# Obsolescence strategies at Thales Hengelo

THALES

UNIVERSITY OF TWENTE.

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**Master thesis**
"Obsolescence strategies at Thales Hengelo"

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# Management summary

**Background and problem setting**

Thales Hengelo is part of the Dutch division of the Thales group. Thales develops, manufactures, and integrates naval mission and radar solutions for high-end markets. The systems of Thales can have a life span of longer than 30 years. During the operational life cycle multiple services such as spare parts management and obsolescence management are offered to customers. The importance of obsolescence management is increasing since technological changes, in combination with more complex developed systems, result in shorter item life cycles and higher supplier dependency. Future trends towards Performance Based Logistics (PBL) are expected where Thales is responsible for managing obsolescence, making it crucial to solve potential obsolescence issues in advance. Although Thales Hengelo has developed a wide range of obsolescence management strategies, the practical implementation to compare different strategies is not completed yet. The goal of this research is as follows:

*"Construct a model to assess the differences and impact of obsolescence strategies related to maintenance significant items, after the design phase at Thales Hengelo in order to create a guideline on how to manage and to decrease the impact of obsolescence over the system life cycle".*

We focus on Line Replaceable Units (LRU) that are categorized as spare part and might require maintenance during the operational life cycle. With the use of the model, the optimal strategy related to obsolescence should be determined over (part of) the life cycle.

**Approach and model design**

In order to create a suitable model for Thales, we incorporated three main strategies. The first strategy is to buy all expected demand at the start of the life cycle with a Risk Mitigation Buy (RMB). The second strategy is to perform obsolescence monitoring until the LRU becomes obsolete and either perform a Last Time Buy (LTB) (scenario 1), or initiate a redesign (scenario 2), to supply spare parts in the remaining part of the life cycle. The third strategy is to incorporate the LRU in predetermined technology upgrades. Furthermore, the repair of failed parts from the field is incorporated in all strategies (if applicable). Based on a literature study, studies that focus on (multiple) strategies are reviewed and we conclude that existing literature mainly focuses on parts that are already announced obsolete and obsolescence monitoring is therefore not applied.

The principle of the constructed model is that the life cycle of a LRU is divided into multiple time intervals. At the start of each interval, decisions regarding order quantities and redesign activities must be made. The decisions depend on the obsolescence state of the LRU and obsolescence monitoring is applied if the LRU is not obsolete. Only if a RMB strategy is followed, obsolescence monitoring is not applied since the expected required parts are already put in inventory. All ready-to-repair parts are directly repaired, and this is therefore not a decision. The Total Expected Costs (TEC) and the average cycle service level (i.e., no stock-out probability) are used as performance indicators. The cost factors that are incorporated are: purchase costs (part price and fixed order costs), holding costs, backorder costs, repair costs, obsolescence monitoring costs, (un)planned redesign costs, disposal costs. Stochastic Dynamic Programming (SDP) is applied as modelling technique, which uses backward recursion to find the optimal solution for the given problem (i.e., minimize the TEC to attain an average cycle service level of 90%). The cycle service level is determined using a forward recursion method. The model is validated by consulting multiple experts of Thales. Furthermore, a simulation is constructed to verify the model and to conduct several analyses.

**Results**
For the model analysis, we conducted a case study and sensitivity analysis on two different types of LRU's. The optimal strategy for the 'waveform generator', which is a high value LRU, is to use an obsolescence monitoring strategy with an LTB once obsolescence occurs. The other strategies result in a higher TEC of 22,41% (€157.403) for the RMB strategy, 38,12% (€267.682) for the obsolescence monitoring with redesign strategy, and 27,12% (€190.464) for the planned redesign strategy. Sensitivity analysis shows that the optimal strategy only changes to an obsolescence monitoring with redesign strategy if the life cycle length increases, or the non-recurring engineering costs related to redesigning are significantly lower (<€100.00) than estimated (€300.000). An RMB strategy at the start of the life cycle is the optimal strategy for the 'relay', which is a low value LRU, under all analysed circumstances. Since the impact of fixed order costs and redesign costs are relatively high for low value LRU's, the other strategies result in a substantial higher TEC (of €4.685 for the obsolescence monitoring with LTB strategy, €28.087 for obsolescence monitoring with redesign strategy, and € 20.338 for the planned redesign strategy). Due to the high degree of uncertainty in installed base development and the Years Till End Of Life (YTEOL) where obsolescence occurs, we analysed the impact of variation in these two parameters when a certain strategy is followed. The impact on the relay with RMB strategy is relatively small. Concerning the waveform generator. The impact is more significant, below we summarize the main insights:

- The impact of **lower actual future sales** (-17% till -75%) or a **higher actual YTEOL** (+20% till +60%) is lowest for the obsolescence monitoring with LTB strategy, compared to the obsolescence monitoring with redesign strategy, the TEC is respectively 9,48% and 13,09% lower.
- The impact of **higher actual future sales** (+17% till +208%) or a **lower actual YTEOL** (-20% till -60%) is lowest for the obsolescence monitoring with redesign strategy, compared the obsolescence monitoring with LTB strategy, the TEC is respectively 4,96% and 2,31% lower.
- Updating the installed base development at an **early stage**, before the YTEOL have passed, results in a substantial lower TEC compared to when variation is noticed at a **later stage.** For the obsolescence monitoring with LTB strategy, the difference in TEC is 40,59% for lower actual future sales and 4,53% for actual higher future sales.
- Obsolescence monitoring can reduce the TEC for high value LRU's with approximately 8,6% in case obsolescence occurs in an **earlier stage** of the life cycle. In case obsolescence occurs at a **later stage**, obsolescence monitoring results in a lower TEC of 11,5% compared to when obsolescence is not monitored from the start of the life cycle.

**Conclusions and recommendations**
We conclude that an obsolescence monitoring with LTB strategy is optimal and most robust for high value LRU's (which can be repaired). For low value LRU's, an RMB strategy is optimal and most robust against variation. Furthermore, we conclude that updating the installed base development before obsolescence occurs and monitoring obsolescence from the start of the life cycle result in substantial lower TEC. We recommend Thales to conduct future research regarding obsolescence forecasting since accurate YTEOL information is crucial and the constructed model can be extended by changing the obsolescence state into a stochastic, instead of deterministic, variable. Another valuable model extension is incorporating a redesign lead time longer than one year, which can be increasingly important if the YTEOL is uncertain. We also recommend Thales to establish thresholds for which LRU characteristics each obsolescence strategy is optimal. Finally, we recommend Thales to evaluate the possibility to extend the repair process for longer period since this can result in a flexible source of supply near the end of the life cycle to maintain a high cycle service level.

