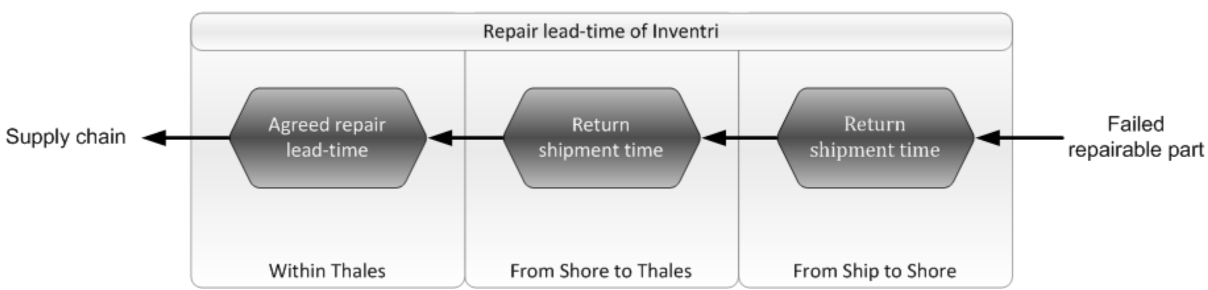


Figure 16: Division of the repair lead-time

T. Groener concluded that the repair lead-time could be reduced by storing components instead of LRU could. Reducing repair lead-time could create large cost reductions on the initial spare parts costs. (Groener, 2013)But reducing the repair lead-time could impact the components spare part stock. It is important to study what the effects are to the components spare parts costs.

The combination of conclusion of M.C. Zwam and T. Groener should create low cost steady state scenarios, which could be used in Simlox. This way, low cost scenarios are determined and should cope some variations of MTBF. In this chapter a choice is made which scenarios are used to find a solution which respects the mission availability target.

The objective of this chapter is to define the time parameters for different scenarios which are more in depth researched in chapter 6. These scenarios should result in spare parts costs reduction compared to the common procedure. Firstly, we will discuss the inventory of the components calculation in paragraph 5.1. Secondly, we will discuss the repair lead-time in paragraph 5.2. Finally we will discuss the conclusions of this chapter in paragraph 5.3.

5.1 Initial component spare part cost per repair lead-time

Thales uses Inventri to calculate the spare part stock levels in the supply chain. Inventri also provides an option to calculate the component inventory level at the depot. In case of the PBL contract Thales is the depot. They are responsible for the availability of the systems and perform the repairs of the LRUs themselves. In paragraph 4.3 the depot repair function of Inventri is reviewed. In the depot repair model a standard repair lead-time and a repair lead-time has to be entered. The standard repair lead-time is the repair lead-time when everything is ready-for-use. All the components and tools are available and there is no administrational delay. For this reason the standard repair lead-time is discussed first.

Standard repair lead-time

The antenna contains three LRUs which are repaired at Thales namely the LRU 1, LRU 2, and LRU 3 as displayed in Figure 7 in section 2.1.1. The initial components spare parts are calculated for these parts, because these parts are repairable. For these parts it is useful to store components.

- LRU 1
    - SRU 1A (SRU)
    - SRU 1B (SRU)
- LRU 2
- LRU 3

LRU 1 could be repaired by exchanging SRUs. Thales' choice is to stock either complete SRUs or to stock components to repair the SRU of the LRU. It is technically not possible to test the SRUs apart of LRU 1. Thales designed a test cabinet to determine whether the SRU 1A has failed or the SRU 1B has failed. The test cabinet is a functional test for the LRU 1. The repair of either the SRU 1B or the SRU 1A will take one day at most. This is based on a professional estimation with the assumptions that all the spare parts are available and the LRU could be repaired directly.

The LRU 2 and the LRU 3 are LRUs which consist of a printed circuit board and mechanical protection SRUs. The mechanical protection SRUs are neglected, because the mechanical protection SRU hardly ever fail. The only SRUs of these parts are the printed circuit boards. These printed circuit boards are repaired by replacement of components. The repair of the LRU 2 and LRU 3 by replacement of components is at most one day. The repair lead-time is also based on a professional estimation with the assumptions that all the spare parts are available and the LRU could be repaired directly.

For the complete standard repair flow see appendix D.

The standard repair lead-time is used to calculate components inventory stock level with certain delivery reliability for a certain repair lead-time. The repair lead-time as determined by Donderwinkel (Donderwinkel, 2005), at a minimum of 14 days. The delivery reliability and the repair lead-time whereby the standard repair lead-time is an input variable will be discussed.

Repair lead-time

The standard repairs of the LRUs are estimated at one day. The repair lead-time will be discussed in this section. With the calculation of Depot repair (Inventri) Thales could calculate the spare part stock level cost for a certain delivery reliability target that there is no waiting time for components e.g. with a delivery reliability target of 95%, an standard repair lead-time of one day and repair lead-time of 14 days at Thales needs at least €183,- of spare parts.

The repair lead-time as determined by Donderwinkel (Donderwinkel, 2005), is a minimum of 14 days. In addition, every part must follow the procedure which is decribed in the flow diagram of appendix B.

The component spare part cost should reduce when the repair lead-time is increased. Therefore the question arises:

What influence has the repair lead-time on the spare parts inventory cost?

The complete calculation of the components spare part inventory cost could be found in appendix E. This research uses the probability of 99.5%. This means 99.5% of the time the repairs should be repaired within the repair lead-time. Thus 1 of 200 repairs will not be performed within the repair lead-time. This is only possible when components are stocked. The total cost of the components inventory will be maximal €1,502 (Table 18). Compared to the part prices which are more than €20,000 this is relatively low.

Table 18: Total cost of components per repair lead-time

Repair lead-time	Total costs
Repair lead-time 14 days	€1,502.13
Repair lead-time 21 days	€1,502.09
Repair lead-time 28 days	€1,497.56
Repair lead-time 35 days	€1,484.43
Repair lead-time 42 days	€1,481.25
Repair lead-time 49 days	€1,479.53

We could conclude that the different repair lead-times have barely an influence to the component spare part inventory cost. The maximal difference is €23 on initial spare parts costs and maximal components spare parts costs are €1502.13

5.2 LRU inventory in the supply chain

The LRU inventory in the supply chain can also be calculated with Inventri. The full support option in Inventri is the option whereby the LRU and SRU inventory level can be calculated. Therefore the repair lead-time is an important factor. Nowadays, Thales uses on average repair lead-time of 180 days. These lead-times are used by a traditional “On Demand” contract. Research has to be conducted on what the initial spare parts cost reduction can be when the repair lead-time is reduced.

As mentioned before Inventri’s full support option consists of multiple parameters namely: the return shipment from ship to shore, the return shipment from shore to Thales and the repair lead-time of Thales. We will use the product structure of Figure 7 in section 2.1.1, supply chain of Figure 10 in section 3.2.3 to investigate what the influences are. Logically, the return shipment time will be the same as the forward shipment time (section 3.2.3), although administrational delay is not applicable to the return shipment time. Therefore the return shipment time will be 15 or 30 days from ship to shore and 5 from shore to Thales. We will use return shipment time of 21 days instead of 20 days, because this will be calendar weeks, 35 days are already calendar weeks. In addition the minimal repair lead-time is added of 14 days. Thus the minimal repair lead-time of Inventri is 35 days or 49 days because two shipment cycles is researched, namely one moth and two months. Like displayed in Figure 10 of section 3.2.3. Total inventory costs as a function of the repair lead-time and return shipment time is plotted in Figure 17.

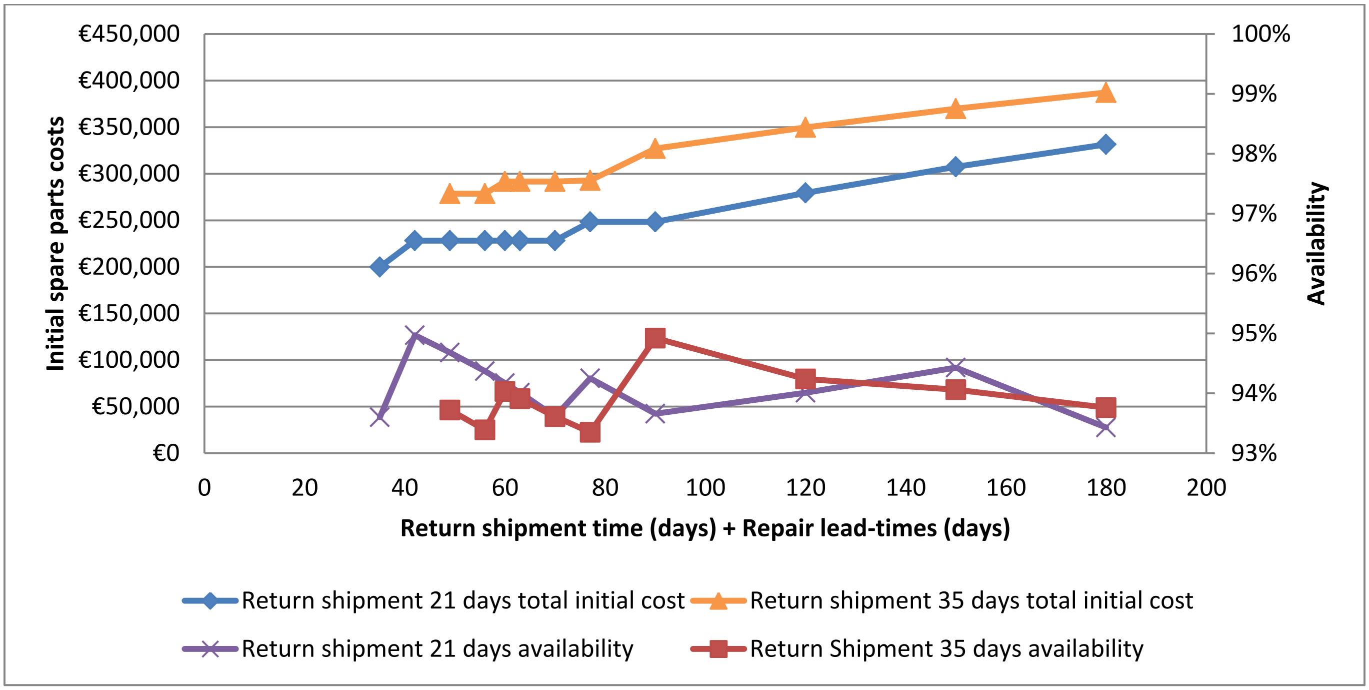


Figure 17: LRU total cost per shipment to ships (VARI-METRIC)

Figure 17 shows that the 35 days shipment starts at 49 days and the 21 days shipment starts at 35 days. The horizontal axis is the varied time parameters and the left vertical axis is the total initial spare parts cost and the right vertical axis is the average operational availability. This due the earlier mentioned minimal repair lead-time. The costs are calculated at a minimal target level of 93.3%. This means that all the costs and repair lead-times plotted in Figure 17 are at least at 93.3%. When the minimal availability descents below 93.3% then a spare part is added. Consequently, the cost increases and the availability increases. There is an LRU added to the 35 days return shipment when the return shipment plus the repair lead-time is modified from 56 days to 63 days. Like mentioned the forward shipment and return shipment should be equal. Therefore both cycles will have different forward shipment lead-times. This results in different availabilities and will result in different allocations despite the equal return shipment time plus the repair lead-time. This difference will also be notable in Table 19 and Table 20.

The orange and the blue line are the total initial spare parts cost, per repair lead-time increase. The purple and the red line are the operational availability per repair lead-time increase. Notable is that the availability is the highest at the left side of the horizontal cost line. For example: The availability is the highest at 42 days. This is most left side of the horizontal 21 days of shipment cost line.

Comparison (LRUs) with average repair lead-time of 180 days

The repair lead-time of 14 days and return shipment of 21 days has a total cost of minimal €200.000 instead of the common average repair lead-time of 180 days which has a total cost of €330.000.

(Figure 17) These costs are initial supply costs. The cost reduction of LRU inventory level by a shipment of 21 days is 39.76%. Practically, it will probably be more advisable to use an LRU inventory level of at least €228.000, because this way the system is more stable. The availability is higher and therefore it could probably take some MTBF variations. This way the initial spare part cost reduction is 31.16%.

The shipment to ship of 35 days has a minimal €278.000 total cost (14 days repair lead-time) instead of the common average repair lead-time of 180 days which has a total cost of more than €387.000. These initial costs have a reduction of 28.09%.

Comparison (LRUs + Components) with average repair lead-time of 180 days

The reduction of repair lead-time is only possible when the components are available at the repair shop (Thales). The inventory costs of those components (Table 18 in section 5.1) are relatively cheap compared to LRU inventory cost. In Table 19 the total costs are summarized. The most expensive option is 21 days of repair lead-time, but compared to the 180 days of repair lead-time it is a reduction of more than 30%.

Table 19: Total cost for 20 days return shipment time

Repair lead-time	Total component spare parts costs	Total LRU spare parts cost	Total cost
Repair lead-time 14 days	€1,502.13	€199,733.85	€201,235.98
Repair lead-time 21 days	€1,502.09	€228,239.36	€229,741.45
Repair lead-time 28 days	€1,497.56	€228,239.36	€229,736.92
Repair lead-time 35 days	€1,484.43	€228,239.36	€229,723.79
Repair lead-time 42 days	€1,481.25	€228,239.36	€229,720.61
Repair lead-time 49 days	€1,479.53	€228,239.36	€229,718.89

When the return shipment times are larger, then the LRU spare part stock level costs are higher. The most expensive option in this case is a repair lead-time of 42 days. The total initial spare parts cost of a 35 days return shipment time and a repair lead-time of 42 days compared with 180 days, then the reduction of cost which could be established is still more than 24%.

Table 20: Total cost for 35 days return shipment time

Repair lead-time	Total component spare parts costs	Total LRU spare parts cost	Total cost
Repair lead-time 14 days	€1,502.13	€ 278,499.68	€280,001.81
Repair lead-time 21 days	€1,502.09	€ 278,499.68	€280,001.77
Repair lead-time 28 days	€1,497.56	€ 291,578.90	€293,076.46
Repair lead-time 35 days	€1,484.43	€ 291,578.90	€293,063.33
Repair lead-time 42 days	€1,481.25	€ 292,753.48	€294,234.73

Comparison shipment cycles

Two different shipment times are stated in this paragraph. We compared a month cycle shipment (return shipment of 21 days) and the two months cycle shipment (return shipment of 35 days). The shipments will be performed by parcel service like DHL. It is shown in the graph of Figure 17 that the one month cycle shipment has lower initial spare parts cost compared to the two month cycle shipment. The initial spare parts costs are consequently lower. The largest initial spare parts cost reduction of Table 19 and Table 20 is 28.13%. This reduction is derived from the repair lead-time of 14 days. The minimum initial spare parts cost reduction of Table 19 and Table 20 is 17.95%. We can conclude that it is advisable to shorten the shipment cycle time.

Scenario choice

This research could not investigate all the shipment cycles with corresponding repair lead-times. The corresponding shipment cycle and repair lead-times are chosen because they have either highest availability per lowest spare parts cost or the highest availability, or the highest repair lead-time for the same (almost the same) cost as the highest availability. Therefore there are five repair lead-time chosen which are noted in Table 21.

Table 21: Variable setting which will be studied more in depth

Return shipment lead-time	Repair lead-time	Choice argumentation
21 days	14 days	highest availability for lowest spare parts cost
	21 days	the highest availability
	49 days	highest repair lead-time for the same cost as 21 days
35 days	14 days	highest availability per lowest spare parts cost
	42 days	highest repair lead-time for almost the same cost as 14 days

5.3 Conclusion

The reduction of the repair lead-time could reduce the initial spare parts cost in this case with 39.76%, but it could only be realized by stocking component spare parts.

The largest total initial spare parts cost is achieved by reducing the repair lead-time. The reduction of the repair lead-time is only allowable when Thales stocks component spare parts. The component spare parts stock costs are much lower than the LRU spare parts stock.

The reduction of the shipment cycle time reduces the initial spare parts costs, in this case 28.13%.

The total initial spare parts cost is higher for the two month shipment cycle then the total initial spare parts cost month shipment cycle. The conclusion could be drawn that reducing shipment times reduces the initial spare parts cost. The reduction in the Smart-L ELR case could be at least 17.95% and up to 28.13% and maybe even more.

There is hardly a difference among the total components spare parts cost when the repair lead-time is varied. Most components have a larger procurement lead-time than the repair lead-time thus must be stocked anyway.

The delivery reliability does have an impact to the total components spare parts cost. A 99.5% delivery reliability and a 14 days repair lead-time has a total initial components inventory cost of

€1,502.13. The total component spare parts stock compared to the most expensive LRU is only 5.3%. Reducing one repairable spare part reduces already the initial cost in this case.

By stocking components the repair lead-time reduction could be realized. This results in lower total initial inventory costs of more than 39.76% by 35 days of shipment time and more than 28.09% by 21 days of shipment time parameter. Five scenarios are chosen to investigate in chapter 7. The corresponding repair lead-times, the return shipment time and the selection argumentation are as followed:

Return shipment lead-time	Repair lead-time	Selection argumentation
21 days	14 days	highest availability per lowest spare parts cost
	21 days	the highest availability
	49 days	highest repair lead-time for the same cost as 21 days
35 days	14 days	highest availability per lowest spare parts cost
	42 days	highest repair lead-time for almost the same cost as 14 days

6 Transition procedure from Inventri to Simlox

This chapter will answer the research question:

How to step-by-step transform the VARI-METRIC (operational availability) solution to a mission availability solution?

We investigate the differences between Simlox and Inventri to answer this question. The study investigates whether Simlox is a good simulation tool and that the supply chain is implemented correctly. Simlox will have different result than Inventri, because both software has different approached to calculate the availability. Although, there may not have any significant differences. We will discuss the evaluation of both software tools in paragraph 6.1.

We will examine the differences between operational and mission availability in paragraph 6.2. We expect that the mission availability is lower than the operational availability. The largest differences are compared in this paragraph.

Inventri uses the VARI-METRIC model variant of Rustenburg to calculate the spare part stock levels. It is known that VARI-METRIC model variant of Rustenburg could generate optimal solutions when the cost/availability curve is convex. Consequently the allocation procedure will also be optimal in the model. This allocation procedure is based on the assumption that the delta EBO is linearly proportional to the delta operational availability. In paragraph 6.3 a study will be performed whether the delta EBO is also linearly proportional to the delta mission availability.

When we assume that the delta EBO is linearly proportional to the delta mission availability then the procedures could be developed. In this research there are four procedures. We will elaborate the procedures in paragraph 6.4.

Finally in paragraph 6.5 the key findings are concluded.