## List of abbreviations

During this research, some abbreviations are used. Therefore, we provide an overview with used abbreviations:

| | |
|---|---|
| ATB: | All Time Buy |
| COTS: | Commercial Off-The-Self |
| FFF: | Form, Fit, Function |
| FPRD: | Frequency of Planned Redesign |
| KPI: | Key Performance Indicator |
| LRU: | Line Replaceable Unit |
| LTB: | Last Time Buy |
| MARCONI: | Maritime Remote Control Tower for Service Logistics Innovation |
| MRO: | Maintenance Repair and Overhaul |
| MSI: | Maintenance Significant Item |
| MTBF: | Mean Time Between Failures |
| OEM: | Original Equipment Manufacturer |
| PBL: | Performance Based Logistics |
| PDN: | Product Discontinuance Notice |
| PS: | Part Support |
| RMB: | Risk Mitigation Buy |
| SA: | Sensitivity Analysis |
| SDP: | Stochastic Dynamic Programming |
| SRU: | Shop Replaceable Unit |
| TEC: | Total Expected Costs |
| TNL: | Thales Nederland B.V. |
| YTEOL: | Years Till End Of Life (of a part) |
| VBA: | Visual Basic for Applications |

# Glossary

Some definitions used during this research are defined to avoid ambiguity:

| | |
|---|---|
| COTS: | Conforming to the manufacturer's datasheet and available to any purchaser. |
| Item: | An item is defined as an individual part or component that is purchased from a supplier. |
| LRU: | Part of a system which can be removed and replaced at operational level (e.g., on board of a frigate) to restore the end item to an operational ready condition. |
| SRU: | Part of a LRU that is not directly replaceable on operational level, but can be removed and replaced at one echelon level closer to the OEM (e.g., base). |

# List of figures

# List of tables

# Preface

In order to complete the master program Industrial Engineering and Management at the University of Twente, with specialization Production and Logistics Management, I conducted my thesis at Thales Hengelo related to obsolescence management strategies. During the first weeks at the office, I learned a lot about Thales and the processes related to obsolescence and other after-sales related topics. Due to the emerging pandemic, most of my time at Thales I had to work from home. Although this was for from ideal, my experience and time at Thales is very good so far and I appreciate the offered flexibility.

I would like to thank my supervisors from the University of Twente. First, I would like to thank Matthieu van der Heijden. Matthieu brought me into contact with Thales and provided me with good guidance and feedback during my research as primary supervisor. I also want to thank Engin Topan for being the second supervisor and providing meaningful feedback near the end of the research.

I would also like to thank my supervisor from Thales, Rindert Ypma, for this support, feedback, and guidance throughout my entire research. Although we had to work from home most of the time, Rindert was always available to answer my questions and to discuss all kind op topics. Furthermore, I would like to thank the involved employees within Thales, especially the obsolescence management department members for their involvement and feedback during the research.

Finally, I would like to thank my mother, brothers, sisters-in-law, friends and colleague students for their contribution and support during the master program. Especially my mother and brothers helped me through the last, sometimes difficult, months of my master thesis period.

Now I have completed the master, my time as a student comes to and end and it is time for a new challenge. As of the start of the new year, I will start working within the obsolescence management department of Thales Hengelo. I would like to thank Thales for the great opportunity!

Wouter Reimert

Heeten, December 2020

# Table of contents

# 1. Introduction

This research is carried out on behalf of Thales Nederland B.V. and is also part of a project called "Maritime Remote Control Tower for Service Logistics Innovation" (MARCONI). The focus of this research lays on obsolescence strategies. In this chapter we describe the context of the proposed research.

## 1.1 Thales

The Thales Group is a French multinational that designs and manufactures systems for the worldwide market. The Thales Group is active in 68 countries, has over 80.000 employees worldwide and total sales in 2018 of 19 billion euros (Thales Group, 2019). Thales has customers that can be categorized into governments, institutions, cities, and companies. Thales is engaged in five market sectors:

- Digital identity and security
- Defence and security
- Aerospace
- Space
- Ground transportation

Thales Nederland B.V. is the Dutch division of the Thales Group. Thales Nederland (TNL) is founded in 1922 and has approximately 2100 employees. The majority (±1500 employees) is located at the headquarters in Hengelo (OV). In the Netherlands, Thales has four more offices, one in Huizen, one in Eindhoven, one in Delft, and one in Enschede. In 2018, Thales Nederland had total sales of 495 million euros and 85% of these sales is defence related. This research will be performed in Hengelo (OV), which is a worldwide leader in the latest and most innovative radar technologies and radar systems for naval ships (Thales Nederland B.V., 2019). Hengelo (OV) is the main location of Naval NL which develops, manufactures, and integrates naval mission and radar solutions for the defence market. Furthermore, Thales offers several services such as the repair of failed parts, the supply of spare parts and obsolescence management.

## 1.2 MARCONI project

Thales is currently involved in a project that is initiated in 2018 and which consists of maritime companies, knowledge institutes and service providers. Together, these participants are engaged in service logistics innovation. The project focuses on the development of service logistic control towers, in a maritime setting, in which several supply chain players participate. The project aims at developing decision support models that integrate the planning of operations, maintenance and resources, and the design of control towers from a business and information management perspective. The project is divided into three work packages with each a specific objective:

1. *Developing and demonstrating innovative service logistics concepts:* aimed at (1) reducing maintenance costs, (2) increasing safety by lowering the probability of unplanned system downtime, and (3) reducing the number of unnecessary sailing movements (emissions) through smarter planning and/or clustering of maintenance activities.
2. *Demonstrating the actual functioning of the remote service logistics control tower:* with the long-term goal of developing and exploiting a scalable supply chain function in the maritime world.
3. *Information management and creating value propositions:* aimed at valorisation and dissemination of knowledge, experiences and results, but also to contribute to an increased interest of young talents in "the logistics world".

## 1.3 Obsolescence

Obsolescence is a crucial problem in the defence sector. This concerns often complex systems (e.g., battleships) that are subject to continuous technological changes during their long life-time (Eruguz, Tan, & Houtum, 2017). Within this research, obsolescence is defined as: "the *transition of an item from available to unavailable from the manufacturer in accordance with the original specification"* (IEC 62402, 2019). One of the optimization services that Thales offers is proactive obsolescence management to ensure lifetime supportability of systems with optimum cost-effectiveness. Thales has created a policy for managing obsolescence, following an international standard. Since the first work package of the MARCONI project focuses, among others, on identifying obsolescence risks and designing a policy to prevent obsolescence-related problems, knowledge and information regarding the subject is shared between Thales and participants of the MARCONI project.

Managing obsolescence is becoming more and more important within Thales, mainly because of the following changes:

- Thales has changed from a project-oriented organization towards a product-oriented organization. This has led to an increase in standardized solutions and an increased awareness about obsolescence issues within the organization.
- The complexity of developed systems increases over the years. As a result, the maintenance of systems also increases in terms of complexity and therefore the impact of obsolescence is more significant.
- An increasing part of production is outsourced and due to technological changes, more parts are purchased from suppliers. This results in decreased life cycles and higher supplier dependency, making it crucial to manage obsolescence.

Thales is interested in obsolescence of tangible (i.e.,, physical) parts of products, restricted to two main areas:

1. *Electronics:* electronic part obsolescence is generally a result of rapid growth of technological developments within the industry. As a result, many of the electronic parts in a system have a life cycle that is significantly shorter than the life cycle of the system that they support (Bartels, Ermel, Pecht, & Sandborn, 2012). Obsolescence of electronic parts is shown to be a major reason for the high life cycle cost of complex systems (Solomon, Sandborn, & Pecht, 2000).
2. *Mechanical hardware:* technological changes in non-electronic parts, such as mechanicals, is happening at a much slower pace than for electronic parts. Mechanical parts in aging systems can break down frequently and in unexpected ways, triggering obsolescence due to the potential unavailability of spare parts. The principles for managing electronic part obsolescence and non-electronic part obsolescence issues are basically the same (Bartels, Ermel, Pecht, & Sandborn, 2012).

## 1.4 Previous research related to obsolescence at Thales

In this section we briefly describe previous research that is conducted in relation to obsolescence and has a connection with Thales, since Thales collaborates frequently with the University of Technology Eindhoven, the University of Twente, and the Dutch Navy.

The master thesis study of Hellegers (2017) focused on a quantitative comparison of obsolescence strategies for electrotechnical systems in the maritime sector. Within this research, three strategies are compared to indicate how to manage obsolescence. The first strategy is to perform a Last Time Buy (LTB), with repair option, to cover the demand of obsolete items during the remaining life cycle. Performing a LTB is defined as the procurement of items sufficient to support the item throughout it's life cycle, or until the next planned upgrade (IEC 62402, 2019). The second strategy is to modify the system to replace the obsolete item with a new, more sophisticated, technology. The last strategy is a combination of the LTB and modification options, meaning varying the timing of modification and the resulting LTB quantity. The study concluded that the LTB strategy can be beneficial, especially if the planning horizon is relatively short, and the demand rate low. Concerning the modification strategy, the study states that the optimal timing of modifications can often be classified into two categories. Either modifying as soon as possible or continuing as long as it is allowed with the LTB strategy. This indicates that a clear turning point exists between the LTB and modification strategy. However, sometimes there exists an extremely small range in which a combination is preferred. Hellegers (2017) concludes that the obtained benefits of such combination are usually low compared to implementing one of two defined solution categories.

Another master thesis study (Seuren, 2018) focused on changing from reactive to proactive obsolescence management. This study provided a decision support tool for the risk assessment process towards obsolescence. The tool is based on three main elements which are item criticality, probability of obsolescence issue, and solution consequences. Each main element has specific parameters and combining all these parameters, highly critical items that should be managed proactively are recognized. Although this research is performed with a broader view and in cooperation with multiple partners, Thales is currently implementing a more detailed risk assessment procedure.

Finally, a bachelor thesis study (Janssen, 2020) about the current obsolescence landscape is recently performed. This study focused on the current obsolescence management processes and procedures. This research is part of the MARCONI project and focuses, next to Thales, also on the Royal Netherlands Navy and their interrelationship. The research suggests, among others, that future research should be done on the exact cost calculation for different obsolescence solution strategies, since this could possibly influence the order in which the strategies and methods are being investigated in the future.

This master research study has a connection with the above-described research since we are interested in a (quantitative) comparison of obsolescence strategies in the maritime sector. The obsolescence risk and corresponding parameters could be incorporated in our research and the (exact) cost calculations of different strategies play an important role in determining the strategies. The main difference between the mentioned previous research and this study is that we incorporate that part of the life cycle before obsolescence occurs. Furthermore, not all details concerning the different processes and strategies are relevant for Thales Hengelo.

## 1.5 Problem description

In this section we describe the problem that Thales Hengelo is facing, and which part of the problem will be addressed in this research. As already described in section 1.3., managing obsolescence is becoming increasingly important. Since the systems that Thales manufactures have life cycles that may exceed 30 years, and often must be kept in service during a specified number of years, it is necessary to make sure that Thales is able to supply and maintain all spare parts.

Thales is currently trying to manage obsolescence more proactively and to standardize the whole obsolescence management process. Proactive obsolescence management means mitigation of future obsolescence at an early stage of the life cycle. Despite the standardization and documentation of processes and procedures is largely done (and still ongoing), the practical implementation is not as far as wished, and it is partially unknown how to proceed with this. It is expected that there will be a future trend towards Performance Based Logistics (PBL). This means that Thales is responsible for the availability of the customers system for a fixed price. Possible risks and (extra) costs regarding obsolescence are accountable to Thales in such PBL contracts. Whenever agreed service levels (e.g., system availability level) are violated, pre-defined penalties will result in for example extra costs or damage the reputation of Thales. Based on this, managing obsolescence in advance will become more and more crucial in future decades. This could be translated into the following problem:

*"The progress of the practical implementation of the defined proactive obsolescence management strategy is not as desired and not complete, which results in the fact that Thales is not ready for future trends towards PBL".*

Since the implementation of a proactive obsolescence management approach consists of multiple subjects (e.g., enhanced risk assessment, more frequent obsolescence monitoring and reporting, risk mitigation buy), we will specify our research. Whenever a new system is designed and sold to a customer, the supportability department determines which parts need to be maintained during the whole life cycle and how this should be performed. There is no model available to determine and compare different strategies for such parts that guides the process over (part of) the life cycle. In order to mitigate risks when a service contract is concluded with a customer, the expected required parts are purchased in advance to make sure that all spare parts can be supplied during the contracted service period. The result of this is that part of the purchased quantities remains left because the actual consumption is often lower than the quantity that is purchased. Keeping excessive stock results in extra costs, and finally part of the stock needs to be discarded. Thales does not know if the company possesses all knowledge about available strategies, the parameters which are available and how to incorporate this in a (mathematical) model. This research deals with the following problem:

*"Thales does not know which obsolescence strategy to choose for parts that need service during the life cycle of a system, right after the design process is finished, and what the impact of choosing a specific strategy will be".*

## 1.6 Research goal

The goal of this research is defined as follows:

*"Construct a model to assess the differences and impact of* *__obsolescence strategies__* *related to* *__maintenance significant items__**, after the design phase at Thales Hengelo in order to create a guideline on how to manage and to decrease the impact of obsolescence over the system life cycle".*

<u>Obsolescence strategies:</u> measures to minimize the impact or likelihood of having a demand for an item that cannot be fulfilled due to insufficient stock and the fact that the item is no longer available, over the long-term. Since we are interested in a strategy once the design phase is finalized (i.e.,, the system structure and spare part list are specified), considerations/strategies (e.g., using multi-sourced items) that could be used before, or during the design phase, will not be incorporated.

<u>Maintenance Significant Items (MSI):</u> tangible electronical items or mechanical hardware, which are part of a radar system, that potentially require maintenance during the system life cycle and can be replaced at an operational level (LRU) or at shop level (SRU). An MSI may be an assembly (i.e.,, consists of multiple items) or contain only one item. In case it concerns an assembly, Thales is the design authority. Otherwise, the MSI is purchased at the supplier and the supplier is the design authority. An MSI is reported as obsolete (e.g., becomes unavailable, if at least one item of this MSI is reported obsolete).

This research will deliver a prototype model, in Microsoft Excel or another applicable program, in which different strategies with corresponding parameters for obsolescence strategies can be calculated. The approach, results, conclusions, and recommendations will be reported in a thesis report.