6.1 Differences between Inventri and Simlox

Currently, Thales uses Inventri to calculate the spare parts provisioning. As discussed in a previous chapter, Inventri is based on the VARI-METRIC model variant of Rustenburg. Inventri's output is an operational availability/cost curve with the corresponding spare parts list. Inventri only has one availability output despite of multiple ships. Towards the mission availability and the PBL contract Thales would like to gain more insight in what the mission availability is. This is one of the reasons why Thales procured Simlox. Simlox is a commercial of the shelf simulation software. Furthermore it has the capability to handle mission profiles.

In order to verify whether Simlox is a simulation software which corresponds with Inventri and the scenarios are implemented correctly, a simulation is conducted using Simlox in the same setup as when using Inventri. One of the assumptions (like discussed in section 4.1.1) is that the demands occur according to a Poisson process. This means that the parts fail even when the system in down. Inventri calculates the availability following assumption 1 of section 4.1.1. Simlox is a simulation software where the failure will not occur when the system is down. The availability of Simlox should be higher than the availability of Inventri. Therefore a correction on the Inventri output is necessary to compare the output with Simlox. The correction formula is deviated from the Annual Operating Hours, yearly failure demand of the system and the Inventri availability. The derivation can be found in appendix F. This correction could be calculated by the formula:

$$\text{Simlox Availability} = A_v^2 - A_v + 1$$

The availability, as used in the comparison, is a parameter that will change, but the correction means that if the Inventri availability is 93% then the Simlox availability should be about 93.49%.

This correction can be implemented into Excel and a comparison could be made with Simlox. To accomplish this Simlox must be programmed in the same way as Inventri. This means that the breakdown and the supply chain variables are adopted. For this experiment we will also use the product structure of Figure 7 in section 2.1.1, supply chain of Figure 10 in section 3.2.3.

The repair success rate of Inventri cannot be exactly modelled in Simlox. Therefore the repair success is neglected in this comparison. Both success rates are set to 100% avoid strange comparisons.

Simlox needs a mission profile to simulate. Inventri uses the Annual Operational Hours (AOH) per year that means AOH per ship / 365 days.

There is still a small difference between corrected Inventri availability and Simlox availability. The difference between the Simulation model and the corrected Inventri is less one percent. The reason for this small difference is unknown.

Differences smaller than one percent are acceptable and therefore we can assume that Simlox is a good simulation tool and the scenarios are well modelled without mission profiles.

6.2 Operational availability versus mission availability

In the previous paragraph we discussed if Simlox is a tool whereby Inventri can be simulated. If Inventri could be simulated, the assumption could be made that Simlox is a good simulation software and that the Simlox model is programmed correctly. In this chapter we investigate the differences between mission availability and the operational availability of Inventri. Before the comparison between the mission and operational availability can be made, an availability study has to be conducted to identify the worst case scenario in terms of mission profile and mission deployment. The worst case scenario of the mission intensity is that the ships are deployed in which the average mission availability is at its lowest. The study to this worst case scenario is discussed in section 6.2.1. Afterwards a comparison is made between the mission availability and the operational availability.

6.2.1 Mission intensity

The worst case towards mission availability among missions is assumed to be the deployment of two mission ships at the same time. This seems logical, because that the demand of parts failure will start at the same moment. The two ships create a demand at the same time. The best case scenario will probably be that the mission ships are deployed consecutive to each other during the year. For example: Mission ship one deploys in the first half year and the second mission ship deploys in the second half year. The short-mission ship will be deployed around mission ship one and two.

What the intensity of the missions are studied by changing the deployment of the ships. Mission intensity is studied by an experiment in which the mission profiles are modified weekly. One mission ship (mission ship 1) and the short-mission ship are unmodified. The other mission ship (mission ship 2) is modified. This second mission ship (mission ship 2) is deployed at Week 0, 1, 2 …, or 30. For the overview see appendix G. For this experiment we will also use the product structure of Figure 7 in section 2.1.1, supply chain of Figure 10 in section 3.2.3.

Figure 18 shows where the mission availability is displayed in respect of the mission deployment. The vertical axis is the mission availability and the horizontal axis is the deployment week of the second mission ship. Like it was assumed the availability is higher when the mission ships are deployed consecutive to each other.

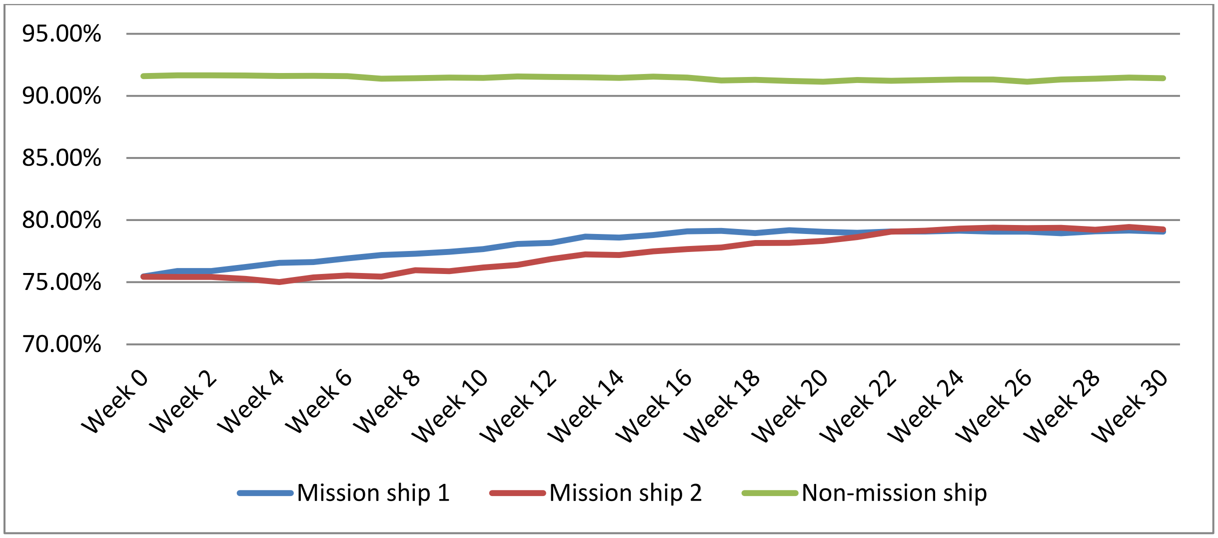


Figure 18: Mission availability differences per ship

Note that the mission availability of the second ship is consequently lower until week 22. This seems quite logical; the spare parts are ordered on a first-come-first-serve basis. The failed parts which are ordered first will be handled first. Logically this will be mission ship 1. The first mission ships creates a demand from t = 0 and the second ship from t > 0.

The short-mission ship will have high mission availability. The short-mission ship will sail multiple missions during a year with a mission duration from 3 to 7 days. In this case the chance a part fails is much smaller, because of the small mission durations.

The total difference among the average mission availabilities of three ships in respect to deployment of the second mission ship is displayed in Figure 19. The vertical axis is the average mission availability; the average mission availability of three ships. The horizontal axis is the deployment week of the second mission ship. The difference will increase up to more than 2%. These differences are created using the scenario with two mission ships and a short-mission ship. When the mission ships have larger or smaller mission lengths, then the difference will probably change in accordance with the mission length.

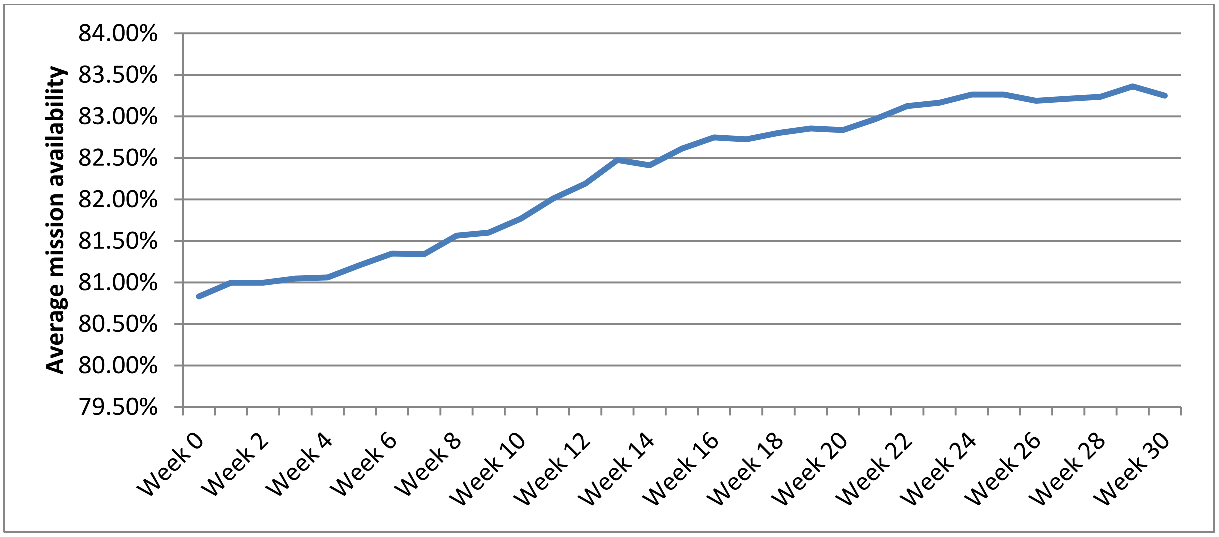


Figure 19: Differences in average mission availability

We can assume that the mission intensity is the highest when two mission ships deploys at the same time. The worst case scenario is used in this research, because Thales aims to have penalties as little as possible, because penalties could create high costs over a very short period of time. By using the worst case scenario the chance in having penalties will be reduced, because in general the ships will not be deployed at the same time.

6.2.2 Comparison between mission and operational availability

The missions are implemented within Simlox following the sequel of Table 5 in section 3.2.3. The simulation run is 5 years with one year warm-up period using 25000 replications. For this experiment we will use the product structure of Figure 7 in section 2.1.1, supply chain of Figure 10 in section 3.2.3, the time parameters: repair lead-time 14 days & return shipment of 21 days and worst case ship deployment of Figure 18 in section 6.2.1. The results are plotted in Figure 20. The vertical axis is the average availability of three ships per year. ($\frac{A_{ship1} + A_{ship2} + A_{ship3}}{3}$ This is the operational or the mission availability. The horizontal is the costs of the spare parts.

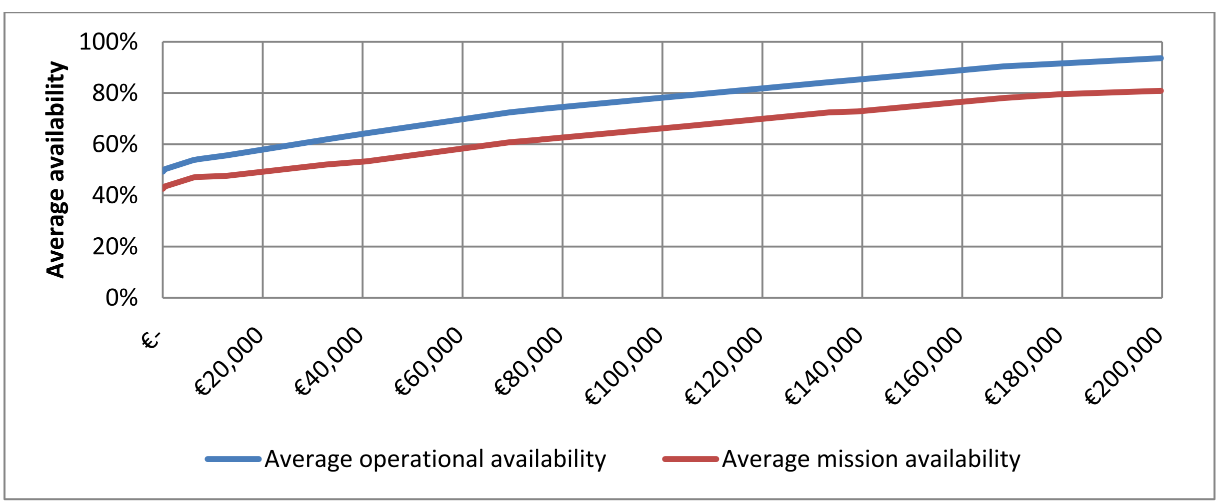


Figure 20: Difference between operational availability and mission availability

Using the mission implementation a comparison could be made between operational availability (Inventri) and the average mission availability (Simlox).

The average operational availability of three ships is calculated when using Inventri. Again, multiple ships are used and again the average is calculated of three ships. Despite the two mission ships and the short-mission ship, the differences between Inventri availability and mission availability is approximately 13% for the 21 days return shipment and a repair lead-time of 14 days. The other scenarios are simulated in the same way. No significant differences were found.

There is a big difference between mission profiles and the Inventri calculation. Inventri calculates the supply availability. This means that the calculation is done in a steady state. The supply availability is also taken into account when the ship is in the harbor and the system is not operational. The spare parts supply for the ships are available during a large part of a year when the ship is in the harbor. The mission availability only takes the spare parts supply availability into account when the ship is on a mission. The measurement period of the mission availability is therefore much shorter than the supply availability when calculated using Inventri. Figure 21 gives better overview.

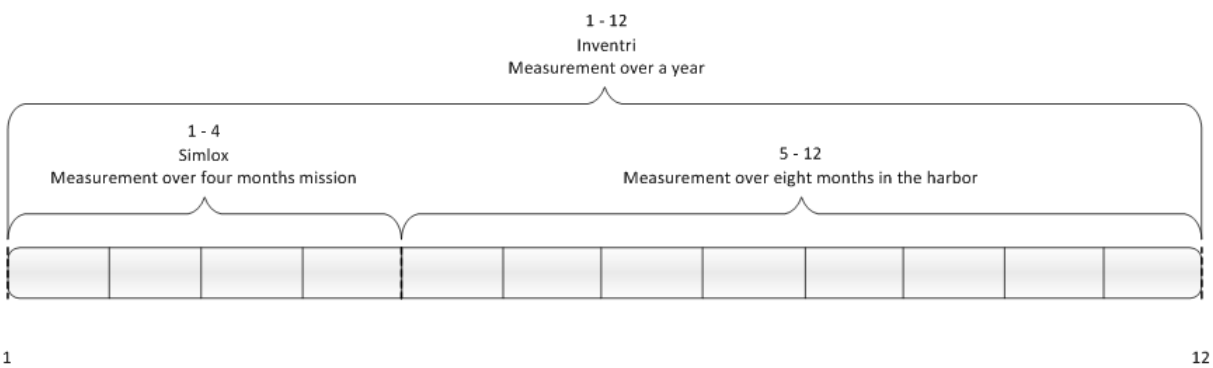


Figure 21: Example measurement 4 months mission availability in respect to operational availability

If Thales uses the spare parts provisioning based on Inventri than Thales will get penalties. With a mission availability target set at 93.3% Thales will not be able to reach this level of availability. For this reason Thales has to calculate the mission availabilities with the software Simlox.

6.3 Could the allocation procedure of METRIC be used?

As discussed in section 4.1.3 Inventri calculates the spare parts based on the VARI-METRIC model variant of Rustenburg. The greedy allocation procedure of Rustenburg could be convex and thus optimal. The convexity is dependent on the initialization of the greedy procedure. It would be very convenient to use the allocation procedure provided by the greedy allocation procedure of Rustenburg. The greedy algorithm of Rustenburg uses the delta probability of backorders (PBO) to determine which spare parts *i* should be stocked at which location *j*. The delta PBO is PBO(s_{ij})-PBO(s_{ij}+1). The question arises if the delta PBO is linearly proportional to the delta mission availability of the ship. In Table 22 the variables are explained briefly.

Table 22: Explanation of variable for availability per base and the delta PBO proposition

Variable	*Meaning variable*
i*=1,…,*I	Number of LRU
***A*(s_i)**	Operational availability with stock level equals s_i
***Am**$_i$*(s_i)**	Mission availability with stock level equals s_i
***PBO**$_i$*(s_i)**	Probability of backorders for LRU *i* if the stock level equals s_i
s_i	Stock level of LRU *i*
C	Constant of the probability of backorders of other LRUs
k	Factor between mission and operational availability

The operational availability per base *j* is formulated by Rustenburg as:

$$A(s_i) = \prod_{i=1}^{I} (1 - PBO_i(s_i))$$

The derivation that the comparison could be made between PBO(s_{ij}) - PBO(s_{ij}+1) and A(s_{ij}+1) - A(s_{ij}) could be made is described in appendix H. This comparison uses the operational availability of Rustenburg. We also assume that we can compare the delta PBO and the delta mission availability (*Am*) with a certain k. The following proposition could be formulated:

$$PBO_i(s_i) - PBO_i(s_i + 1) = C * k * (Am_i(s_i + 1) - Am_i(s_i))$$

The expectation is that the delta PBO is linearly proportional to the delta mission availability. This is tested by three experiments. The experiments use the product breakdown as shown by Figure 7 in section 2.1.1. Initial spare parts allocation is made with Inventri. Following this, at each iteration a "random" spare part is added by one and calculated with Simlox. We will add spare parts of each LRU to have some structure. Subsequently, each LRU is added by another spare part and calculated with Simlox.

This proposition is studied the following paragraph. First, the linear proportionality is studied by adding spare parts to **the ship** in section 6.3.1. Secondly, the linear proportionality is studied by adding spare parts to **the customer's site** in section 6.3.2. Finally, the linear proportionality is studied by adding spare parts at **Thales** in section 6.4.3.

6.3.1 Linear proportionality between delta PBO and delta mission availability by adding spare parts onboard the ship

The relation is studied by simulating a scenario with one ship. This ship is varied by mission length namely: one, two, three, four and five months. The supply chain looks as follows:

Figure 22: Linear proportionality is simulated at the ships scenario

This experiment uses the product breakdown as shown by Figure 7 in section 2.1.1. Firstly an initial spare parts allocation with Inventri is made. Following this, a "random" LRU at the ship is added with a spare part and calculated with Simlox. To have some structure we will increase the spare part stock of each LRU at the ship. Subsequently, each LRU is added by another spare part and calculated with Simlox. This experiment will generate 14 delta PBO and delta mission availability measurements per mission length. We will test five mission lengths. The complete spare parts allocation could be found in appendix I.

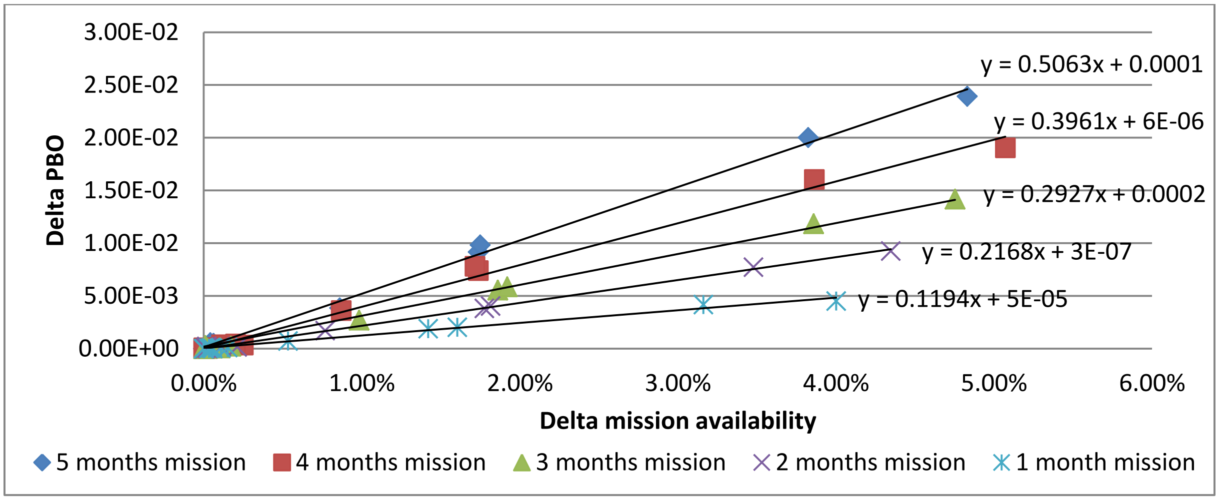


Figure 23: Linear comparison of delta PBO and delta mission availabilities per ship

The delta PBO and the delta mission availability are plotted per mission length (Figure 23). The vertical axis is the delta PBO of the ships and the horizontal axis is the delta mission availability. This is measured before and after the increased spare part stock. The difference between the $PBO_{ij}(s_{ij})$ and the $PBO_{ij}(s_{ij}+1)$ measurement is the delta PBO. The delta mission availability (Am) is the difference between the $Am_{ij}(s_{ij})$ and the $Am_{ij}(s_{ij}+1)$ measurement. The straight line reflects the linear proportionality line per mission length.

The experimental results are really close to the linear line. The lines are probably starting from the zero point, the small inconsistency is probably due to the simulation error. When we interpret the graph the assumption can be made that the delta PBO is linearly proportional to the delta mission availability.

Note that the mission length has an influence on the slope. It seems that the slope is the mission length divided by a year. For example: 3650/8760=0.42. It is not exactly the same, but it is nice starting point for future research. In this research the linear proportionality is the most important aspect. Following the graph, it can be concluded that the delta PBO has a very strong linearly proportional to the delta mission availability.

6.3.2 Linear proportionality between delta PBO and delta mission availability by adding spare parts at customer's site

It could also be financially interesting to add a spare part at the customer's site. The customer's site serves usually more than one ship. Otherwise it would make more sense to only add spare parts to the ships. A scenario is created incorporating two ships to study if the delta PBO onboard the ships and delta mission availability is linearly proportional. Both ships have different mission lengths. For this case there are two scenarios simulated. (Figure 24 and Figure 25)

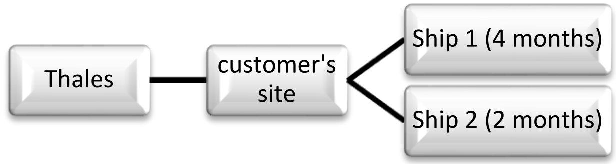


Figure 24: Linear proportionality is simulated at customer's site scenario 1

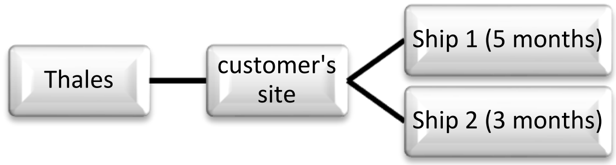


Figure 25: Linear proportionality is simulated at customer's site scenario 2

This experiment uses the product breakdown as shown by Figure 7 in section 2.1.1. Firstly, an initial spare parts allocation with Inventri is calculated. Following this, a "random" LRU at the customer's site is added with a spare part and calculated with Simlox. To have some structure we will increase the spare part stock of each LRU at the customer's site. Subsequently, each LRU is added by another spare part and calculated with Simlox. This experiment will generate 14 delta PBO and delta mission availability measurements per scenario (Figure 24 and Figure 25). The PBO and mission availability will be measured at the ships, because the systems must naturally be available at the ships. We will test both scenarios. The complete spare parts allocation could be found in appendix J.

Like mentioned before, it would make sense to add spare parts at the customer's site when it provides more than one ships. It would then be logical to measure the impact over both ships. If spare parts are added to the customer's site, what will the impact over the PBOs and the mission availabilities be? To measure the impact the delta PBOs over the ships and the deltas over the mission availabilities are summed. These summed delta PBOs and delta mission availabilities are plotted in Figure 26. This is measured before and after the increased spare part stock. The difference between the $PBO_{ij}(s_{ij})$ and the $PBO_{ij}(s_{ij}+1)$ measurement is the delta PBO. The delta mission availability (Am) is the difference between the $Am_{ij}(s_{ij})$ and the $Am_{ij}(s_{ij}+1)$ measurement. The vertical axis is the delta PBO of the ships and the horizontal axis is the delta mission availability. Judging from the graph the assumption can be made that the summed PBOs and summed mission availabilities are linearly proportional.

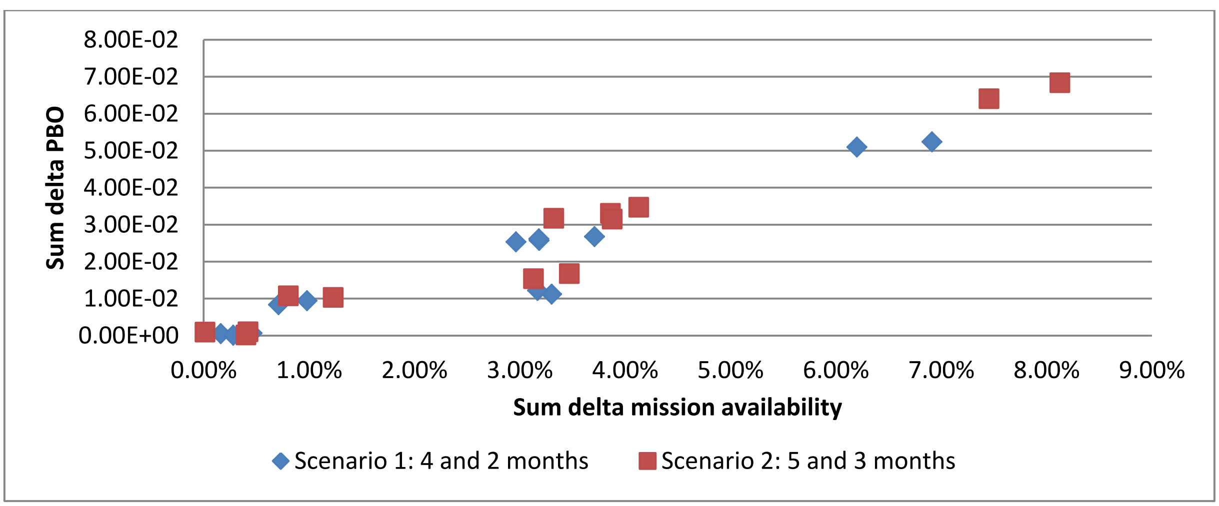


Figure 26: Summation of delta PBO and delta mission availability over the ships when spare parts are added at customer's site

6.3.3 Linear proportionality between delta PBO and delta mission availability by adding spare parts at Thales

This experiment uses also the product breakdown as shown by Figure 7 in section 2.1.1. Firstly, an initial spare parts allocation with Inventri is calculated. Following this, a “random” LRU at Thales is added with a spare part and calculated with Simlox. To have some structure we will increase the spare part stock of each LRU at Thales. Subsequently, each LRU is added by another spare part and calculated with Simlox. This experiment will generate 14 delta PBO and delta mission availability measurements per scenario (Figure 24 and Figure 25). The PBO and mission availability will be measured at the ships, because the systems must naturally be available at the ships. We will test both scenarios. The complete spare parts allocation could be found in appendix K.

When a spare part is added to the spare part stock of Thales than the measurement should be the same as the measurement of customer’s site. This is measured before and after the increased spare part stock. The difference between the $PBO_{ij}(s_{ij})$ and the $PBO_{ij}(s_{ij}+1)$ measurement is the delta PBO. The delta mission availability (Am) is the difference between the $Am_{ij}(s_{ij})$ and the $Am_{ij}(s_{ij}+1)$ measurement. The delta PBOs of the ships and the delta mission availabilities are summed and plotted (Figure 27). The vertical axis is the delta PBO of the ships and the horizontal axis is the delta mission availability. The summed delta PBOs and the summed delta mission availabilities are linearly proportional judging from the graph.

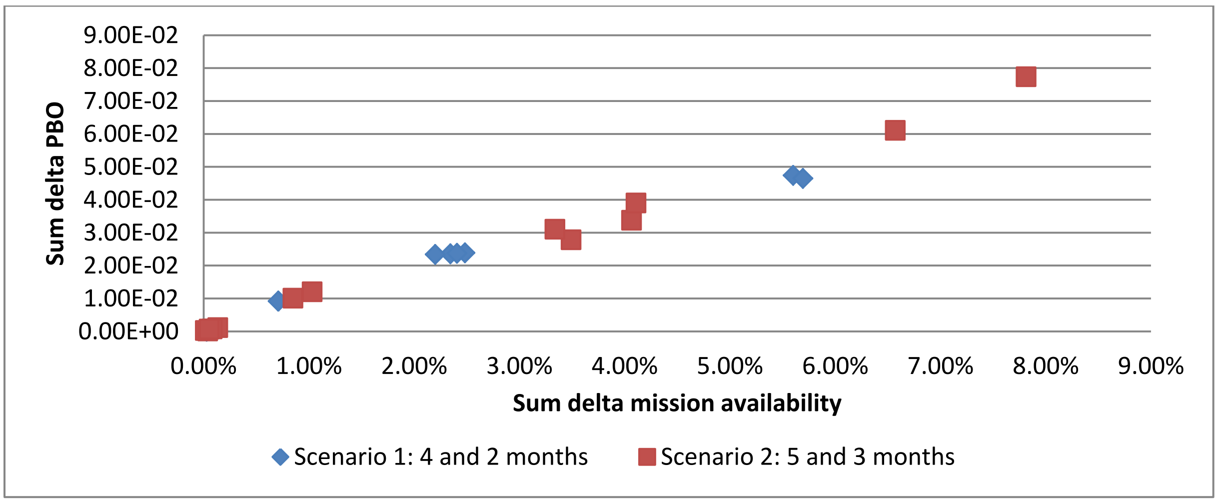


Figure 27: Summation of delta PBO and delta mission availability over the ships when spare parts are added at Thales

The summed delta PBO is very strongly linearly proportional to the delta mission availability. With the final test completed it seems that the delta PBO is linearly proportional to the delta mission availability at every location in the supply chain. This could to be very interesting for Thales, because the VARI-METRIC allocation procedure can be used. The allocation choices of Inventri (VARI-METRIC) could be used to allocate spare parts to the different locations in the supply chain.

6.4 Transition procedures

In the previous paragraph a study has been conducted in order to verify whether the greedy allocation procedure of Rustenburg could be used. The delta PBOs of all the spare part stock locations are assumed linearly proportional to the delta mission availability. As concluded in paragraph 6.2 the mission availability is much lower than the operational availability. Therefore a transition procedure has to be developed.

Thales currently uses two tools to calculate the spare parts availability. Inventri is used for the operational spare part availability. Simlox is used to evaluate mission availability. A Simlox simulation of 2500 runs could take more than 60 minutes to calculate the mission availability. The aim is to calculate the optimal spare part stock level with respect to calculation time, spare parts costs and mission availability target. Inventri can be used to reduce calculation time as much as possible. An Inventri calculation takes one minute at most. Therefore four procedures are developed to calculate the spare part stock level in this paragraph. The first procedure is discussed in section 6.4.1, the second procedure in section 6.4.2, the third procedure in section 6.4.3 and the procedure based on VARI-METRIC choices in section 6.4.4.

All the procedures have the assumption that Inventri calculates the optimal spare part stock level at the customer's site and Thales. It is therefore important that the step from Inventri to Simlox should be after as many Inventri iterations as possible. This could be all Inventri choices whereby the target is set to 93.3% or Inventri is ran to 99.99% and the allocation is continued in Simlox. After the Inventri calculation the procedures will only look at the ships, because it is a relatively hard calculation by hand (especially with the Simlox outputs) to evaluate a multi-echelon, multi-indenture model. By doing so, the model can be considered as single-site, whereby the multiple ships are considered as one site.

Simlox gives a simulated average probability of no backorders (PNBO). Probability of no backorders is similar as one minus the probability of backorders (1-PBO). We would like to use this PBO to choose which spare part at which location is the most cost-effective to add a spare part. When the system is considered single-site then we could use the following delta formula whereby the PBO is the simulated 1-PNBO. In Table 23 the variables are explained briefly.

Table 23: Explanation of variable for the derivation of delta

Variable	*Meaning variable*
i*=1,…,*I	Number of LRU
J*=1,…,*J	Number of ships
EBO$_i$(s$_j$)	Expected backorders for LRU *i* if the stock level equals s_i
PBO$_i$(s$_i$)	Probability of backorders of LRU *i* if the stock level equals s_i
PNBO$_i$(s$_i$)	Probability of no backorders of LRU *i* if the stock level equals s_i
s$_i$	Stock of LRU *i*
m$_i$	Failure demand of LRU *i*
T$_i$	Repair lead-time of LRU *i*
c$_i$	Cost of LRU *i*

$$\Delta_{ij} = \frac{1 - PNBO(\mathrm{s_{ij}})}{c_i} = \frac{PBO(s_{ij})}{\mathrm{c}_i} \text{ for all spart} i, \text{ship } j$$

We could use this formula to determine the delta EBO per spare part, because the following derivation could be made for a single-site model.

$$PBO(s_i) = 1 - \sum_{n=0}^{s_i} \frac{(m_i T_t)^n e^{-m_i T_i}}{n!} = \sum_{n=s_i+1}^{\infty} \frac{(m_i T_t)^n e^{-m_i T_i}}{n!} = EBO_i(s_i) - EBO_i(s_i + 1)$$

The complete derivation is shown in appendix L. Delta EBO per spare part is equal to the PBO of Rustenburg and equal to the output of Simlox. Therefore the location where a spare part will be added is determined by the following formula:

$$\Delta_{ij} = \frac{PBO(s_{ij})}{\mathrm{c}_i} \text{ for all spart } i, \text{ship } j$$

6.4.1 Procedure 1

The first procedure is the most straight forward procedure and will probably not be the best procedure. This procedure makes the shift from Inventri to Simlox on the mission availability target. This target is set at customer's request.

The logic behind this procedure is that when the mission availability target is used to calculate operational availability spare part allocation (Inventri) then the mission ships should be below mission availability target (Figure 20). Inventri is used to minimize the calculation time. The short-mission ships could reached the mission availability target. The objective is to minimize the cost; therefore if spare parts are allocated to the short-mission ships then these spare parts are removed. Now all the ships should be below the mission availability target. At this point this transition procedure will shift to Simlox and use the simulated variables and the simulated mission availability. The simulated PBO of Simlox per invested euro determines where the next spare part will be allocated. The spare parts will only be allocated at the ships, when the shift is made to Simlox. We will use the single-site greedy allocation procedure in Simlox with the simulated variables, until the requested mission availability of all the ships is reached.

The procedure is described in more detail in Table 24. In this procedure the PBO could be used which Simlox returns in the output.

Table 24: Allocation procedure 1

Step	Activity	How
1	Calculate the starting point.	Calculate the spare part stock list by Inventri. The target which the customer requests is used to calculate the spare part list with Inventri. The complete supply chain is implemented in Inventri.
2	Run baseline simulation.	Run the simulation with the spare part list from Inventri. This simulation is the baseline for the Simlox allocation.
3	Simlox returns the mission availability per ship. When the output of the baseline simulation returns that the short-mission ships are above requested mission availability target then delete spare parts from the short-mission ships which already reached the requested target.	If there are spare parts added to short mission ships which already reached the mission availability target then delete those spare parts from the spare part list. Because the previous run is not correct a new baseline simulation without short-mission spare parts allocation must be run.
4	Determine which spare part *i* at ship *j* has the highest reduced probability of backorders per invested euro. Add this spare part in the next iteration.	Calculate the marginal probability of backorder reduction per invested euro for each item at the ships with the simulated PBO. $\Delta_{ij} = \dfrac{PBO(s_{ij})}{c_i} \text{ for all spart} i, \text{ship } j$ Add the spare part with the highest reduced probability of backorders per invested euro in the next iteration of Simlox simulation.
5	Repeat step 4, until one ship reaches the customer's requested target. Then exclude the ship which reached the target from the spare part determination and repeat step 4.	The objective is to allocate spare parts to the ships to ensure the availability target. So if one ship reaches this target then this ship should be excluded from step 4 determinations and focus should be places on the other ships. Repeat step 4, but add new spare parts only to the ships *j* which have not reached the mission availability target yet.
6	Repeat step 5, until all ships have reached the requested target	Stop procedure when all the ships have reached the mission availability target.

The assumed risk of this procedure is that the spare part stock of the customer's site and Thales are not optimal. This will result in imbalance of spare parts stock levels and extra spare parts onboard the ships with the consequence that the initial spare parts costs are higher than necessary.

The cost/availability curve is plotted in Figure 28. The mission availability is simulated with the product structure of Figure 7 in section 2.1.1, supply chain of Figure 10 in section 3.2.3, the time parameters: repair lead-time 14 days & return shipment of 21 days and worst case ship deployment of Figure 18 in section 6.2.1. The vertical axis is the average availability of three ships, like in section 6.2.2. This is the operational or mission availability. The horizontal is the costs of the initial spare parts. From these curves it is clear that the mission availability is consequently lower compared to the operational availability. This is because the mission availability is calculated over the mission time and the operational over the mission plus the time when a ship is in the harbor.