## 1.7 Research questions

Based on the problem description and the research goal, we have formulated the following research questions.

**Chapter 2: Current situation**

This chapter describes how obsolescence is managed and the performance towards obsolescence at this moment in time.

*Q1.* *<u>What obsolescence strategies uses Thales Hengelo currently?</u>*

It is important to understand the current obsolescence strategies that are used for systems of Thales. In order to design eventually a suitable model, it is important to know which approach is used at which circumstances and how this affects business. Furthermore, the costs of the used approaches are to be determined. To answer this question, information and data is obtained from Thales by interviewing employees and accessing internal information systems. The following sub-questions are defined:

Q1.1 Which approaches for handling obsolescence are currently used and in which frequencies?
Q1.2 How are the costs of obsolescence approaches determined and how high are these costs at this moment?
Q1.3 Which service levels and corresponding Key Performance Indicators (KPI's) are used by Thales Hengelo to assess the performance of obsolescence management strategies?

First, we want to gain knowledge about the current strategies concerning obsolescence. This means the measures that are taken to minimize the impact or likelihood of having obsolescence problems.

Second, we will analyse how the costs of obsolescence strategies are determined and which factors play a role in this. Finally, we analyse the service levels and corresponding KPI's at this moment. This will give an indication of the improvement potential within Thales.

**Chapter 3: Literature study**
Chapter 3 describes the necessary literature to execute the research and to propose a proper model and conduct analysis. The research question is formulated as follows:

Q2. *What literature is available to construct and analyse a model for obsolescence strategies at Thales Hengelo?*

A literature study will be performed to elaborate on existing (scientific) literature. The following sub-questions are formulated:

Q2.1 Which obsolescence management strategies are used in literature?
Q2.2 Which parameters are relevant for determining an obsolescence strategy?
Q2.3 What are the Key Performance Indicators (KPI's) in obsolescence strategies?
Q2.4 How can the different strategies and parameters be modelled?

We start by creating an overview of relevant strategies concerning obsolescence, to see which knowledge is applicable for Thales. Secondly, research on the parameters (e.g., cost factors, lead times) that are of interest in determining a strategy is needed. KPI's are the subject of the third sub-question, we should investigate which KPI's play a role in obsolescence and under which circumstances we should focus on which specific KPI's. The final part of the literature study will focus how to model the specific strategies and their corresponding parameters.

**Chapter 4: Model development and solution design**
This chapter describes the model development and solution design for this research problem in detail.
*Q3. How can a model that assesses different obsolescence strategies for MSI's after the design phase at Thales Hengelo be constructed?*

Q3.1 Which method(s) should be used to construct a model?
Q3.2 What is the model formulation to assess possible obsolescence strategies?

In order to answer this research question, the proposed literature and process specifics are used to formulate the alternatives for modelling and solving the problem.

**Chapter 5: Model validation and analysis**
Chapter 5 deals with the validation and analysis of the proposed alternative(s) in chapter 4 to provide an answer to the following research question:

*Q4. Which strategy should Thales Hengelo use under which circumstances?*

In order to validate the formulated model, we need a case study to check the model. A case study based on real-life data will be performed to investigate the properties and performance of the proposed alternative(s), and to validate the proposed model. Expert opinions will also be used in the validation process. In addition, sensitivity analysis will be used to analyse the robustness of the constructed model (e.g., does the model results change if certain input data values are different) and to gain additional managerial insights.

**Chapter 6: Conclusions and recommendations**

*Q5. What are the conclusions of this research and what are the recommendations?*

In the final chapter the conclusions of this research will be given. Furthermore, the recommendations towards the implementation of the results and future research areas concerning obsolescence management within Thales Hengelo will be discussed.

## 1.8 Research scope

In order to emphasize the scope of this research, we have formulated the following delimitations:

- We focus on logistical obsolescence (i.e.,, items that become unavailable) in this research. Functional obsolescence (i.e.,, system requirements change) will not be considered.
- We will only consider tangible items restricted to electronic items and mechanical hardware of a system. Other area's (e.g., software, materials) are not incorporated in this research.
- We consider MSI's that can be replaced at an operational level (LRU) and can consists of multiple items, either produced by Thales or a subcontractor. Parts that can be replaced at a shop level (SRU) or parts for example only need to be cleaned will not be incorporated.
- We focus on radar system structures in general with a specified spare part list. We will indicate how the research/model applies to LRU's of a specific product (parts that are standard incorporated in a specific type system). Combining multple LRU's, or types of systems, is not within the scope of this research.

# 2. Current situation

In this chapter, we describe the current way of managing obsolescence at Thales Hengelo. We start by describing relevant obsolescence mitigation strategies for this research in Section 2.1. In Section 2.2 we describe the resolution strategies that Thales recognizes to resolve obsolescence. Thereafter, the life cycle stages and the corresponding service support phases are the subject of Section 2.3. The repair process will be described in Section 2.4. Section 2.5 describes the demand calculation of the final order quantity. Finally, relevant KPI's regarding obsolescence are given in Section 2.6.

## 2.1 Obsolescence mitigation strategies

Thales distinguishes multiple strategies to mitigate the risk and impact of obsolescence regarding their systems. Whenever the design of a product/project of Thales is finalized and the maintenance plans with corresponding spare parts are formulated, the first step is to perform a risk assessment. Based on the outcome of the risk assessment, the decision is made either to monitor obsolescence or to perform a risk mitigation buy. Another aspect that is incorporated is the process of technology upgrades to cope with obsolescence.

### 2.1.1 Obsolescence risk assessment

The aim of the risk assessment process is to understand the risk of items becoming obsolete. The risk assessment is executed on MSI level, where MSI´s that are produced by Thales are investigated on item level and purchased MSI are investigated on LRU level. Approximately 85% of all obsolescence issues are being experienced at item level at Thales.

The current procedure concerning the risk assessment process is based on an internationally defined standard (IEC 62402, 2019). This standard incorporates three main parameters to perform the risk analysis per item. The first parameter is the probability of an obsolescence issue. The probability of items becoming obsolete is indicated by looking at indicators that determine the supply risk. The first indicator is the Years till End of Life (YTEOL), which represents the expected number of years until the item will be obsolete. Whenever this indicator is not available, the average years until a new technology is introduced is used. The second indicator is the number of available sources/suppliers for the item. The second parameter is operational impact criticality. This parameter describes the potential loss of the product operational availability or capability. This focuses on the impact of the product in case that an item becomes obsolete. Thales wants to determine if it is still possible to deliver (part of) the product to the customer. Two main indicators play a role in determining the operational impact criticality. The first indicator is the probability of failure. It indicates the probability that the obsolete item in question needs to be replaced in the future, until the end of life (e.g., of product, or service period). This is calculated by multiplying the multiplicity of the item with the Mean Time Between Failure (MTBF). The second indicator is the impact on resolution costs, which indicates the impact on the total cost to resolve obsolescence. In general, the installed base is considered and the costs of either a Last Time Buy (LTB) or redesign, with providing new spare parts, are calculated to indicate the approximated costs. The last parameter is the consumption rate in relation to the stock level. Whenever an item is already obsolete, the stock levels and corresponding consumption rates are considered to indicate the risk of this parameter. The procedure results in the fact that approximately 95% of all items are categorized as medium risk. Since the procedure is very sensitive to individual indicators, Thales is improving this procedure and the accuracy of important measures.