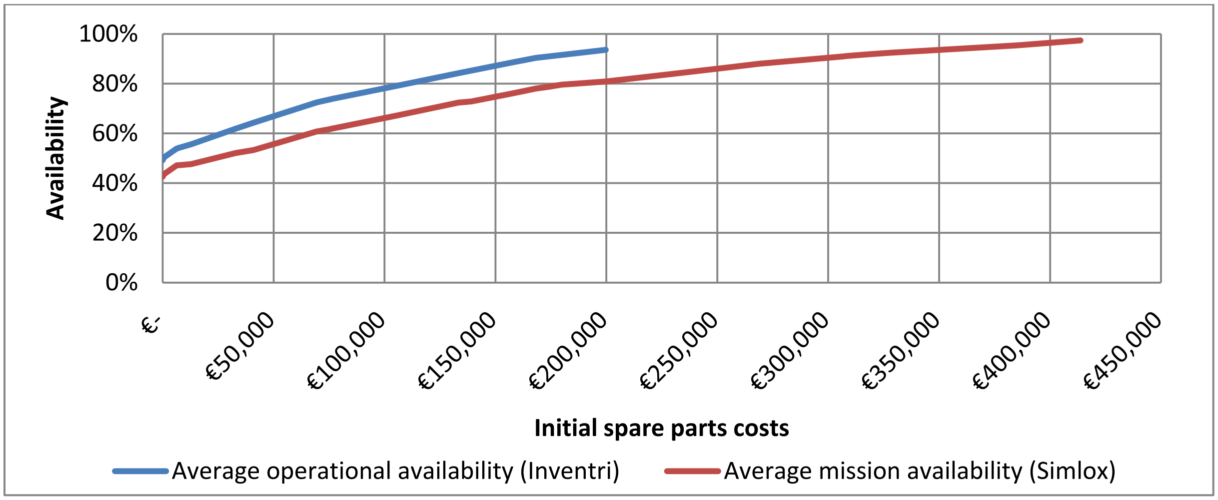


Figure 28: Procedure 1 Cost/Availability curve

The total cost when Inventri stops in this procedure is about €199.000. Thirteen more iterations have to be done with an additional cost of more than €200.000. With an additional €200.000 all the ships have reached the target. The total initial spare part costs are approximately €410.000 to reach the requested mission availability per ship. In this procedure it is clear that the slope of average mission availability is less than the operational availability.

6.4.2 Procedure 2

In this research two types of ships are used, namely mission ships and short-mission ships. This procedure will use this division. The starting point will be calculated using two separate Inventri models: a mission ship model and a short-mission ship model. The supply chains of those models are like Figure 29 and Figure 30.

Figure 29: Supply chain of the short-mission ship model of Inventri

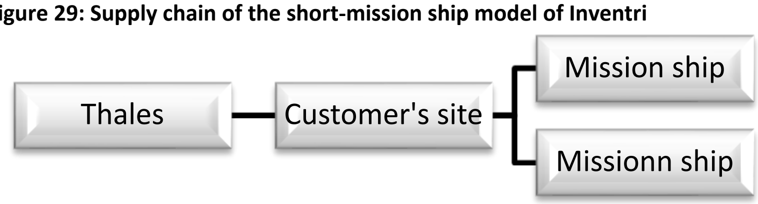


Figure 30: Supply chain of the mission ship model of Inventri

The logic behind this separation is that the mission ships produce the most failure demand and has lower average mission availability down, because of the larger Annual Operating Hours. Especially in this case study because of the large difference between annual operational hours of the mission ships and the short-mission ships. This means that the average mission availability could be lifted by the non-mission ship. By calculating the mission ships and short-mission ship operational availability separately, there has to be done more spare parts allocation for the mission ships. This procedure should be closer to the requested mission availability than the previous procedure. When both operational availabilities are calculated then the spare part allocation of the mission ship will be adopted into Simlox. When the short-mission ships calculation has any ship allocations then these spare parts will also be adopted into Simlox. This way both spare parts allocation are combined to a baseline Simlox simulation. At this point this transition procedure will shift to Simlox and use the simulated variables and the simulated mission availability. The simulated PBO of Simlox per invested euro determines where the next spare part will be allocated. The spare parts will only be allocated at the ships, when the shift is made to Simlox. We will use the single-site greedy allocation procedure in Simlox with the simulated variables, until the requested mission availability of all the ships is reached. The procedure is described in more detail in Table 25. In this procedure the PBO could be used which Simlox returns in the output.

Table 25: Allocation procedure 2

Step	Activity	How
1	Calculate the starting point.	Calculate the spare part stock list by Inventri. Run two Inventri models. A mission ship model and non-mission ship model. Both Inventri models are calculated by the customer requested availability.
2	Run baseline simulation.	Combine the mission ship spare part list and the ship allocation spare parts of the short-mission ship (Inventri). Simulate this combined model in Simlox as a baseline simulation.
3	Determine which spare part *i* at ship *j* has the highest reduced probability of backorders per invested euro. Add this spare part in the next iteration.	Calculate the marginal probability of backorder reduction per invested euro for each item at the ships with the simulated PBO. $\Delta_{ij} = \dfrac{PBO(s_{ij})}{c_i}$ for all spart i, ship j Add the spare part with the highest reduced probability of backorders per invested euro in the next iteration of Simlox simulation.
4	Repeat step 3, until one ship reaches the customer's requested target. Then exclude the ship which reached the target from the spare part determination and repeat step 3.	The objective is to allocate spare parts to the ships to ensure the availability target. So if one ship reaches this target then this ship should be excluded from step 3 determinations and focus should be places on the other ships. Repeat step 3, but add new spare parts only to the ships *j* which have not reached the mission availability target yet.
5	Repeat step 4, until all ships have reached the requested target.	Stop procedure when all the ships have reached the mission availability target.

Using this procedure we expect the same expectations as when using procedure 1; that the assumed risk of this procedure is that the spare part stock of the customer's site and Thales are not optimal. This will result in imbalance of spare parts stock levels and extra spare parts onboard the ships with the consequence that the initial spare parts costs are higher than necessary. Still this procedure should calculate spare parts allocation faster, because the shift should be much later than the previous procedure. This procedure must be as least as good compared to the previous procedure.

The cost/availability curve is plotted in Figure 31. The mission availability is simulated with the product structure of Figure 7 in section 2.1.1, supply chain of Figure 10 in section 3.2.3, the time parameters: repair lead-time 14 days & return shipment of 21 days and worst case ship deployment of Figure 18 in section 6.2.1. . The vertical axis is the average availability of three ships, like in section 6.2.2. This is the operational or mission availability. The horizontal is the costs of the initial spare parts.

From these curves it is clear that the mission availability crosses the operational availability. This is because the Inventri model is only derived from the mission ships and the average mission availability derived from the average of all three ships. This means that the short-mission ship is lifting the average.

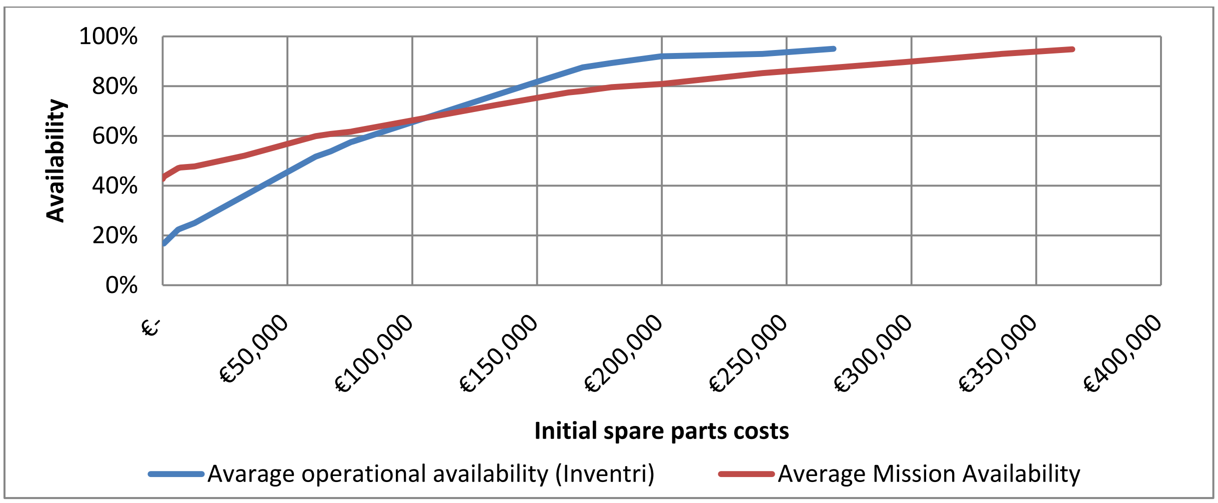


Figure 31: Procedure 2 Cost/Availability curve

The total cost when Inventri stops when using this procedure is about €275.000. Five more iterations have to be made with a total cost of about €100.000. With an additional €100.000 all the ships have reached the mission availability target. The total spare part costs are approximately €365.000 to reach the requested mission availability per ship.

6.4.3 Procedure 3

In paragraph 6.3 the proposition that the delta operational PBO is linearly proportional to the delta mission availability is confirmed. That means that the allocation procedure of Inventri could be used to determine the allocation choices for the mission availability.

The starting point of this procedure is determined by the allocation list of Inventri. The spare parts allocation list is calculated by Inventri with a operational availability target of 99,99%. We assume in this procedure that the short-mission ship has a higher operational availability than the mission ships. The short-mission ship will lift the average operational availability. The VARI-METRIC will allocate the spare parts to the short-mission ship when the mission ship operational availabilities are approximately leveled. Therefore the iteration must be found from the spare parts allocation list where the short-mission ship is allocated too. This could be performed manually. This case has large difference between the annual operating hours of the mission and the short mission ships. Thus the spare part allocation for the operational availability target should be much closer to the mission availability target. Therefore the spare parts allocation is better performed, because VARI-METRIC also allocates the shore locations. The Simlox spare part allocation list will be the spare part allocation list until the short-mission ship is allocated too. At this point this transition procedure will shift to Simlox and use the simulated variables and the simulated mission availability. The simulated PBO of Simlox per invested euro determines where the next spare part will be allocated. The spare parts will only be allocated at the ships, when the shift is made to Simlox. We will use the single-site greedy allocation procedure in Simlox with the simulated variables, until the requested mission availability of all the ships is reached. The procedure is described in more detail in Table 26. In this procedure the PBO could be used which Simlox returns in the output.

Table 26: Allocation procedure 3

Step	Activity	How
1	Calculate and determine the starting point	Calculate the spare part stock list by Inventri. The target of Inventri is 99.99%. Determine when short-mission ship is added a spare part too.
2	Run baseline simulation	Run the simulation with the spare part list until the iteration where the short-mission ship is added a spare part too. In other words, the spare part list of Inventri may have spare parts on the locations: mission ship, customer's site and Thales. The list does not have short-mission ship spare parts allocations.
3	Determine which spare part *i* at ship *j* has the highest reduced probability of backorders per invested euro. Add this spare part in the next iteration.	Calculate the marginal probability of backorder reduction per invested euro for each item at the ships with the simulated PBO. $\Delta_{ij} = \frac{PBO(s_{ij})}{c_i} \text{ for all spart } i, \text{ship } j$ Add the spare part with the highest reduced probability of backorders per invested euro in the next iteration of Simlox simulation.
4	Repeat step 3, until one ship reaches the customer's requested target. Then exclude the ship which reached the target from the spare part determination and repeat step 3.	The objective is to allocate spare parts to the ships to ensure the availability target. So if one ship reaches this target then this ship should be excluded from step 3 determinations and focus should be placed on the other ships. Repeat step 3, but add new spare parts only to the ships *j* which have not reached the mission availability target yet.
5	Repeat step 4, until all ships reaches the requested target	Stop procedure when all the ships have reached the mission availability target.

This procedure could probably be performed quite easily and relatively fast. When the allocation choices are made by Simlox and Table 26, then there is a small risk of understock the shore stock locations.

The cost availability curve is plotted in Figure 32. The mission availability is simulated with the product structure of Figure 7 in section 2.1.1, supply chain of Figure 10 in section 3.2.3, the time parameters: repair lead-time 14 days & return shipment of 21 days and worst case ship deployment of Figure 18 in section 6.2.1. The vertical axis is the average availability of three ships, like in section 6.2.2. This is the operational or mission availability. The horizontal is the costs of the initial spare parts. Note that the average operational availability ends much closer to the average mission availability. This is due to the little extra iteration to the requested mission availability.

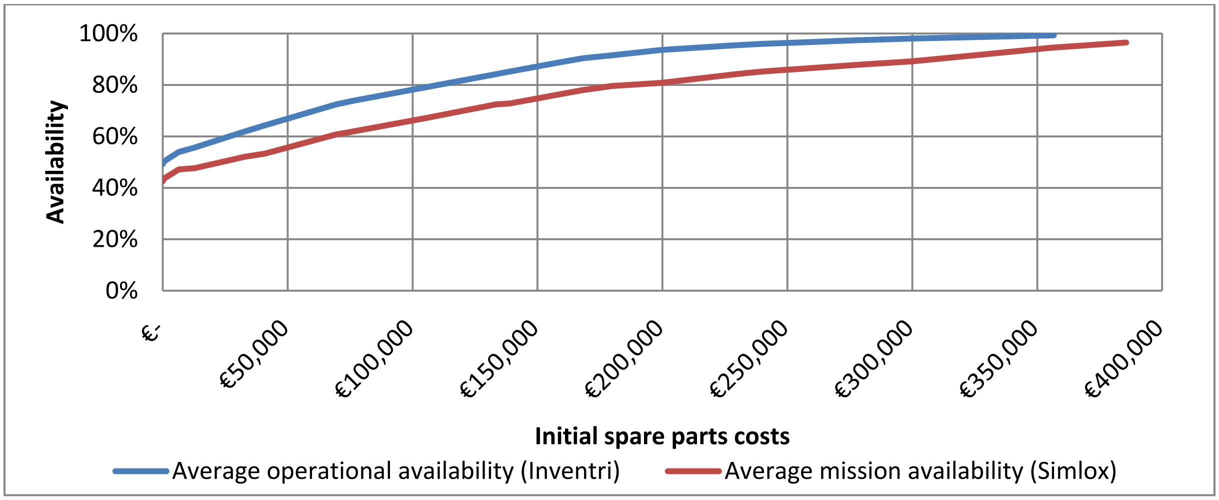


Figure 32: Procedure 3 Cost/Availability curve

The total cost when Inventri stops when using this procedure is approximately €355.000. Five more iterations have to be made with a total cost of about €30.000. With an additional €30.000 all the ships have reached the mission availability target. The total spare part costs are approximately €385.000 to reach the requested mission availability per ship.

6.4.4 Procedure VARI-METRIC choices

In paragraph 6.3 the proposition that the delta operational PBO is linearly proportional to the delta mission availability is confirmed. That means that the allocation procedure of Inventri could be used to determine the allocation choices for the mission availability. When this procedure is used, the allocation choices of Inventri could speed up the spare parts allocation process. The allocation of shore stock locations could also be used, because Inventri considers the shore location optimal and extra calculations are not necessary. Therefore the chance that the shore and depot are understocked is minimized.

The starting point of this procedure is determined by the allocation list of Inventri. The spare parts allocation list is calculated by Inventri with a target availability of 99,99%. These spare part allocations are implemented into Simlox. The simulations are evaluated to determine at which allocation the requested mission availability is reached. This procedure is solely based on the allocation choices of VARI-METRIC.

The cost availability curve is plotted in Figure 33. The mission availability is simulated with the product structure of Figure 7 in section 2.1.1, supply chain of Figure 10 in section 3.2.3, the time parameters: repair lead-time 14 days & return shipment of 21 days and worst case ship deployment of Figure 18 in section 6.2.1. . The vertical axis is the average availability of three ships, like in section 6.2.2. This is the operational or mission availability. The horizontal is the costs of the initial spare parts. Note that the average operational availability ends much closer to the average mission availability. This is due to little extra iteration to reach the requested mission availability.

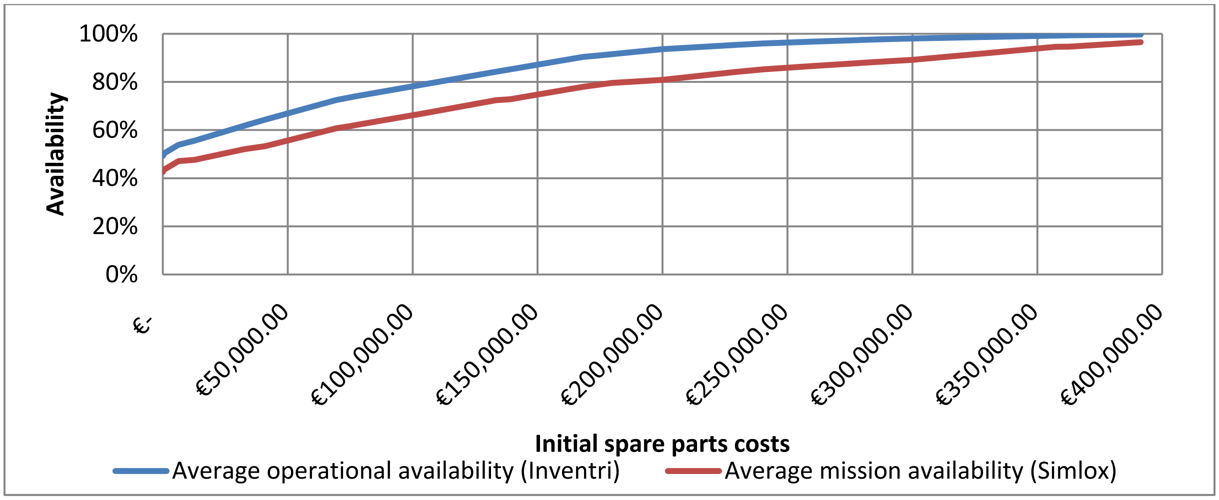


Figure 33: Procedure VARI-METRIC choices Cost/Availability curve

The total cost when Inventri stops when using this procedure is about €390.000. There is no extra iteration necessary, because this procedure is based on the choices of VARI-METRIC (Inventri). The total spare part costs are approximately €390.000 to reach the requested mission availability per ship.

6.5 Conclusion

The probability of backorders reduction per invested euro is made plausible linearly proportional to the mission availability addition.

This research made it plausible that the delta PBO is linearly proportional to the delta mission availability in all the stock locations. This results that the choices of the VARI-METRIC model could be used to allocate the spare parts to multi-echelon stock locations.

Thales uses the software tools Simlox and Inventri. Inventri calculates the spare parts to an operational availability and Simlox could evaluate the spare parts stock levels towards the mission availability. The conclusion could be made that Simlox is a well-structured simulation tool.

When the average mission availability and the average operational availability are compared then there the difference is approximately 10%. The comparison is made by the worst case mission deployment. This is logical, because mission availability is measured only using the mission length. This means that operational availability is also measured when the ship is in the harbor.

In the last paragraph four procedures are elaborated and have their own characteristics. These characteristics will be evaluated more in depth in chapter 7.