### 2.1.2 Obsolescence monitoring

Thales monitors obsolescence for the products that are manufactured and operational at customer sites. The objective is to monitor the status of systems and to detect obsolescence (in advance). By doing this, actions can be taken to prevent the system in question from becoming less available than planned. On a periodically basis (e.g., quarterly), products and projects of Thales are scanned for obsolescence. Thales uses an in-house built program called 'obsolescence management information system'. This program represents the connection between different databases (e.g., inventory levels, historical demand, bill of material). First of all, Thales focuses on items that are already obsolete (i.e.,, Product Discontinuous Notice (PDN) is already received) and are expected to cause problems within 4 years. Secondly, items that are expected to become obsolete within 4 years are reviewed. A horizon of 4 years is chosen to make sure that there is enough time to execute a resolution (e.g., redesigns can have a lead time of multiple years). Since most items are incorporated in multiple products/projects, notes on already taken resolutions/actions are incorporated. Based on the analysis on item level, Thales looks which MSI's are affected. The costs of obsolescence monitoring will be described in Section 2.6.1.

### 2.1.3 Risk mitigation buy

Performing a Risk Mitigation Buy (RMB), also known as All Time Buy (ATB), means the procurement of items sufficient to support the product or project throughout the remaining life cycle/service period, or until the next planned technology upgrade. The aim is to reduce an identified obsolescence risk to a product or project. Thales defines a risk mitigation buy as a proactive risk mitigation measure, triggered by an unacceptable obsolescence risk. Risk mitigation buys are, when decided to use this strategy, often performed at the beginning of the life cycle of a project to make sure that defined service levels (e.g., spare part availability) will be attained at all time. The purchase price per item might be lower when Thales buys a large quantity in advance, but this is supplier/case dependent and not the main goal of pursuing this strategy. The order quantity is calculated in the same way as for the Last Time Buy (LTB), which will be explained in Section 2.5. Furthermore, especially for relatively cheap items this is often assumed to be a legit strategy at Thales. The advantage of this strategy is that obsolescence monitoring of such items is no longer necessary in general.

### 2.1.4 Technology upgrade

At predetermined points in the life cycle of a product, a technology upgrade (planned redesign) is performed by Thales Hengelo to upgrade the current product (installed base). Such technology upgrades are part of the technology roadmap and are initialized by the responsible product team at Thales since they construct and make products for customer solutions (including accompanying services). Whether specific parts of a system can be incorporated in a technology upgrade is established by the product team. The reason of such upgrades can have multiple origins. For example, because it is expected that specific items/parts of the system will become obsolete in several years. Another important point is the fact that the product team wants to maintain the product in the future and therefore, after some years a refreshment should be performed. This will result in the fact that the product stays compatible with required specifications and business opportunities will continue to arise for Thales. In practice, technology upgrades at Thales are often performed each 5 or 10 years. In general, Thales assumes that electronical items become obsolete after approximately 7 years. By using the repair option (both performed by Thales or subcontractors), this period can generally be extended with a few years (e.g., 3 years). Although a technology upgrade can result in improvements of the product (e.g., higher reliability or reduced power requirements), the main purpose of technology upgrades is to prevent obsolescence.

## 2.2 Obsolescence resolution strategies

Thales uses multiple sourcing options to cope with items that are announced obsolete. Once a PDN is received, a change request is initialized to deal with the item(s) that are announced obsolete. Although the used strategy depends on the circumstances and can differ per case, Figure 1 shows the general resolution process that is used by Thales.

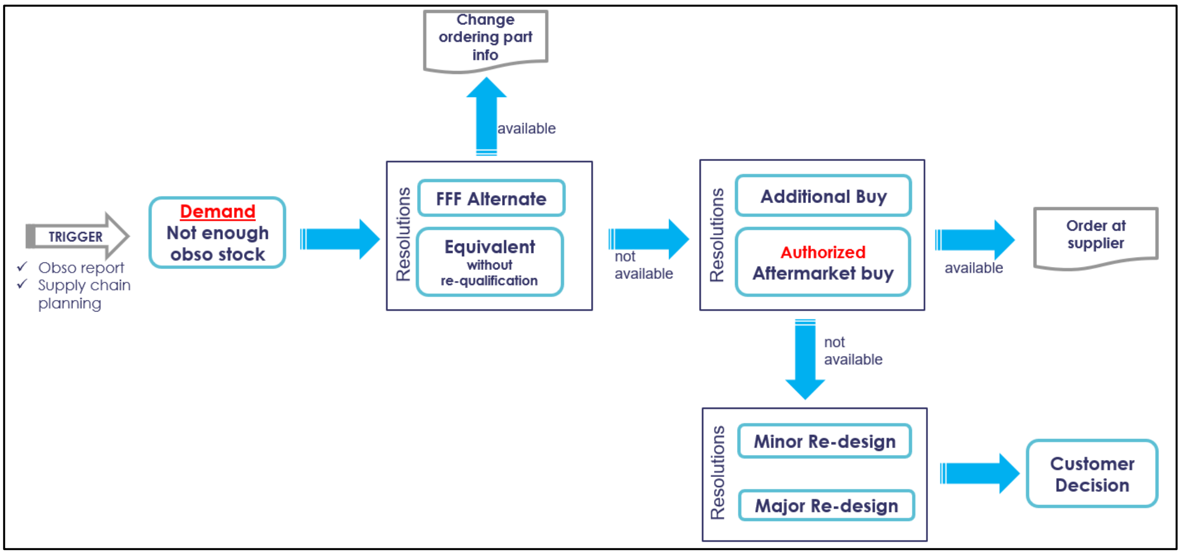


*Figure 1: Flowchart of the resolution decision process at Thales Hengelo.*

Whenever an item is expected to become obsolete at a certain point in time, an obsolescence trigger arises to start the change process. Once an obsolescence trigger arises during the obsolescence monitoring process or when a PDN is received from the supplier, first the existing stock is analysed. Available existing stock that is already stored in warehouses, is sometimes already allocated to specific projects due to contractual agreements. All other ‘free stock’ can be used to cope with demand. Since the existing stock is rarely sufficient, the second step in the resolution process is to investigate whether a substitute item can be found. Substitute items can replace the obsolete item and are characterized by having the same form, fit, and function (FFF). Thales distinguishes two categories. The first category are equivalent items (i.e., items that are functionally, parametrically, and technically interchangeable with the obsolete item). Only minor testing might be required to validate the use of such items. The second category are alternate items, which have a different performance than the obsolete item. This category is assumed to contain more complex replacements and need more testing and requalification, which means that it is more expensive. In practice, the two categories are not treated separately. It often concerns substitutes that require no design changes, or only minor modifications. This option is relatively cheap if requalification is not needed, as the internal change process is assumed to be no higher than €15.000 in general. Requalification is needed when an alternate item is not identical to the original item and needs to be requalified. Items with a low obsolescence risk can often be replaced by a substitute.

The next step in the resolution process, probably in combination with a substitute item, is to perform an additional buy, which is basically an LTB. This strategy can be used in case a substitute is not available, or to procure items for future demand. As mentioned in Section 1.4, an LTB is the procurement of items sufficient to support the life cycle demand of the product or until the next planned redesign. The difference between an RMB and an LTB is that an LTB is a consequence of a PDN from the supplier. Normally, this is the last opportunity to buy the item from the original manufacturer. To calculate the LTB quantity, an impact analysis is performed on the expected demand for new products, spare parts, and repair activities. This calculation will be described in more detail in Section 2.5. Furthermore, in some situations the authorized aftermarket might be consulted to gain additional stock. Although this strategy is not preferred at Thales and is not standard pursued, in some cases it is a valuable sourcing option to cope with (unforeseen) future demand. This sourcing option is sometimes used to buy additional items when the item is already obsolete and future customer demand arises at a later stage of the life cycle.

In case the obsolete item cannot be replaced by any of the above-described strategies, a redesign is used to modify the product. A redesign may also be required whenever the LTB quantity is insufficient to cover demand during the rest of the life cycle. Another reason for a redesign might be related to the large uncertainty in estimating the size of an LTB. Having too much risk to proceed with the LTB option, might make a redesign favourable over the LTB option. Based on experience and expert opinions, Thales determines the redesign impact of items. Thales categorizes redesigns as either low, medium, or high impact. Impact refers to the degree the MSI/system needs to be adjusted, but also to cost related aspects. The category 'low impact' is assigned to minor redesigns (e.g., a small adjustment for one item), where the costs are relatively low (<€15.000). Approximately 85% of all cases are limited to a minor, low impact, redesign. The 'medium impact' category represents a redesign that effects multiple items and where the costs are significant (e.g., board re-layout), typically between €15.000 and €200.000. About 10% of the redesigns are categorized as medium impact. Redesigns that are categorized as 'high impact' affect in general the whole MSI (e.g., board replacement with new layout) and investment costs are high, often higher than €200.000. Such redesigns on individual an MSI only occur sometimes (about 5% of all cases). Furthermore, there are multiple types of modification kits that are used. By using such modification kits, depending on the complexity of the obsolete item, the obsolete item can be replaced by another item with only relatively small changes. The costs for redesigning are related to engineering, program management, integration, requalification, and testing. Engineering change proposals are used to document and manage all redesigns within Thales. A redesign caused by obsolescence should have a life cycle time of at least 5 years to avoid customer frustration. This means that the redesigned item can be produced for at least 5 years. Furthermore, the support activities should be available for at least 10 years. Table 1 gives an indication of the frequencies of the used resolution strategies in 2019. Approximately 200 items were announced obsolete in 2019, not all change requests to cope with this are finished yet. In case there is no action needed, there is for example no expected future demand or only a part order number has changed.

*Table 1: Frequency of used resolution strategies in 2019.*

| **Resolution strategy** | **Frequency used 2019** |
|---|---|
| No action needed | 18 |
| Existing stock | 12 |
| Substitute (FFF alternate) | 11 |
| Substitute (equivalent) | 31 |
| Last time buy | 38 |
| Authorized aftermarket[1] | 51 |
| Minor redesign (modification kit) | 5 |
| Major redesign | 1 |

[1] Authorized aftermarket is used for items that were announced obsolete before 2019.

## 2.3 Repair process

A subset of MSI’s of each product of Thales can be repaired. Whether an MSI can be repaired or not is indicated by the engineering department of Thales or by the supplier and is based on the technology. In case an MSI is repairable, it is assumed that repairs can only be performed for 5 subsequent years after the part is announced obsolete (e.g., after receiving PDN). After these 5 years, the required test equipment and/or knowledge is often not available anymore. Furthermore, Thales assumes that suppliers are only willing to repair supplied items for approximately 5 years after they are announced obsolete. The decision whether to perform a repair depends also on the purchase price of the failed MSI. Experts of Thales state that the minimum costs for a repair (diagnostics and simple repair activities) are approximately €3.000. Since it is assumed that an MSI is beyond economic repair when the repair costs are higher than 60% of the original purchase price, MSI’s that have a cost price of less than €5.000 are not repaired at all in general. Experts of Thales assume a repair yield of 90% in general for all repairable MSI’s, which means that 10% of the failed MSI’s is not successfully repaired and a new MSI needs to be used in such cases. Thales also recognizes a restriction on the maximum number of repairs performed per MSI. For electronical parts, the maximum is assumed to be around 3 repair activities since the required specifications are no longer guaranteed after more repair activities. Finally, Thales follows a policy where all failed parts are repaired immediately. This means that the repair process can be used in all obsolescence management strategies to fulfill spare part demand requests.

## 2.4 Life cycle management

In this section, first we describe the product life cycle stages and the corresponding service support phases at Thales. Thereafter, we shortly describe the life cycle of items.

### 2.4.1 Product life cycle stages and service support phases

Each product of Thales has its own life cycle. The product life cycle consists of five stages. For each stage, a corresponding service support phase is defined. The content depends on the contracted services (e.g., solving obsolescence, repairs, inventory optimization). The duration of each product life cycle depends largely on the market and sales evolution. As described in Section 2.2.4., Thales uses technology upgrades and therefore creates new versions of a product. Each product team formulates a policy for the transition between different product versions and for the corresponding service support phases. Figure 2 visualizes the phases.