7 Transition procedure evaluation

We evaluate the four explained subtracted procedures in paragraph 6.4 in this chapter by evaluating different criteria. With different criteria the quality of the procedure will be estimated. The evaluation criteria are:

- As low as possible total initial spare parts cost
- Minimum mission availability per ship of 93.3%
- Minimum 95% mission lower percentile of 80% per ship
- As low as possible calculation time
- As little as possible impact to MTBF variation

The first four criteria are evaluated based on the outcomes in previous chapters. The fifth criterion needs an extra experiment to evaluate the impact to the mission availability by MTBF variations. The impact by variation of the MTBF is evaluated among the procedures, but also among the different scenarios. This chapter will answer the research question:

What is the impact of the allocation procedures in respect to MTBF variations?

This chapter is divided into multiple paragraphs. Firstly, we will discuss the allocation procedures based on the first four criteria in paragraph 7.1. Secondly, we will discuss the last criteria and will evaluate the impact procedures in respect to the MTBF variation in paragraph 7.2. Finally, the key findings are presented in paragraph 7.3.

7.1 Procedure results evaluation

The mission availability is simulated with the product structure of Figure 7 in section 2.1.1, supply chain of Figure 10 in section 3.2.3, the time parameters times of chapter 5 and worst case ship deployment of Figure 18 in section 6.2.1.

Thales has demands for their spare parts allocations. The important and relevant demands for this research are the mission availability and the impact by MTBF variation. As mentioned earlier, the mission availability of each ship must be at least 93.3%. The procedures of paragraph 6.4 are calculated with the key scenarios of chapter 5.

Thales does not know what the mission lower percentile does when missions are simulated. Therefore this is investigated in this research. The demand of Thales is that with confidence of 95% the mission availability must be at least 80%. Simlox simulates the mission availability and could give a mission lower percentile output. The percentile of Simlox is the lower percentile on mission time accomplished per ship. The lower percentile *Xp* at level *p* of a stochastic variable *X* is in general defined as the largest value *x* where $\mathrm{Prob}(X \geq x) \geq p$. The lower percentile of Simlox could be interpreted as representing a worst case scenario with a confidence of 95%. (Systecon, 2011) This means that the variances over the replications are small.

Besides the demanded lower percentile, Thales strives for the lowest possible cost. The preferred procedure has the lowest costs and minimal mission availability of 93.3%. Thales acknowledges the problem that lower costs has consequences e.g. the impact of MTBF variation towards the mission availability. Therefore, Thales is willing to pay more for a solution where consequences toward MTBF variations are minimized.

The final criterion is the calculation time. Thales prefers a quick and easy as possible procedure that has the best outcome. A simulation run with 25000 runs could take more than 60 minutes. When a spare parts allocation is determined with Simlox then it needs a small calculation like mentioned in paragraph 6.4. All iterations need an evaluation and calculation which could produce labor-intensive procedures. The simulations can only be run with operator present. The amount of extra iterations in Simlox is the measurement of this criterion. The results of these criteria per procedure are displayed in Table 28. The key findings are:

- Overall, the average mission availability is high
- Procedure 2 has overall the lowest costs
- Maximum cost difference among procedures is €73,764.46
- All procedures have a mission lower percentile with 95% confidence are more than 80%
- Procedure 1 and 2 are the most labor-intensive procedures

Overall, the average mission availability is high

The average mission availability is typically high. Almost all the percentages are more than 1.5% higher than the target. This is partially due to the short-mission ship. This ship scores most of the time a few percentages higher than the mission ships. Therefore Thales could decide two things. They can subtract spare parts so that the total initial spare parts costs are lower, but are still higher than the mission availability target. Alternatively, Thales could do nothing and the average mission stock creates higher mission availability and could take some variations.

Procedure 2 has overall the lowest costs

The total initial spare parts costs are mostly lower at procedure 1 and 2. Both procedures takes the most extra iterations thus allocates more spare parts at the ships. Thus, ship allocation is more beneficial towards the mission availability compared to the operational availability. The difference between lowest cost (best solution) and cost of the procedures 1 and 2 can be calculated (Table 27). The total difference between procedure 2 solutions and the best solutions is smaller compared procedure 1 solutions and the best solutions. Therefore is procedure 2 the most cost-effective solution.

Table 27: Costs difference between best solution and procedure 1 and 2

Scenario	Best solution	Solution procedure 1	Difference between best solutions and solution procedure 1	Solution procedure 2	Difference between best solutions and solution procedure 2
21-14	€ 364,465.56	€ 413,682.70	€49,217.14	€ 364,465.56	€ -
21-21	€ 385,626.54	€ 385,626.54	€ -	€ 385,626.54	€ -
21-49	€ 385,177.19	€ 385,177.19	€ -	€ 405,157.59	€ 19,980.40
35-14	€ 442,188.21	€ 442,188.21	€ -	€ 462,168.61	€ 19,980.40
35-42	€ 442,188.21	€ 462,168.61	€19,980.40	€ 442,188.21	€ -

Procedure VARI-METRIC choices is based on the operational allocation procedure of Rustenburg and the total initial costs are almost all the time higher than the other procedures. Notable: the higher cost results in higher average mission availability.

Maximum cost difference among procedures is €73,764.46

Procedure VARI-METRIC choices is in almost all the time the most expensive procedure. The maximal difference among the other procedures can be €73,764.46. More labor-intensive procedure could save in this case study at most €73,764.46.

All procedures have a mission lower percentile with 95% confidence are more than 80%

The minimal lower percentile of all the solutions is larger than 80%. The minimal lower percentile over the ships means that the lowest lower percentile of the ships is more than 80%. The minimal lower percentile is minimal 83.9% and sometimes even 90%. This means that the variances over the replications are small.

Procedure 1 and 2 are the most labor-intensive procedures

This case procedure 1 needs more than 10 extra iterations to meet the target and procedure 2 more than 6 extra iterations to meet the target. The calculation time of procedure 1 and 2 are thus much higher compared to procedure 3 and procedure VARI-METRIC choices. In a larger case this could result in much more extra iterations.

The results of these criteria per procedure are displayed in Table 28.

Table 28: Criteria results of each procedure per scenario

		Procedure 1	Procedure 2	Procedure 3	Procedure VARI-METRIC choices
Return shipment 21 days + Repair lead-time 14 days	Total initial spare parts costs	€413,682.70	€364,465.56	€385,626.54	€391,353.14
	Average mission availability	97.39%	94.85%	96.46%	96.54%
	Minimum 95% lower percentile	91.54%	85.45%	89.11%	89.26%
	Extra iterations	14	6	3	1
Return shipment 21 days + Repair lead-time 21 days	Total initial spare parts costs	€385,626.54	€385,626.54	€393,292.66	€393,742.01
	Average mission availability	96.26%	96.26%	96.29%	96.33%
	Minimum 95% lower percentile	88.32%	88.32%	88.65%	88.61%
	Extra iterations	13	10	2	1
Return shipment 21 days + Repair lead-time 49 days	Total initial spare parts costs	€385,177.19	€405,157.59	€405,157.59	€405,606.94
	Average mission availability	94.97%	95.85%	95.85%	95.93%
	Minimum 95% lower percentile	84.22%	86.93%	86.93%	87.06%
	Extra iterations	12	10	2	1
Return shipment 35 days + Repair lead-time 14 days	Total initial spare parts costs	€442,188.21	€462,168.61	€470,693.72	€476,869.67
	Average mission availability	96.17%	96.32%	97.01%	97.33%
	Minimum 95% lower percentile	87.39%	87.91%	90.01%	89.82%
	Extra iterations	10	12	4	1
Return shipment 35 days + Repair lead-time 42 days	Total initial spare parts costs	€462,168.61	€442,188.21	€491,123.47	€515,952.67
	Average mission availability	95.99%	95.60%	96.87%	97.35%
	Minimum 95% lower percentile	85.27%	83.90%	88.88%	89.92%
	Extra iterations	11	10	5	1

7.2 Procedure evaluation by variation of the MTBF

Thales indicated that they rather have a more expensive solution which is less sensitive to MTBF variation, than a cheap solution which is more sensitive to MTBF variation. Thales does not know how reliable the MTBF data are. This paragraph will explain which procedure of paragraph 6.4 is the most sensitive to MTBF variations and which procedure is less sensitive. The expectation is that the more expensive solutions should cope MTBF variation better than the cheap solutions. M.C. van Zwam stated in his master thesis that adding spare parts and reducing time parameters will result is less sensistivity in variation of the annual operating hours (AOH). (Zwam, 2010) The MTBF and the AOH are directly related. Failure demand per year is equal to the MTBF divided by the AOH. Therefore the expectation is also that reducing time parameters and stocking extra parts will lead to less sensitivity.

An experiment is performed to eveluate the impact of MTBF changes. In this experiment we used the product structure of Figure 7 in section 2.1.1, supply chain of Figure 10 in section 3.2.3, the time parameters times of chapter 5, worst case ship deployment of Figure 18 in section 6.2.1 and the solutions of the procedures of section 7.1. The MTBF is decreased in steps of 5% to 75%. Thus, the MTBF is multiplied with 95%, 90%, 85%, 80% and 75%. The MTBF of all the LRUs and SRUs in product structure of Figure 7 in section 2.1.1 are decreased.

The expectation is that the mission ships will be more sensitive to MTBF variation, because they have longer time parameters than the short-mission ships. The restriction is that all the ships must be more than 93.3% available. Therefore, it makes sense to scope only the mission ships, because the mission ships are more sensitive to MTBF variatons as could be read in Figure 34. The vertical axis is the mission availability per ship. The horizontal axis is the MTBF decrease rate, whereby the MTBF is multiplied by the percentage. Figure 34 is a typical figure of the sensitivity of the MTBF variations. The other solutions are checked on the same way and the missions ships are more sensitive in all the solutions. Therefore the solution is to scope the mission ships, because they are the most critical.

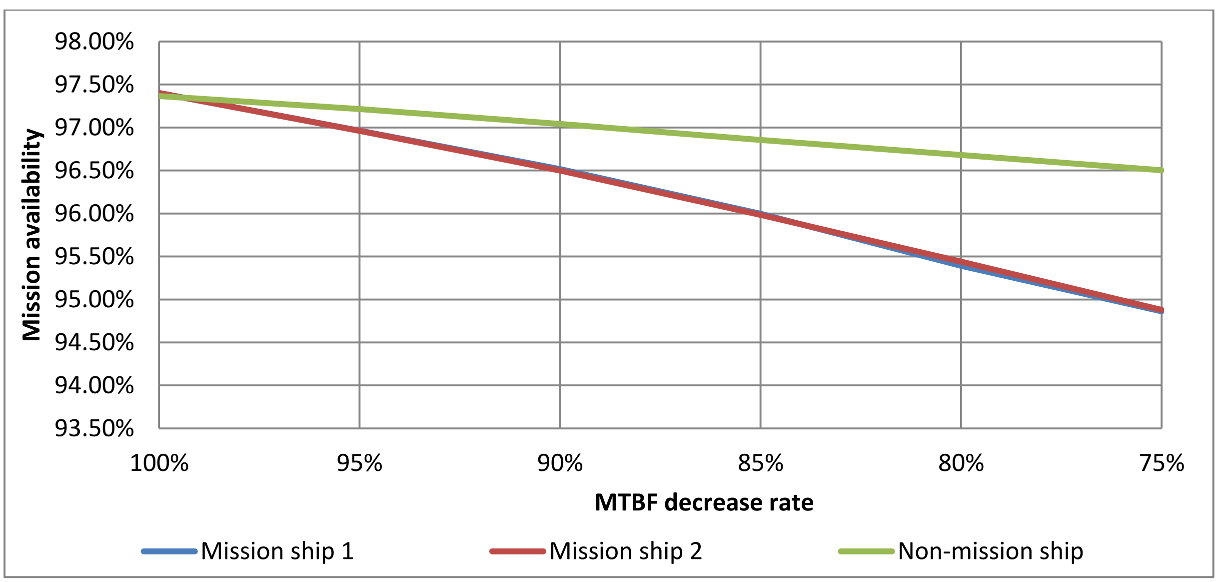


Figure 34: Typical differences among procedures in respect to MTBF variation

Obviously, the antenna mission availability is dependent on the antenna MTBF. When the MTBF of the antenna is decreased, then mission availability will also decrease. In this research we assume that only the MTBF of antenna is decreased and that the MTBF of rest of the Smart-L stays the same. All the MTBFs of the LRUs and SRUs in the Smart-L antenna are modified. The target will be modified following the same fomulas in section 2.1.1. The new mission availability targets are shown in Table 29. The complete derivation could be found in appendix M.

Table 29: New target in respect of MTBF variation

MTBF decrease rate	New mission availability target
100%	93.28%
95%	93.18%
90%	93.08%
85%	92.98%
80%	92.89%
75%	92.81%

Preferable is that the solution will not decrease below the target when the MTBF is modified. Whether the solution will decrease below the target is dependent on the spare parts stock levels of the solutions and probably the time parameters. Therefore the procedures are seperatly investigated over the five scenarios, which have different time parameters. The time parameters in Figure 35 till Figure 38 are displayed as followed:

- 21-14: Return shipment time 21 days and repair lead-time 14 days
- 21-21: Return shipment time 21 days and repair lead-time 21 days
- 21-49: Return shipment time 21 days and repair lead-time 49 days
- 35-14: Return shipment time 35 days and repair lead-time 14 days
- 35-42: Return shipment time 35 days and repair lead-time 42 days

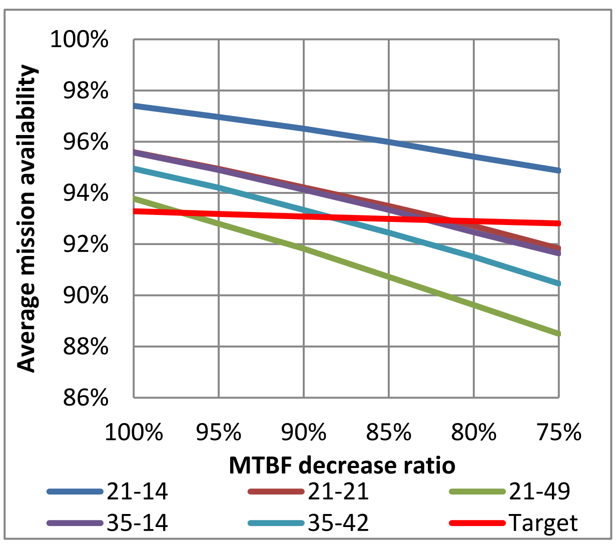


Figure 35: MTBF variation among scenarios in procedure 1

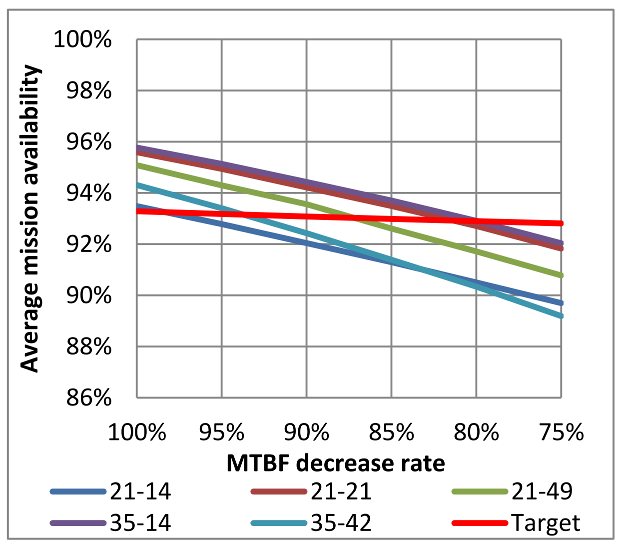


Figure 36: MTBF variation among scenarios in procedure 2

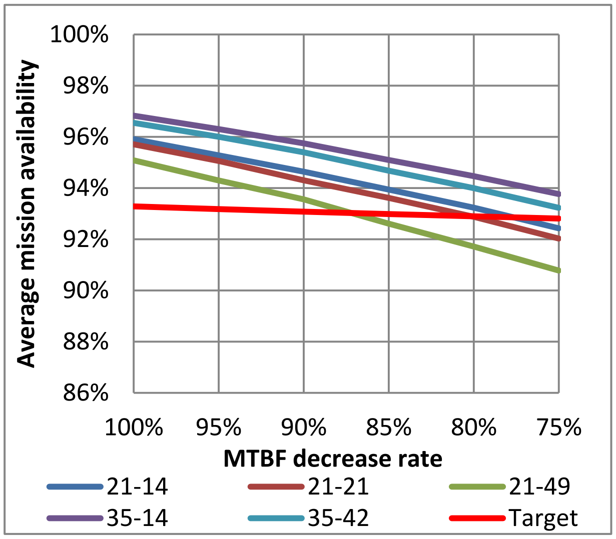


Figure 37: MTBF variation among scenarios in procedure 3

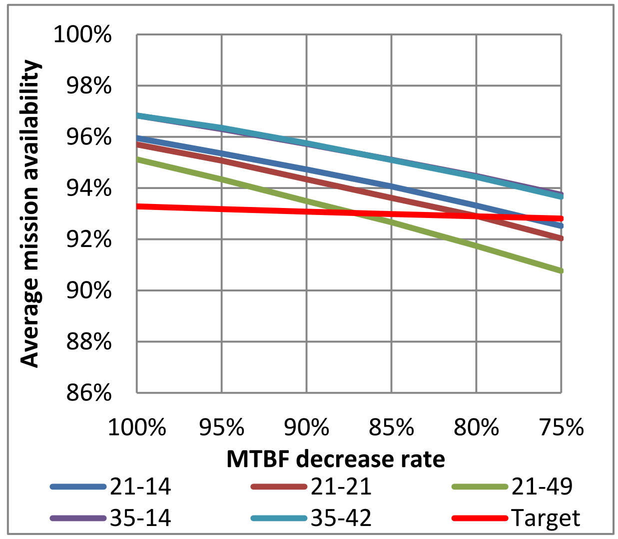


Figure 38: MTBF variation among scenarios in procedure VARI-METRIC choices

In Figure 35 till Figure 38 only the average missions ships are plotted in respect of MTBF variations. The vertical axis is the average mission ship availability (the avarage availability of two mission ships). The horizontal axis is the MTBF variations, whereby the MTBF multiplied by the percentage. The solutions of procedure 1 and 2 are more sensitive for MTBF variations than procedure 3 and procedure VARI-METRIC choices. The first crossing with the target is in procedure 1 and 2 just after the 100%, because of the low average mission availability. The first crossing in procedure 3 is about 87.5%. The reason of this difference is that procedure 3 and procedure VARI-METRIC choices generate higher mission availability solutions than the other procedures.

When the four procedures are compared than procedure 3 and procedure VARI-METRIC choices cope the best to MTBF variations. The main differences between the procedures is that procedure 3 and procedure VARI-METRIC choices keep allocating the shore stock locations. Whereby procedure 1 and 2 stop earlier and continue only allocating the ships. By doing so procedure 1 and 2 have lower initial spare parts costs, but also lower mission availabilities. When the mission availability is higher the system could cope better to decreased MTBFs.

There is no clear difference in availability by adjusting the time parameters. Scenario 35-42 does not decrease much more than 21-14. Therefore it cannot be concluded that the MTBF variation could be influenced by the time parameters. There is only one clear difference in procedure 2. The largest time parameters decreases the most compared to the others and crosses the 21-14 line. This is probably not caused by the time parameters, but by the understocked shore stock locations. When the time parameters are an issue in this procedure then the line 21-49 should behave more aggressive than it does in Figure 36.

There seems to be another factor which influences the availability when the MTBF is modified. It seems that the mission availability level has possitive influence to the MTBF variations. The higher the mission availability solution of paragraph 7.1 then the larger the slope over the MTBF variation is. This seems to be a non-linear relation. It could not be determined in this experiment what the cause is.

7.3 Conclusions

The procedures are evaluated in this chapter. This is done by using the scenarios of chapter 5. The procedures are evaluated on five criteria, namely:

- As low as possible total initial spare parts cost
- Minimum mission availability per ship of 93.3%
- Minimum 95% mission lower percentile of 80% per ship
- As low as possible calculation time
- As little as possible impact to MTBF variation

All the procedure could create a solution whereby the minimum mission availability is 93.3% per ship and have a 95% mission lower percentile of 80% per ship. All the solutions score much higher than the targets. The average mission availability is often more than 1.5% higher. The minimum 95% confidence mission lower percentile of the ships is at least 4% higher and even sometimes more than 10%.

Thales should use procedure 3, because it is less sensitive to MTBF variations, but cost slightly more

The last criterion is what the impact is on the mission availability of the procedure when the MTBF is decreased. Thales experience that the MTBF data is not reliable due to different environments. The conclusion of the conducted experiment is that procedure 3 is less sensitive to MTBF variations, due to higher average mission availability solutions. Thus, the slightly more expensive procedure copes better to MTBF variations. There are scenarios in procedure 1 and 2 which descend below the minimum mission availability target when MTBF decreased to approximately 98%. The first scenario in procedure 3 descend below the minimum mission availability target is when the MTBF is decreased to approximately 87.5%. Thus the third procedure could cope approximately 10% better to MTBF variation due to higher average mission availability solutions. Therefore Thales should use procedure 3.

Procedure 2 generates overall the most cost-effective solutions

Procedure 2 generates overall the most cost-effective solutions. All the ships have a minimum mission availability of 93.3%, but these procedures could take some time. Compared to the third procedure these are more labor-intensive procedures (more iterations). Thus with extra labor the solutions could get cheaper.

The mission ships are more sensitive to MTBF variation than the short-mission ships. This is logical, because the mission ships have much larger annual operating hours. The demand is higher thus the mission availability lower when the MTBF is decreased. After all, higher failure demand needs more spare parts stock to preserve the mission availability.

8 Conclusion & recommendations

In this final chapter conclusions are drawn, and recommendations are presented. Also the limitations of this research are pointed out and opportunities for new research are given. The sub research questions of paragraph 2.2 and the main research question are answered in paragraph 8.1. We will recommend Thales in paragraph 8.2. This research has some limitations, these are presented as assumptions in paragraph 8.3. We will suggest opportunities for new researches in paragraph 8.4.

8.1 Conclusions

The following sub research questions are generated to answer the main research question. In this paragraph all the questions will be answered. The first research question is:

1. *How is the service supply chain of the Smart-L ELR structured?*
    a. *What is a Performance Based Logistic (PBL) contract?*
    b. *What is the supply chain of the antenna of the Smart-L ELR?*
    c. *How is the repair process organized for the Smart-L ELR?*

The service supply chain will change when the service contracts shift from a traditional contract to a "contract for availability". Contract for availability is better known as a Performance Based Logistic (PBL) contract. Thales is responsible for the maintenance of the system when a PBL contract is sold. This implicates that Thales will repair the spare parts and that Thales trains and certifies the crew maintainer who maintains the system during missions. The case study consists of a 3-echelon, multi-indenture supply network with three ships, one shore stock location and one original equipment manufacturer (Thales). The spare parts supply is calculated with Inventri (VARI-METRIC) for a traditional service contract condition, which calculates average supply availability as Key Performance Indicator (KPI). For a PBL contract the KPI will be the mission availability per ship. A procedure is developed, which transforms step-by-step the operational availability solution into a mission availability solution. The second research question is generated to get a better understanding of the supply availability calculation and allocation procedure of VARI-METRIC.

2. *How is the literature of METRIC and VARI-METRIC applicable to the case study of the Smart-L ELR antenna?*

The VARI-METRIC model is an extension of the METRIC model. The VARI-METRIC model allocates the spare parts in a steady state until minimal average supply availability target is reached Maximizing the supply availability is approximately equivalent to minimizing the expected backorders. The probability of backorders of the parts can simply be reduced by adding spare parts. The choice which spare parts should be allocated is done by the marginal probability of backorders reduction per invested euro. It is also possible to decrease the repair lead-time and shipment cycle lead-time to reduce the total initial spare parts costs.

3. *What are the optimal spare parts time parameters with Inventri (VARI-METRIC) and what influence has the repair lead-time on the spare parts inventory cost?*

In the third research question the influences of the repair lead-time shipment cycle lead-time is studied. We expect that by decreasing the repair lead-time, the total initial spare parts costs will also decrease. The total amount of LRU spare parts costs of the supply can be reduced, but components spare parts are necessary at Thales. The component costs are relatively low compared to the LRU costs. The repair lead-time reduction has barely influence to initial component costs. With the conclusion of this research question five scenarios were chosen. Firstly, the cheapest scenarios are chosen in a steady state. Secondly, the scenarios which cost slightly more but have a larger repair lead-time. This could be beneficial to the delivery reliability.

4. *How to step-by-step transform the VARI-METRIC (operational availability) solution to a mission availability solution?*

The mission availability is calculated with the simulation tool called Simlox. Simlox is a proven simulation tool and can calculate the mission availability and the probability of backorders. The Inventri (VARI-METRIC) solution is compared to the worst case mission deployment for the mission availability. This comparison results in a shocking difference of more than 10%. Therefore, a transition must be made from average supply availability to the mission availability per ship. The proposition that the delta EBO is linearly proportional to the delta mission availability is made plausible for a 3-echolon structure. This means that the choices, which Inventri (VARI-METRIC) makes, can be used to allocate the spare parts, until the mission availability target per ship are reached. In this research there are four allocation procedures constructed, whereby the transfer point from Inventri to Simlox is different per procedure. The first procedure calculates the supply availability for requested targets and subsequently, uses Simlox to allocate the spare parts following a single-site METRIC allocation process, whereby the ships together are considered as single-site. The second procedure calculates the supply availability of the mission ships and the short-mission ships separately by Inventri. The mission ship allocation is combined with the ship's spare parts of the short-mission ship allocations. Subsequently, Simlox is used to allocate the spare parts following a single-site METRIC allocation process, whereby the ships together are considered as single-site. In the third procedure VARI-METRIC will allocate the spare parts to the ships until spare parts are allocated the short-mission ship. Subsequently, this procedure uses Simlox to allocate the spare parts following a single-site METRIC allocation process, whereby the ships together are considered as single-site. The last procedure is based solely on the allocation choices of VARI-METRIC.

5. *What is the impact of the allocation procedures in respect to MTBF variations?*

Thales has multiple criteria factors for the solutions. The solutions should have as low as possible total initial cost, a minimal mission availability of 93.3%, a 95% confidence lower percentile of 80% and as little as possible impact to variations of the MTBF. In addition the calculation time is added as criterion to qualify the allocation procedures. All the procedures generate spare parts allocations which have mission availability of more than 93.3% per ship and 95% confidence mission lower percentile of 80%. Total initial spare parts costs of procedure 2 is overall the lowest, which allocates more spare parts to the ships then procedure 3. On the other side procedure 3 is a lower labor-intensive procedure and copes much better to variations of the MTBF. Procedure 3 can cope more than 10% variations of the MTBF without descent below the mission availability target due to higher average mission availability solutions.

<u>What is the optimal spare parts allocation procedure of the antenna of the Smart-L ELR to ensure that the minimum mission availability constraint is satisfied, the cost are minimized, considering mission profiles, annual operational hours, and repair lead?</u>

The conclusion of this research is that procedure 3 is less sensitive to MTBF variations, due to higher average mission availability solutions. Thus, the slightly more expensive procedure copes better to MTBF variations. The first scenario in procedure 3 descend below the minimum mission availability target is when the MTBF is decreased to approximately 87.5%. The third procedure can cope for this case at least to 12.5% lower Smart-L antenna MTBF values due to higher average mission availability solutions, but costs maximal 11% more.

Therefore the best procedure for Thales is procedure 3. The cheapest scenario within procedure 3 is the repair lead-time of 14 days and a monthly shipment cycle. This scenario of the Smart-L case can cope approximately 22.5% lower antenna MTBF values and costs only 5.8% more compared to the cheapest solution.

8.2 Recommendations

The objective of this research is to find an optimal spare parts allocation procedure for the antenna of the Smart-L ELR. An optimal spare parts allocation procedure involves minimizing the cost and maximizes the mission availability constraint with a minimum availability target for the Smart-L ELR. Simultaneously it should take into account the mission length, annual operational hours, repair lead-time, of the multi-indenture antenna. In addition Thales prefers an allocation procedure which is "robust". The solutions of the procedure are as little as possible sensitive for variations of the Mean Time Between Failure. Thales prefers solutions which are less sensitive to variations to the Mean Time Between Failure, which may have slightly higher cost.

Use the third procedure to allocate the spare parts for requested minimum mission availability target, because it generates higher mission availability solutions which are less sensitive to MTBF variations

This procedure, which generates higher average mission availability solutions with slightly higher costs, can cope better to MTBF variations. An experiment is conducted whereby it seems that the mission availability in the third procedure is less sensitive to MTBF variations due to higher mission availability solutions. This procedure, which generates solutions with slightly higher cost, can cope better to MTBF variations due to higher average mission availability solutions. The third procedure can cope at least to 12.5% lower Smart-L antenna MTBF values due to higher average mission availability solutions but costs maximal 11% more. Nevertheless it is recommended.

Reduce the repair lead-time, because it reduces initial spare parts cost

In the systems of Thales there are a lot of printed circuit boards. These printed circuit boards are designed to be an LRU. In a PBL contract environment the inventory costs are at the expense of Thales. By modifying the repair lead-time from 180 days to 14 days in a steady state model the total initial spare parts cost can be reduced 39.76% in the Smart-L EWC antenna case. Therefore the recommendation is that costs can be saved by reduction of the repair lead-time in a PBL contract environment, but it can only be realized by stocking component spare parts.

T. Groener and M.C. van Zwam also concluded in their research that short repair lead-times can reduce total initial spare part stock cost. This research confirms their research.

Reduce the shipment time between customer's site and the ships from two months to one month

The one month (average spare parts waiting time 15 days) and two months (average spare parts waiting time 30 days) shipment time is studied and how it influences the initial spare parts costs.

The total initial spare parts cost is higher for the shipment time of two months than the total initial spare parts cost of one month. The initial spare parts costs reduction in this Smart-L case is 28.13%.

The conclusion is also drawn by M.C. van Zwam, namely that in a steady state the reduction of the time parameters will create a reduction of the initial spare parts costs. This research confirms his research.

8.3 Research limitations

The first limitation of this research is that one mission profile is considered. This mission profile is the worst profile in terms of the mission deployment. It seems that two mission ships deployments at the same time creates the lowest mission availability. This research did not take into account different mission deployment over multiple years. The expectation is that when the customers decides to deploy two mission ships at the end of year one and deploy the mission ships at the beginning of year two that this has impact on the mission availability. These variations in ship deployments are not taken into account in this research.

The second limitation is that this research considers a steady state model. All the simulations ran with a first year deletion in this research. The measurement of the simulations started in year two. This research neglected the results of the start-up period of the system. In theory, the system should have lower mission availability in the steady state model then in the start-up period.

The third limitation is that this research is restricted to the simulation software Simlox and the output data of Simlox. Simlox allows some latitude in the output choice. The user of Simlox can choose the outputs from a list. Simlox does not allow programmable outputs, which is a limitation of this research. This research uses the standard output of Simlox.

The fourth limitation is that the assumption is made that only the MTBF of the antenna of the Smart-L ELR varies. This means that the MTBF of the rest antenna is unmodified. The MTBF calculation procedure by the reliability department is assumed correctly.

8.4 Further research

Several items are found during the research, which cannot be processed in this research due to the time constraint. Further research is needed in order to get a better understanding of the impact.

Procurement lead-time

In chapter 5 the repair lead-time is studied. The conclusion is drawn that short repair lead-times reduces the total initial spare parts costs. Every system has also procurable parts. The repair lead-time has no influence to the procurable parts stock. The procurement lead-time has, beside the procurable part stock, also influence on the repairable parts stock. Thales uses typically 90% repair success rate. Thus 10% of the repairable part must be procured. Altogether, the expectation is that a shorter procurement lead-time will also reduce the total initial spare parts costs.

Various mission profiles

The limitation of this research is one mission profile due to time constraints. Thales has no control on the deployment of missions. In this research the deployment was at the beginning of each year. The customer will not deploy the mission every year in January, therefore it could be interesting to do further research into different deployments. What impact has different mission deployments to the mission availability? One worst case scenario could be that two mission ships are deployed in the last part of year one and the two mission ships will again be deployed in the first part of the second year. This can be interpreted as one large mission over two years, which should have consequences to the mission availability.

The slope of mission lengths

The delta EBO is assumable linearly proportional to the delta mission availability by adding spare parts at the ships in chapter 6. It seems that each mission length has a slope. The slope of each mission is nearly at the mission length per year. The mission length slope disappears when the spare parts are added to a higher level (section 6.3.3). This could be a reference to define the “k” of the hypothesis:

$$PBO_i(s_i) - PBO_i(s_i + 1) = C * k * (Am_i(s_i + 1) - Am_i(s_i))$$

When the “k” is known there is a direct relation between the delta probability of backorders and delta the mission availability.

Impact of the MTBF on mission availability

It seems that the mission availability decreases non-linear when the MTBF decreases. See paragraph 7.2. There is a direct relation between the variation of the MTBF and the mission availability. It could be interesting to find out what the direct relation is, so that Thales could take this relation into account during spare parts allocations.

Reference

Data Sheet Thales Smart-L. (2012, 10 19). Retrieved from http://www.thalesgroup.nl/countries/netherlands/documents/datasheet_smart-L/

Donderwinkel, M. (2005). *Reparatieproces OPS Matrix Reparaties.* Hengelo: Thales Defence.

Groener, T. (2013). *Optimalisatie voorraden reservedelen Squire.* Hengelo: Thales Netherlands.

Heida, S., & Schmal, J. L. (2014). *Baseline Study Thales Nederland, Maintenance on the Smart-L radar system.* Enschede: University of Twente.

Heijden, M. v., & Al Hanbali, A. (2010). Reliabilility Engineering and Maintenance Management.

Law, A. M. (2007). *Simulation Modeling and Analysis.* New York: McGraw-Hill.

Muckstadt. (1973). A model for a Multi-Item, Multi-Echelon, Multi-Identure Inventory System. *Management Science 20*, 472-481.

Palm, C. (1938). Analysis of the Erlang Traffic Formula for Busy-Signal Arrangements. *Ericsson Technics*, 39-58.

Rustenburg, J. W. (2000). *A System Approach to Budget-Constrained Spare Parts Management.* Enschede: Febodruk B.V.

Schipper, L. (2014). Thales: nog altijd koploper in defensieve technologie. *Elsevier Juist*, 76-79.

Sherbrooke, C. C. (1968). Metric: A Multi-Echelon Technique for Recoverable Item Control. *Operations Research*, 122-141.

Sherbrooke, C. C. (2004). *Optimal inventory modeling, Multi-Echelon Techniques.* Boston: Kluwer Academic Publishers.

Systecon. (2011). *Simlox User's Reference.* Systecon.

Thales Group. (n.d.). Retrieved May 15, 2013, from www.thalesgroup.com/countries/netherlands/about_us/history/

Thales group. (2014, May 11). *Surveillance systems: Smart-L 3D long range surveillance radar*. Retrieved from Thales Group Website: https://www.thalesgroup.com/en/content/smart-l-3d-long-range-surveillance-radar

Verrijdt, J. H. (1997). Design and Control of Service Part Distribution Systems. Wageningen: Ponsen & Looijen.

Wolff, C. (n.d.). *www.radartutorial.eu*. Retrieved 5 25, 2013, from http://www.radartutorial.eu/01.basics/rb13.en.html

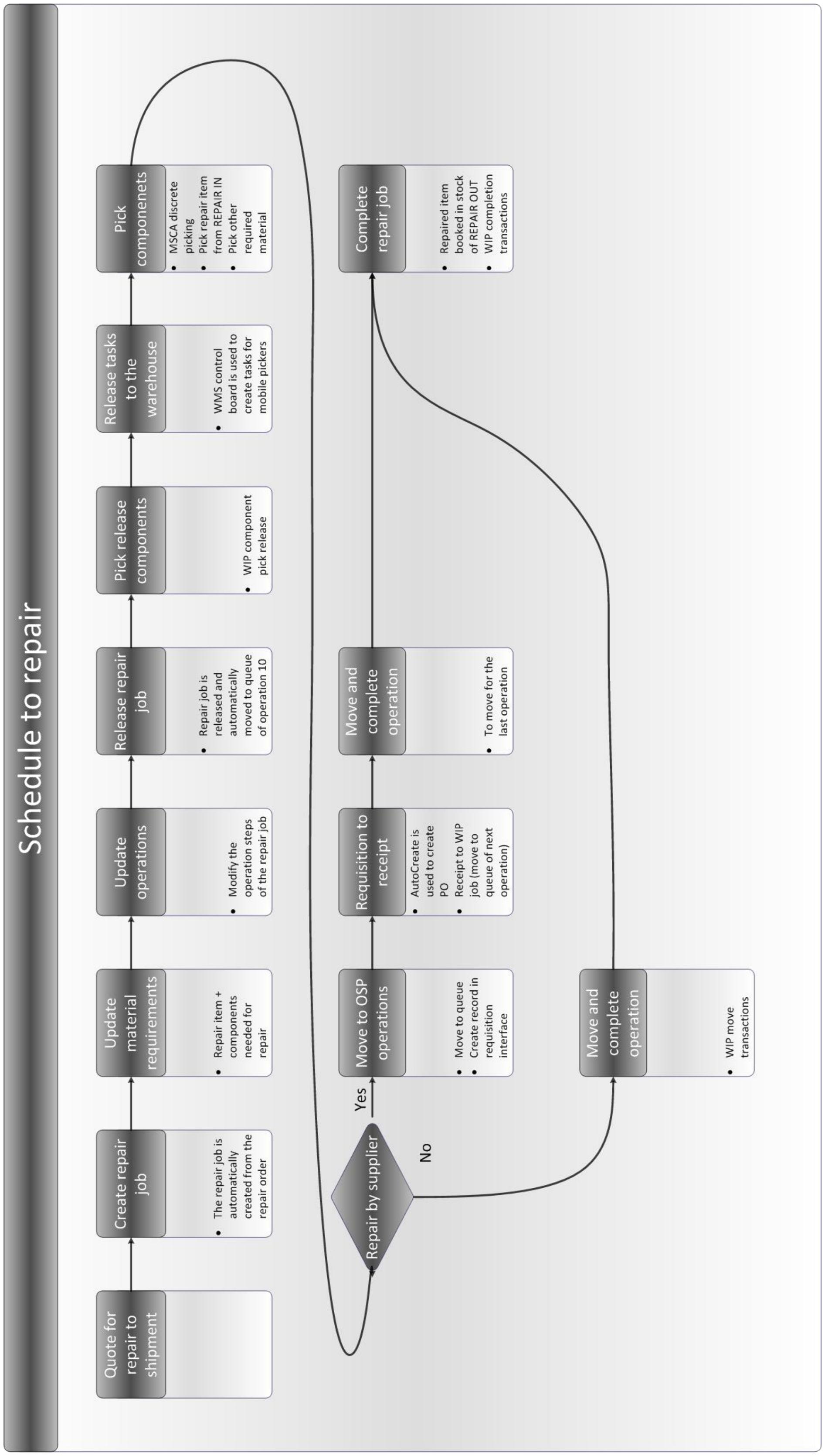
Zwam, M. v. (2010). *Tactical decisions to improve service contract performance: A Case Study at Thales Netherlands.* Enschede: University of Twente.