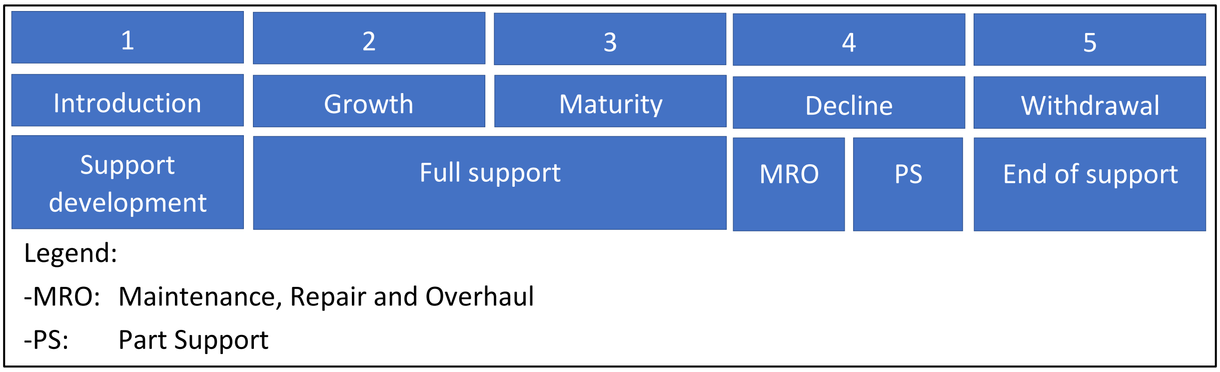


*Figure 2: Product life cycle management and service support phases*

In the introduction stage the product design is finalized, and the marketing and sales departments of Thales create an entry into the market. After a growth stage, in which early adopters and an increasing number of customers acquired the product, the majority stage is reached. In the maturity stage, the product is fully accepted in the market which means that also the expectant customers have acquired the product. After some years, the market demand will decline and usually few additional products are sold. Finally, the withdrawal stage is reached which means that the product is slowly phased-out and the production is stopped. Regarding the obsolescence related services that Thales offers, the first phase is the support development plan for maintaining the product. From the moment the product is installed, it is in full support. Full support means that Thales is fully responsible for managing obsolescence for the complete product. Due to uncertainty in obsolescence, it might occur that obsolescence occurs in an early stage of the life cycle. Thales manages the mitigation and resolution strategies in this phase regarding the product and potential obsolescence issues are incorporated in technical upgrades. Once the product enters the decline life cycle phase, the support is transited into Maintenance, Repair and Overhaul (MRO). This means that obsolescence is monitored and focused on the standard defined spare parts. Resolutions are studied case by case (i.e., per item) and depend on customer requests. Approximately halfway the decline phase, the service support is transited towards Part Support (PS). In the part support phase, Thales monitors obsolescence and corrective actions are only executed whenever customer requests are made. In such cases, the customer has budget to cope with the incurred costs and Thales has no supply obligations. Finally, when the end of support is reached, Thales stops monitoring obsolescence. In case there is still a customer request, Thales makes their best effort to help the customer but (in general) at full expense of the customer. The life cycle of the support phases is determined per product. In some cases, the duration of life cycle phases and/or support phases are extended. Possible extensions should be analysed beforehand to make sure that obsolescence is still manageable, this process is not always aligned within the different departments.

### 2.4.2 Item life cycle

The items that Thales uses in products follow the same five life cycle stages as described in the product life cycle. Thales uses a commercial tool (IHS 4D online BOM Manager) to access external market information about the life cycle stage of each item. This tool collects information from worldwide suppliers, and this is connected to the bill of material of a product. Next to the life cycle stage, the YTEOL are incorporated to give an approximation of the year at which items are expected to become obsolete. Unfortunately, this tool only provides data for a subset of the items. Therefore, Thales uses the following categories to define the status of each item:

- Obsolete, stock available
- Obsolete, no stock available
- Available, life cycle stage and/or YTEOL known
- Available, life cycle stage and YTEOL unknown
- Available, life cycle prediction and YTEOL are unknown but since it concerns low risk items that are cheap, it is expected that YTEOL is minimal 10 years

Thales assumes for items, which have no assigned prediction, that they are available until additional information is available. The result of this is that items are sometimes already unavailable without Thales knowing it. As already described in Section 2.1.4, currently it is assumed that electronical items become obsolete after approximately 7 years due to new technology.

## 2.5 Determining the final order quantity

In case Thales decides to perform either an LTB or RMB, the expected demand and the quantity to procure need to be determined for the corresponding item. Basically, the expected future demand is a summation over the needed (initial) items to manufacture new products, and the number of items needed for service activities (i.e., the provisioning of spare parts and performing repairs). In case the period which needs to be covered with the LTB is not explicitly stated, a period of 10 years is assumed. A distinction is made between two categories. The first category contains relatively cheap items that are used by Thales to manufacture an MSI. For items of the first category the number of items for new production is calculated and it is assumed that a standard additional 15% (over the installed base and future sales) is enough to cope with future needed spare parts and repair activities. Experts of Thales state that this is sufficient for the calculated period in general. Furthermore, for such items a substitute is often available since it concerns relatively simple items which can be ordered at multiple suppliers.

The second category represent more expensive and complex items that form an MSI, without any additional manufacturing activities (i.e., one item represents one MSI). For calculating the demand of such items, Thales incorporates the failure rate of the MSI to calculate the expected annual demand more accurately. A distinction is made between items that are subject to ´wear-out' (i.e., mechanical items) or not. Since the failure behaviour of electronical items have a constant failure rate, the MTBF can be used to calculate the number of required items (i.e., the number of expected failures). The annual demand is calculated by multiplying the total number of operational items with the annual operational hours and then divided by the MTBF, which results in the spare part demand rate per year. This number is then multiplied with the number of years that should be covered with the final order quantity. As described in Section 2.3, in case the MSI is repairable, 90% of the annual demand for the first 5 years is subtracted from the total demand. The required number of items needed for initial production should be added.

Thereafter, a Poisson distribution is used to calculate the required stock with a 99% confidence level. The Poisson distribution calculates the probability of having a certain number of events during a specific period (i.e., the number of years), based on the expected total calculated spare part demand. The minimum number of demands ($X$) to attain the confidence level is found by solving the Poisson function until the cumulative probability is equal to, or lager than, 99% (e.g., there is 1% chance that the actual demand will be higher than accounted for). Once the expected demand is calculated, the on-hand inventory is subtracted, and the calculated number of items is always reviewed by experts of Thales. To minimize the risk of having shortages, the final order quantity is often higher than calculated. There is no standard safety factor included, but this is rather based on experience. In some cases, this might be necessary/appropriate, but in general will this result in excessive stock and therefore higher total costs, which we will discuss in Section 2.6.2.

In order to illustrate the process of determining the final order quantity, for both categories an example is given based on the input of Table 2.

*Table 2: Input for final order quantity calculation examples.*

| Input | Category 1 | Category 2 |
|---|---|---|
| Installed base (nr. systems) | 20 | 20 |
| Future sales (nr. systems) | 15 | 15 |
| Annual operating hours | 2.000 | 2.000 |
| Multiplicity of LRU per system | 3 | 3 |
| Multiplicity of item per LRU | 4 | - |
| MTBF | 1.000.000 hours | 50.000 hours |
| Repairable | No | Yes |
| Planning period (years) | 10 | 10 |

For the category 1 example, the final order quantity (Q) is calculated by:

$$\begin{aligned} Q = (&future\ sales * multiplicity\ of\ LRU * multiplicity\ of\ item) \\ &+ ((installed\ base + future\ sales) * multiplicyt\ of\ LRU \\ &* multiplicity\ of item) * 15\% = (15 * 3 * 4) + \big((20 + 15) * 3 * 4\big) * 15\% \\ &= 180 + 63 = 243\ items \end{aligned}$$

The final order quantity (Q) for the category 2 example is calculated by:

$$\begin{aligned} Q = (future\ sales * multiplicity\ of\ LRU) + \ min \sum_{i=0}^{X} \frac{(SP\ demand)^i * e^{-(SP\ demand)}}{i!} > 99\%) \\ = (20 * 3) + 35 = 95\ items \end{aligned}$$

Where:

$$Spare\ Part\ (SP)\ demand = annual\ SP\ demand * planning\ period - repair\ fraction$$

$$\begin{aligned} = \Big(&\frac{nr.of\ systems * annual\ operating\ hours * multiplicity\ of\ LRU}{MTBF} * planning\ period\Big) \\ &- (5 * 90\% * annual\ SP\ demand) = \frac{35 * 2.000 * 3}{50.000} * 10 - 5 * 90\% * 4{,}2 \\ &= 23{,}1\ items \end{aligned}$$

Concerning the expected future needed initial items for production. The sales and marketing departments are, together with the product team, responsible for forecasting the expected future sales of each product. Based on these forecasts, Thales can indicate the expected required production for a specific number of years. The forecasting is based on orders that are already contracted, and current tenders that could be contracted in de coming years (with some uncertainties incorporated).