Appendix

A. Antenna breakdown

Part name	Breakdown structure	Quantity	LRU?	Repairable?	Return shipment + Repair lead-time	Repair success rate
Antenna system	SL01	1				
Building Block	SL01AB	28				
LRU 1	SL01AB01	8	Yes	Yes	21	100
SRU A	SL01AB01AA	1		Yes	35	90
SRU B	SL01AB01AB	1		Yes	35	90
LRU 2	SL01AB02	1	Yes	Yes	35	90
LRU 3	SL01AB03	1	Yes	Yes	35	90
LRU 4	SL01AB04	1	Yes	No		
LRU 5	SL01AB05	1	Yes	No		
LRU 6	SL01AB06	1	Yes	Yes	35	90
LRU 7	SL01AB07	1	Yes	No		

B. *Schedule to repair*



C. VARI-METRIC formulas

First the Single-Site, multi-Indenture model and successive the multi-Echelon, Multi-Indenture model is explained to get a better overview and a step-by-step knowledge of VARI-METRIC. The derivation is made of the mean and variance of the number in the pipeline per location per indenture. The complete derivation can be found in (Sherbrooke, 2004).

Single-Site, Multi-Indenture model

The assumption in VARI-METRIC is that when the LRU has failed that this is caused by a failure of one SRU *i*. The probability of failure of an SRU could be noted as q_i, whereby the sum of the probabilities is one. The demand of the SRU and LRU will be as followed:

$$\left.\begin{aligned} m_0 &= \sum_{i=1}^{I} m_i \\ m_i &= q_i m_0 \end{aligned}\right\} \begin{aligned} i &= 0 : LRU \\ i &= 1 \ldots I : SRU \end{aligned}$$

With a constant T the expected number of items in the pipeline and the variance of the number of items in the pipeline will be:

$$E[X_0] = m_0 T_0 + \sum_{i=1}^{I} EBO(s_i | m_i T_i)$$

$$Var[X_0] = m_0 T_0 + \sum_{i=1}^{I} VBO(s_i | m_i T_i)$$

The VBO(s_i) could be calculated as followed:

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

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

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

For an easier calculation of the $E[BO^2(s_i)]$, the following derivation could be made.

$$n(n-1) - (2s-1)n + s^2 = (n-s)^2$$

$$E[BO^2(s_i)] =$$

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

These are the formulas to calculate the expected number of item in the pipeline and the variance number of item in the pipeline.

Multi-Echelon, Multi-Indenture model

The expected number of items and the variance of items in the pipeline for base *j* can be calculated by the following formulas:

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

$$Var[X_j] = E[Var(X_j|X_0)] + Var[E(X_j|X_0)] = m_j\{r_jT_j + (1-r_j)O_j\} + f_j\{(1-f_j)EBO(s_0) + f_jVBO(s_0)\}$$

The proof that these formulas are correct could be found in (Sherbrooke, 2004). The fraction f_i of the depot demand due to resupply of base *j* could be calculated as followed:

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

Sherbrooke uses multiple demand calculations for the multi-echelon, multi-indenture model. Each demand calculation depends on the location and the indenture. Sherbrooke takes also into account that the base could repair the system, otherwise the depot has to repair the LRU. The probability whether the base could repair the LRU is r_{ij}. Figure 15 shows how the formula is per location per indenture.

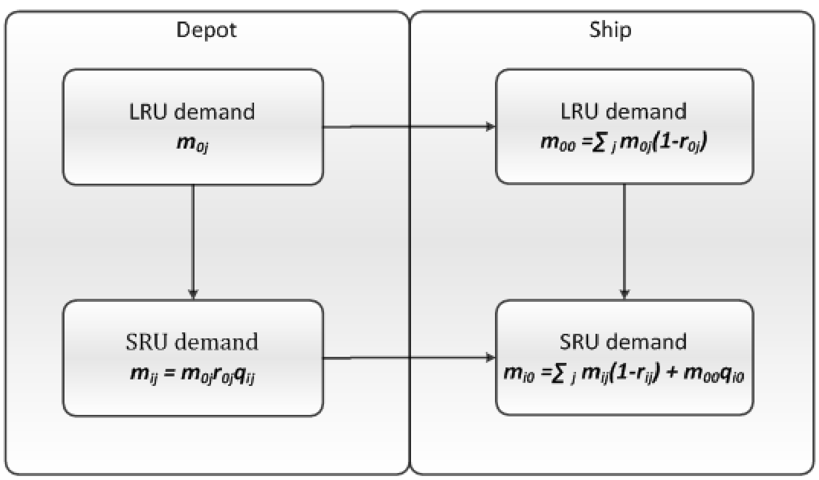


Figure 15: Demand formulas per location per indenture (Sherbrooke, 2004)

From the demand of the LRU at base the demands of the LRU at the depot and the SRU at the depot could be calculated. From the demand of the SRU at base and the demand of the LRU at depot the demand of the SRU at the depot could be calculated.

Now the demands are calculated the pipelines could be calculated. The calculations of the pipelines are made in the opposite direction of Figure 15.

The pipeline for the LRU could be calculated as followed. Start with the calculations of the SRUs in the depot repair. The SRUs in the depot repair have no influences from other items and locations. The numbers of the SRUs in the pipeline have a Poisson distribution with a mean $m_{i0}T_{i0}$. The calculations of the mean and the variance of the SRU *i* at the depot could be done by $EBO_{i0}(s_{i0})$, $VBO_{i0}(s_{i0})$. The following step is the calculations of the depot pipeline of the LRUs. This pipeline is dependent on the SRU pipeline. The third step is the SRU pipeline at the base. The SRU pipeline at the base is dependent on the SRU backorders of the depot. The final step is to calculate the pipeline of the LRUs at the base. The numbers of the LRUs in the base pipeline are dependent on the LRU backorders at the depot and the SRU backorders at the base. All the SRU backorders at base *j* arises from the LRU demand at base *j.*

Depot SRU pipeline

$$E[X_{i0}] = m_{i0}T_{i0}$$

$$Var[X_{i0}] = m_{i0}T_{i0}$$

Depot LRU pipeline

The fraction of depot demand for SRU *i* due to depot LRU repairs is calculated as:

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

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

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

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

Base SRU pipeline

The fraction of all depot demand for SRU *i* that is resupplied to base *j* is calculated as:

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

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

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

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

Base LRU pipeline

The fraction of LRU depot demand for an LRU that arises from base *j* is calculated as:

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

The numbers of the LRUs in the base pipeline are dependent on the LRU backorders at the depot and the SRU backorders at the base. All the SRU backorders at base *j* arises from the LRU demand at base *j.*

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

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

The availability of the bases could be calculated with the calculations of the pipelines. The availability is calculated by the expected backorders of the LRUs at the base. (Sherbrooke, 2004)

D. Repair process for the LRUs

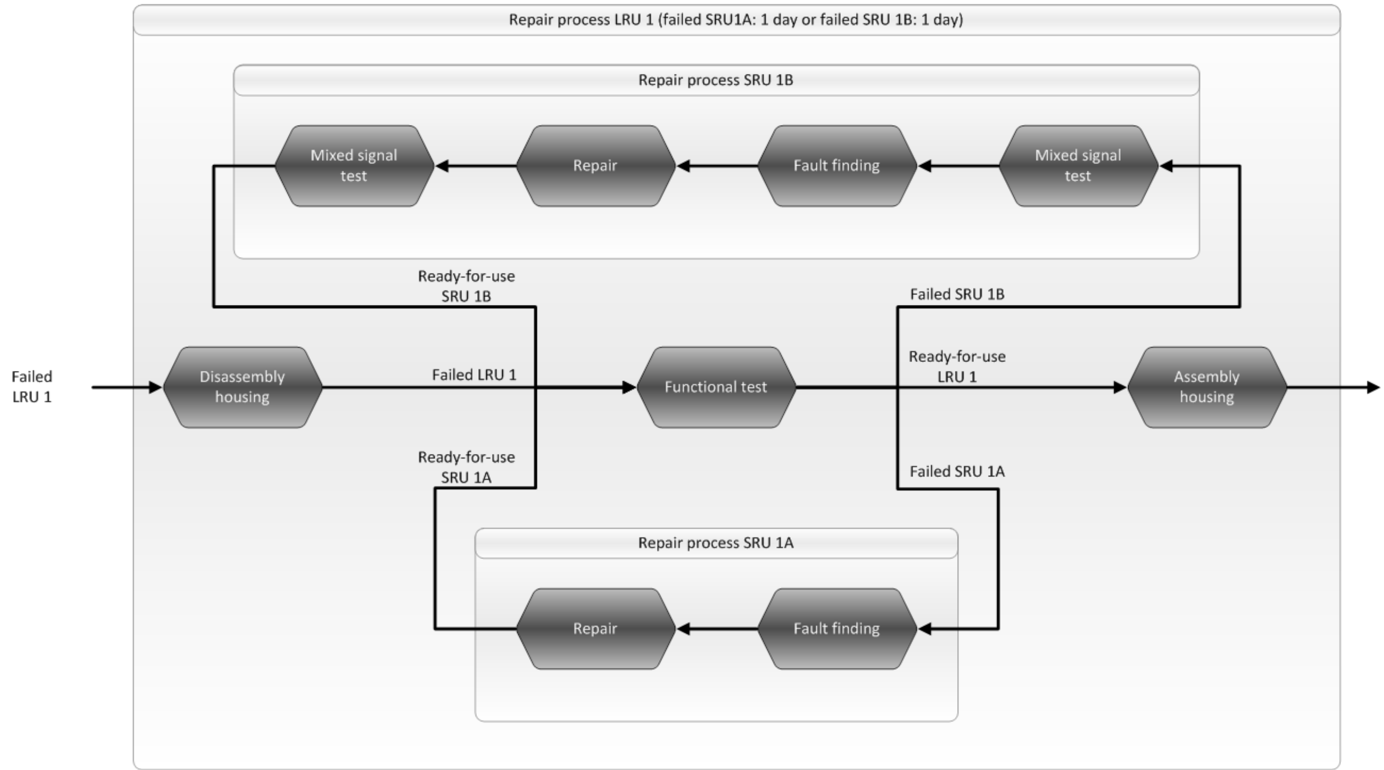


Figure 39: Standard repair lead-time LRU 1

The repair of the LRU 1 takes one day to find and repair the fault in the SRU 1A or in the SRU 1B. In this research the assumption is made that both SRUs cannot fail at the same time. An SRU can be repaired by exchanging components. For this research the standard repair of LRU 1 takes one day.

The LRUs could be repaired by exchanging the SRU or by exchanging the components. In case of the LRU 2 and LRU 3 are repaired by exchanging the components. The standard repair of the LRU 2 and LRU 3 cost at most one day. The repair flows are displayed in Figure 40 and Figure 41.

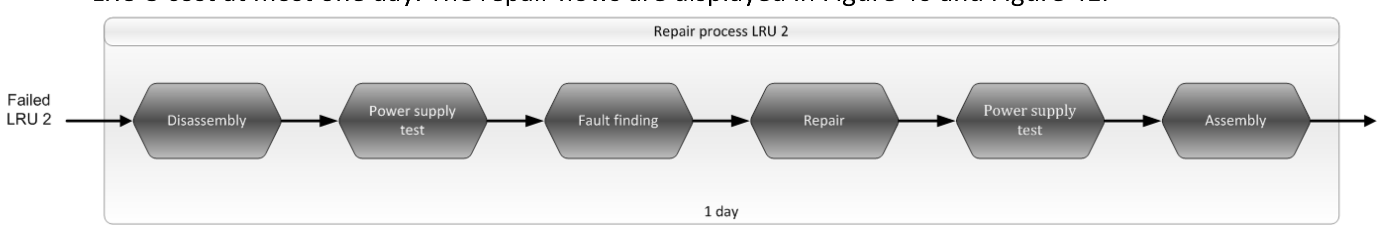


Figure 40: Standard repair lead-time LRU 2

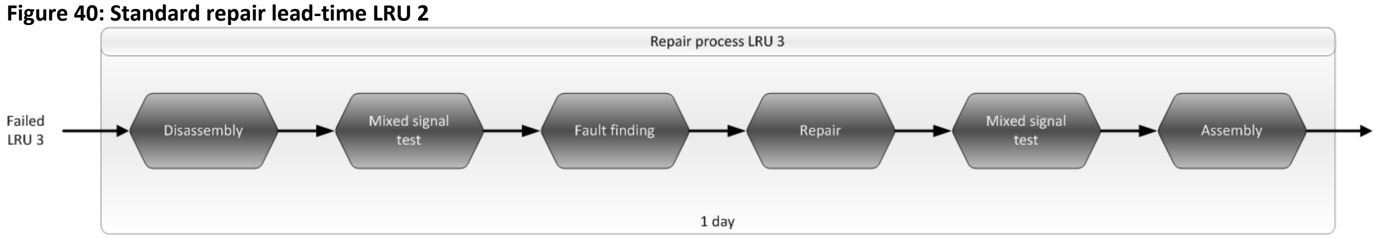


Figure 41: Standard repair lead-time LRU 3

In this research the standard repair of LRU 2 and LRU 3 are one day. All the repairs steps and repair lead-time are professional estimations by experts of Thales.

E. *Initial component spare part costs (Inventri)*

The repair lead-time from 14 to 49 days is increased which influences the initial spare part cost. The initial spare parts costs are also dependent on the delivery reliability. With a lower delivery reliability a lower total components cost is necessary per repair lead-time. Therefore an investigation is performed per percentage delivery reliability for the impact on initial components spare parts costs. The repair lead-time interval increase is 7 days. The parts, LRU 1, LRU 2 and LRU 3 are calculated with the supply chain of Figure 10 in section 3.2.3. These are the repairable LRUs and only for these LRU it is useful to stock components. There are per LRU a breakdown of SRU and components made with the corresponding costs.

Component spare part cost per repair lead-time

The different repair lead-times are displayed in Figure 42 with the associated costs and availability. The lines of the cost/availability curve (Figure 42) nearly exactly overlap. This means that there are almost no differences in cost of spare parts among the different repair lead-times. The maximal difference between the lowest total cost and the maximum total cost is approximately €55. This difference is at a probability of 99.99% and logically between the 14 days and 49 days. This is the largest difference among repair lead-times. We can conclude that financially it does not make any difference whether you repair the LRUs in 14 days of 49 days, because it has barely influence on the initial components spare parts costs.

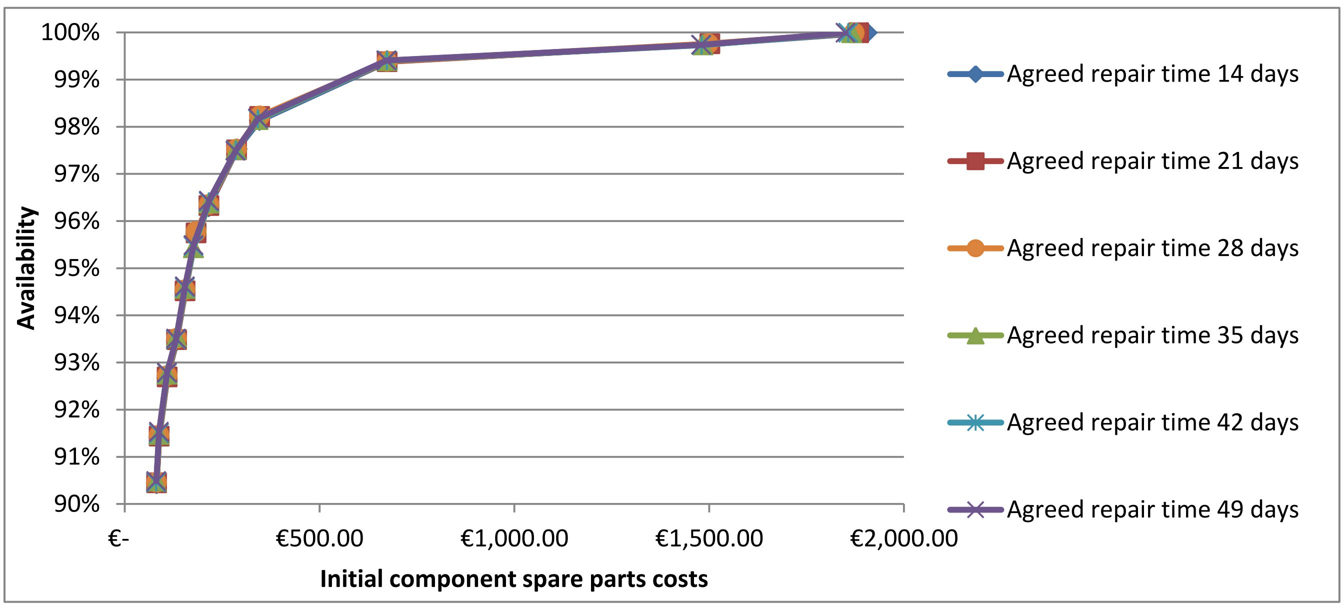


Figure 42: Cost/Availability curve per repair lead-time

The largest difference is among the delivery reliabilities targets. The probability that 90% of the repair can be delivered within the agreed time cost in spare parts are in total €80. When the delivery reliability is 99.99% to repair the spare parts then the total cost of the component inventory is maximal €1905. This is the largest difference among the probabilities. Although, if the comparison is made between LRU spare parts and components spare parts than €1905 is relatively low.

Delivery reliability choice

The repair demand is calculated to choose a delivery reliability. The delivery reliability is dependent on the procurement lead-times of the components and the costs. When the components are not on stock then the LRU cannot be repaired. This could result in repair delay of the LRU. The repair demand is dependent on the failures per year: Annual Operational Hours (AOH) divided by Mean Time Between Failure (MTBF) and multiplied by the probability whether or not the failed part could be repaired with success and the number of parts in the system. The complete formula will be as followed:

$$\text{Repair demand per repairable part} = \frac{\text{AOH} * \text{Repair SuccesRate} * \text{Number of parts in system}}{\text{MTBF}}$$

When the spare parts enters the diagnostics and it seems that the spare parts could not be repaired then this part should be procured. Therefore it has influence to the repair demand.

The demands of the LRUs are noted in Table 30. The demand of part LRU 1 is the sum of SRU 1A and SRU 1B. The maximal demand of repairs is less than 9 per year. The system has a lifecycle of about 20 years. This means that there are maximal 20 * 9 = 180 repairs.

When the Due Date probability is 99% than that means that 1 of the 100 repairs will not be repaired within the repair lead-time because there are not enough spare parts. When we bring this principle to the case of due date probability then it means that more than 180 repairs should be successful. The success probability must be at least 99.45%. This research uses a delivery reliability of 99.5%.

Table 30: Repair demand per repairable part

Part	Demand
• **LRU 1**	8.51
○ **SRU 1A**	6.27
○ **SRU 1B**	1.39
• **LRU 2**	0.85
• **LRU 3**	0.42

F. *Derivation of Inventri correction*

VARI-METRIC has the assumption that the demands occurs according to a Poisson process. That means that the system could fail even when the system is down. Therefore, the Inventri result should be corrected to compare it with the Simlox results. The first step is to calculate the system MTBF of the Inventri result.

Variable	Meaning
A_v	Output availability of Inventri
D	System demand through failures per year
AOH	Annual Operating Hours

$$\text{SystemMTBF} = \frac{AOH}{D}$$

The system MTBF is calculated in Inventri through the annual operating hours. Although this means that the system could fail even when the system is down. The Output availability gives the proportion of the system down time and system uptime.

$$\text{Systemdowntime} = (1\text{-}A_v)*AOH$$

$$\text{Systemuptime} = A_v*AOH$$

The question is now what the demand of the system is in the uptime. Therefore the system MTBF and the uptime are used.

$$\text{Demand throughfailures in uptime} = \frac{\text{Systemuptime}}{\text{SystemMTBF}} = \frac{A_v*AOH}{\frac{AOH}{D}} = A_v*AOH*\frac{D}{AOH} = A_v*D$$

The demand through failures in uptime is known and the demand through failures of Inventri is known. To calculate the new availability a new uptime or new downtime is necessary. This could be calculated by proportions.

$$\text{New downtime} = \frac{\text{Downtime}}{\text{Systemdemand throughfailure}} * \text{Demand throughfailure in uptime}$$

$$\text{New downtime} = \frac{(1\text{-}A_v)*AOH}{D} * \mathrm{A_v} * D = \frac{(1\text{-}A_v)*AOH*A_v*D}{D} =$$

$$(1\text{-}A_v)*AOH*A_v = AOH*A_v - AOH*A_v^2$$

Finally, the corrected Availability could be calculated by $1-\frac{\text{downtime}}{AOH}$. This formula results in:

$$\text{Corrected Availability} = 1-\frac{\text{new downtime}}{AOH} = 1\text{-}\left(\frac{AOH*A_v - AOH*A_v^2}{AOH}\right) = 1-(A_v - A_v^2) = A_v^2 - A_v + 1$$

G. *Mission deployment variations*

Type ship Mission Description	**Mission ship 1** Deployment large mission [week]	**Mission ship 2** Deployment large mission [week]	**Short-mission ship** 5 missions equally divided over a year
Simulation 0	0	0	-
Simulation 1	0	1	-
Simulation 2	0	2	-
Simulation 3	0	3	-
Simulation 4	0	4	-
Simulation 5	0	5	-
Simulation 6	0	6	-
Simulation 7	0	7	-
Simulation 8	0	8	-
Simulation 9	0	9	-
Simulation 10	0	10	-
Simulation 11	0	11	-
Simulation 12	0	12	-
Simulation 13	0	13	-
Simulation 14	0	14	-
Simulation 15	0	15	-
Simulation 16	0	16	-
Simulation 17	0	17	-
Simulation 18	0	18	-
Simulation 19	0	19	-
Simulation 20	0	20	-
Simulation 21	0	21	-
Simulation 22	0	22	-
Simulation 23	0	23	-
Simulation 24	0	24	-
Simulation 25	0	25	-
Simulation 26	0	26	-
Simulation 27	0	27	-
Simulation 28	0	28	-
Simulation 29	0	29	-
Simulation 30	0	30	-

H. Derivation delta availability is linearly proportional to delta EBO

Variable	***Meaning variable***
i*=1,…,*I	Number of LRU
A(s_i)	Operational availability with stock level equals s_i
PBO_i(s_i)	Probability of backorders for LRU *i* if the stock level equals s_i
s_i	Stock level of LRU *i*
C	Constant of the probability of backorders of other LRUs
n	LRU which is measured

$$A_n(s_i) = \prod_{i=1}^{N-1}(1 - PBO_i(s_i)) * (1 - PBO_n(s_n))$$

$$A_n(s_i + 1) = \prod_{i=1}^{N-1}(1 - PBO_i(s_i)) * (1 - PBO_n(s_n + 1))$$

$$A_n(s_i) - A_n(s_i + 1) = \prod_{i=1}^{N-1}(1 - PBO_i(s_i)) * (1 - PBO_n(s_n) - \prod_{i=1}^{N-1}(1 - PBO_i(s_i)) * (1 - PBO_n(s_n + 1)$$

$$A_n(s_i) - A_n(s_i + 1) = \prod_{i=1}^{N-1}(1 - PBO_i(s_i)) * \left((1 - PBO_n(s_n)) - (1 - PBO_n(s_n + 1)\right)$$

$$\frac{1}{\prod_{i=1}^{N-1}(1 - PBO_i(s_i))} * (A_n(s_i) - A_n(s_i + 1)) = (1 - PBO_n(s_n)) - (1 - PBO_n(s_n + 1))$$

$$\frac{1}{\prod_{i=1}^{N-1}(1 - PBO_i(s_i))} = C = \text{constant per n}$$

$$A_n(s_i) - A_n(s_i + 1) = C * ((1 - PBO_n(s_n)) - (1 - PBO_n(s_n + 1)))$$

$$A_n(s_i) - A_n(s_i + 1) = C * (1 - PBO_n(s_n) - 1 + PBO_n(s_n + 1))$$

$$A_n(s_i) - A_n(s_i + 1) = C * (PBO_n(s_n + 1) - PBO_n(s_n))$$

$$A_n(s_i + 1) - A_n(s_i) = C * (PBO_n(s_n) - PBO_n(s_n + 1))$$

I. *Spare part stock variations on the ships*

To study whether the delta EBO is linearly proportional to the delta mission availability three stock locations are researched. The following stock locations are research: ship, at customer's sit and at Thales. This appendix shows the stock allocations per simulation. The spare parts are solely added to the **ship**. This stock allocation is conducted to the one, two, three, four and five months mission lengths. Per mission length there are 14 measurements.

Part name	Stock level	Start stock level	Simulation 1	Simulation 2	Simulation 3	Simulation 4	Simulation 5	Simulation 6	Simulation 7	Simulation 8	Simulation 9	Simulation 10	Simulation 11	Simulation 12	Simulation 13	Simulation 14
LRU 1	**SHIP**	**1**	+1	0	0	0	0	0	0	+1+1	0	0	0	0	0	0
LRU 2	**SHIP**	**1**	0	+1	0	0	0	0	0	0	+1+1	0	0	0	0	0
LRU 3	**SHIP**	**0**	0	0	+1	0	0	0	0	0	0	+1+1	0	0	0	0
LRU 4	**SHIP**	**1**	0	0	0	+1	0	0	0	0	0	0	+1+1	0	0	0
LRU 5	**SHIP**	**0**	0	0	0	0	+1	0	0	0	0	0	0	+1+1	0	0
LRU 6	**SHIP**	**0**	0	0	0	0	0	+1	0	0	0	0	0	0	+1+1	0
LRU 7	**SHIP**	**0**	0	0	0	0	0	0	+1	0	0	0	0	0	0	+1+1
LRU 1	**SHORE**	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LRU 2	**SHORE**	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LRU 3	**SHORE**	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LRU 4	**SHORE**	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LRU 5	**SHORE**	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LRU 6	**SHORE**	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LRU 7	**SHORE**	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LRU 1	**THALES**	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LRU 1A	**THALES**	**2**	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LRU 1B	**THALES**	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LRU 2	**THALES**	**0**	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LRU 3	**THALES**	**0**	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LRU 4	**THALES**	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LRU 5	**THALES**	**2**	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LRU 6	**THALES**	**0**	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LRU 7	**THALES**	**0**	0	0	0	0	0	0	0	0	0	0	0	0	0	0

J. Spare part stock variations at the customer's site

To study whether the delta EBO is linearly proportional to the delta mission availability three stock locations are researched. The following stock locations are researched: ship, at customer's sit and at Thales. This appendix shows the stock allocations per simulation. The spare parts are solely added to the **customer's site location**. The EBO reductions and the availability additions are measured at the ships. The reductions and the additions are summed. Per scenario defined in section 6.4.2 there are 14 measurements.

Part name	Stock level	Start stock level	Simulation 1	Simulation 2	Simulation 3	Simulation 4	Simulation 5	Simulation 6	Simulation 7	Simulation 8	Simulation 9	Simulation 10	Simulation 11	Simulation 12	Simulation 13	Simulation 14
LRU 1	**SHIP 1**	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LRU 2	**SHIP 1**	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LRU 3	**SHIP 1**	**0**	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LRU 4	**SHIP 1**	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LRU 5	**SHIP 1**	**0**	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LRU 6	**SHIP 1**	**0**	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LRU 7	**SHIP 1**	**0**	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LRU 1	**SHIP 2**	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LRU 2	**SHIP 2**	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LRU 3	**SHIP 2**	**0**	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LRU 4	**SHIP 2**	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LRU 5	**SHIP 2**	**0**	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LRU 6	**SHIP 2**	**0**	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LRU 7	**SHIP 2**	**0**	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LRU 1	**SHORE**	**1**	+1	0	0	0	0	0	0	+1+1	0	0	0	0	0	0
LRU 2	**SHORE**	**1**	0	+1	0	0	0	0	0	0	+1+1	0	0	0	0	0
LRU 3	**SHORE**	**1**	0	0	+1	0	0	0	0	0	0	+1+1	0	0	0	0
LRU 4	**SHORE**	**1**	0	0	0	+1	0	0	0	0	0	0	+1+1	0	0	0
LRU 5	**SHORE**	**1**	0	0	0	0	+1	0	0	0	0	0	0	+1+1	0	0
LRU 6	**SHORE**	**1**	0	0	0	0	0	+1	0	0	0	0	0	0	+1+1	0
LRU 7	**SHORE**	**1**	0	0	0	0	0	0	+1	0	0	0	0	0	0	+1+1
LRU 1	**THALES**	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LRU 1A	**THALES**	**2**	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LRU 1B	**THALES**	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LRU 2	**THALES**	**0**	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LRU 3	**THALES**	**0**	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LRU 4	**THALES**	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LRU 5	**THALES**	**2**	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LRU 6	**THALES**	**0**	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LRU 7	**THALES**	**0**	0	0	0	0	0	0	0	0	0	0	0	0	0	0

K. *Spare part stock variations at Thales*

To study whether the delta EBO is linearly proportional to the delta mission availability three stock locations are researched. The following stock locations are researched: ship, at customer's sit and at Thales. This appendix shows the stock allocations per simulation. The spare parts are solely added to **Thales**. The EBO reductions and the availability additions are measured at the ships. The reductions and the additions are summed. Per scenario defined in section 6.4.2 there are 14 measurements.

Part name	Stock level	Start stock level	Simulation 1	Simulation 2	Simulation 3	Simulation 4	Simulation 5	Simulation 6	Simulation 7	Simulation 8	Simulation 9	Simulation 10	Simulation 11	Simulation 12	Simulation 13	Simulation 14
LRU 1	**SHIP 1**	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LRU 2	**SHIP 1**	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LRU 3	**SHIP 1**	**0**	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LRU 4	**SHIP 1**	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LRU 5	**SHIP 1**	**0**	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LRU 6	**SHIP 1**	**0**	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LRU 7	**SHIP 1**	**0**	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LRU 1	**SHIP 2**	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LRU 2	**SHIP 2**	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LRU 3	**SHIP 2**	**0**	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LRU 4	**SHIP 2**	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LRU 5	**SHIP 2**	**0**	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LRU 6	**SHIP 2**	**0**	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LRU 7	**SHIP 2**	**0**	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LRU 1	**SHORE**	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LRU 2	**SHORE**	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LRU 3	**SHORE**	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LRU 4	**SHORE**	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LRU 5	**SHORE**	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LRU 6	**SHORE**	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LRU 7	**SHORE**	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LRU 1	**THALES**	**1**	+1	0	0	0	0	0	0	+1+1	0	0	0	0	0	0
LRU 1A	**THALES**	**2**	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LRU 1B	**THALES**	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LRU 2	**THALES**	**0**	0	+1	0	0	0	0	0	0	+1+1	0	0	0	0	0
LRU 3	**THALES**	**0**	0	0	+1	0	0	0	0	0	0	+1+1	0	0	0	0
LRU 4	**THALES**	**1**	0	0	0	+1	0	0	0	0	0	0	+1+1	0	0	0
LRU 5	**THALES**	**2**	0	0	0	0	+1	0	0	0	0	0	0	+1+1	0	0
LRU 6	**THALES**	**0**	0	0	0	0	0	+1	0	0	0	0	0	0	+1+1	0
LRU 7	**THALES**	**0**	0	0	0	0	0	0	+1	0	0	0	0	0	0	+1+1

L. *Proof delta EBO single-site*

Variable	Meaning variable
i*=1,…,*I	Number of LRU
EBO$_i$(s$_j$)	Expected backorders for LRU *i* if the stock level equals s_i
PBO$_i$(s$_j$)	Probabilities of backorders for LRU *i* if the stock level equals s_i
s$_i$	Stock of LRU *i*
m$_i$	Failure demand of LRU *i*
T$_i$	Repair lead-time of LRU *i*

$$EBO_i(s_i) - EBO_i(s_i+1) = m_i T_i \sum_{n=s_i}^{\infty} \frac{(m_i T_i)^n e^{-m_i T_i}}{n!} - s_i \sum_{n=s+1_i}^{\infty} \frac{(m_i T_i)^n e^{-m_i T_i}}{n!} -$$

$$m_i T \sum_{n=s+1_i}^{\infty} \frac{(m_i T_i)^n e^{-m_i T_i}}{n!} + (s_i+1) \sum_{n=s+1_i}^{\infty} \frac{(m_i T_i)^n e^{-m_i T_i}}{n!}$$

$$EBO_i(s_i) - EBO_i(s_i+1) = m_i T_i \frac{(m_i T_i)^{s_i} e^{-m_i T_i}}{s_i!} + (s_i + 1 - s_i) \sum_{n=s+1_i}^{\infty} \frac{(m_i T_i)^n e^{-m_i T_i}}{n!} - (s_i+1) \frac{(m_i T_i)^{s_i+1} e^{-m_i T_i}}{(s_i+1)!}$$

$$EBO_i(s_i) - EBO_i(s_i+1) = m_i T_i \frac{(m_i T_i)^{s_i} e^{-m_i T_i}}{s_i!} + \sum_{n=s+1_i}^{\infty} \frac{(m_i T_i)^n e^{-m_i T_i}}{n!} - m_i T_i \frac{(m_i T_i)^{s_i} e^{-m_i T_i}}{s_i!}$$

$$EBO_i(s_i) - EBO_i(s_i+1) = \sum_{n=s+1_i}^{\infty} \frac{(m_i T_i)^n e^{-m_i T_i}}{n!}$$

$$\sum_{n=s+1_i}^{\infty} \frac{(m_i T_i)^n e^{-m_i T_i}}{n!} = PBO_i(s_i)$$

$$PBO_i(s_i) = EBO_i(s_i) - EBO_i(s_i+1)$$

M. Availability target by MTBF variations derivation

The MTBF of the system ($MTBF_S$) could be calculated by the MTBF of the antenna ($MTBF_a$) and the MTBF of the rest of the system ($MTBF_R$). This is summed in the failure rate context. This results in the following formula:

$$\text{Smart - L ELR MTBF} = \frac{1}{\frac{1}{\text{AntennaMTBF}} + \frac{1}{\text{Rest system MTBF}}}$$

The MTBF of the Smart-L ELR and the MTBF of the antenna are known. The MTBF of the rest of the system could be calculated with this information. The MTBF of the Smart-L ELR is $MTBF_s$ hours and the MTBF of the antenna is $MTBF_a$ hours. For example:

Variable	Hours
$MTBF_S$	700
$MTBF_a$	900
$MTBF_R$	?

$$700 = \frac{1}{\frac{1}{900} + \frac{1}{\text{Rest system MTBF}}}$$

The MTBF of the rest system is then 3150 hours. The assumption is made that the rest of the antenna will not have any MTBF variations. This means we could calculate with the same formula the new system MTBF when the antenna MTBF is varied.

This case uses the minimal mission availability of 90% for the Smart-L ELR case. Due to MTBF variations the antenna availability is modified.

$$\text{Supply availability Smart - L ELR} = \frac{MTBF}{MTBF + MSD} = 90\%$$

The MTBF variations results that the Mean Supply Delay (MSD) will vary. Now we know the new MSD and the new MTBF we could calculate the corresponding availability target. This target could be calculated with the previous formula. The corresponding antenna availabilities with the MTBF variations are as followed:

MTBF variations	Corresponding availability
100%	93.28%
95%	93.18%
90%	93.08%
85%	92.98%
80%	92.89%
75%	92.81%

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