## 2.6 Key performance indicators

In this section we describe obsolescence related KPI's to state the performance. First, we describe the key drivers of obsolescence costs. Thereafter, we give an indication of the excessive stock level. Finally, we discuss the measures that are important in service related activities regarding MSI's at Thales.

### 2.6.1. Key drivers of obsolescence costs

The costs of managing obsolescence are divided into three key drivers, see Table 3:

*Table 3: Main drivers obsolescence costs (2019).*

| | **Total costs** |
|---|---|
| **Obsolescence management** | €590.000 |
| **Last time buy** | €1.100.000 |
| **Redesign**[2] | €100.000 - €2.000.000 |

Concerning the costs of obsolescence management, we refer to the relevant costs to manage obsolescence for all products of Thales Hengelo. The approximate total costs were €590.000 in 2019. The obsolescence department distinguishes four areas where management hours are spent on. The first area is customer account team, which represents the hours spend on requests for quotation, contract bids and specific customer questions. The second area contains hours spent on monitoring of products. These hours are related to spare/obsolescence review boards and handling change requests. Projects are the third area, and these hours are mainly spent on creating obsolescence reports for customers. Finally, part of the monitoring hours is spent on in-service support contracts. Altogether, a large part of the total costs is spent on performing analysis, reporting of product status, and managing/resolving obsolescence triggers.

In 2019, approximately 38 LTB's were performed to cover expected demand for obsolete items. The total value of all LTB's together is approximately €1.100.000. The variation in individual order characteristics is high, for example one order of 90.000 items with an individual purchase price of €0,50 per item. Another LTB is related to a complex LRU with a purchase price of approximately €5.500 per item and an order quantity of 25 items.

The main cost drivers of redesigning are the non-recurring engineering costs (i.e., engineering hours and requalification) which are required to modify the product and to restore it to its original or required specification. In 2019, a few (minor) redesigns are performed which are initiated because of obsolescence. Due to case dependent costs, a range between €100.000 and €2.000.000 is assumed but this can be different in specific periods of time.

[2] Technology upgrades/planned redesigns are not incorporated since such redesigns are product specific and the relatively high cost depend on the strategy and technology roadmap.

### 2.6.2. Excessive stock

As a result of all (final) order quantities that are purchased from suppliers, excessive stock is build over the past years. This is partly because ordered quantities are sometimes higher than actual demand, and the fact that are mismatches between expected versus actual (future) installed base developments. The market segment in which Thales operates is very uncertain, therefore it is difficult the forecast future demand. Thales Hengelo is currently analysing which part of the obsolete stock might be discarded. A distinction is made between two categories. The first category represents stock for which no future demand is expected (at least not for new production, maybe a proportion can be used to support existing products). The second category represents surplus stock, for which the expected demand for new production and an additional safety stock is already subtracted. The values for both categories are respectively 7.5 million and 2.9 million. Again, since the spare part demand is not incorporated, these values are rough approximations. Over this stock, yearly holding costs are incurred and eventually there is a high chance that a large percentage of this stock needs to be discarded. Although the review process of the excessive stock is recently started, it is expected that at least a fraction will be discarded in future years.

### 2.6.3. Service support related KPI's

Concerning the service support that Thales offers to customers, two main KPI's are in place that are also related to obsolescence. The first indictor is the availability level of the MSI's (spare parts) and inventory, and therefore also of items. Depending on the different customer contracts, Thales aims at a certain availability level of MSI's and inventory which we need to keep in mind. This means that the obsolescence strategy should result in only a predetermined chance of being unable to supply an MSI during the contracted period. For only a few contracts (PBL), a certain spare part availability (e.g., 90%) should be attained. Backorder costs are incurred when this level is not attained. Thales is about to implement the first batch of such contracts, which means that there is no indication concerning the actual performance on this service level. In all other cases, where Thales has no direct obligations to fulfill spare part demand directly, of course the spare part demand should be fulfilled at some point in time. Although there is no evident statement regarding the service level in such cases, some experts of Thales state that a stock-out probability of 10% is plausible (meaning that 90% of the spare part demand should be directly fulfilled).

Second, the incurred cost is an essential performance indicator in the process of managing obsolescence. This means the total costs of choosing a specific obsolescence strategy over the reviewed life cycle period. Currently, Thales reviews the initial investment costs of a strategy but the long-term cost factors (e.g., holding costs, excessive stock) are not incorporated.

## 2.7 Conclusion

Obsolescence management at Thales Hengelo consists of multiple mitigation and resolution strategies. Based on the current risk assessment process, which results in the fact that 95% of all items are categorized as medium risk, we conclude that the probability of obsolescence, operational impact criticality, and the consumption rate versus stock level should be incorporated in our model. Concerning the probability of obsolescence, we should use the YTEOL as main indicator.

Thales Hengelo spends yearly approximately €600.000 on obsolescence management, of which a part is related to obsolescence monitoring, which means that obsolescence issues are often noticed in advance. Based on expected obsolescence issues, measures could be initiated in advance. With the upcoming trend of PBL, Thales considers the possibility to perform risk mitigation buys to minimize risks for projects/products. Whenever items are announced obsolete and there is not enough stock, a substitute item is introduced if one is available. Substitutes can often be found for relatively cheap/simple items and should therefore not be included in the model. In all other cases, an LTB is often executed to build enough inventory for future years. Since redesigns are expected to be relatively costly, this resolution strategy is not often pursued. Performing LTB's contributes to increased excessive stock costs, which represents a high value that should potentially be discarded in the future.

We conclude that the main issue in the current situation is the is the lack of alignment between obsolescence monitoring, using planned redesigns (technology upgrades) and other resolution strategies to deal with obsolescence over the product life cycle. This issue is caused by lack a of communication between departments and product teams. Planned redesigns are performed on a regular basis and require high investment costs. In practice it might be possible that an LTB is performed for an item for the next 10 years, although there is already a (planned) redesign initiated. Furthermore, we conclude that there is no clear analysis concerning the costs and impact of specific obsolescence strategies available.

Therefore, we conclude that our model should focus on the comparison of the following strategies:

- Risk Mitigation Buy (RMB) / All Time Buy (ATB) at the start of the life cycle
- Obsolescence monitoring and react when obsolescence occurs
    - Perform an LTB
    - Initiate an unplanned redesign
- Include the MSI in planned redesign(s) (technology upgrade(s))

In the literature study, we should investigate how the above-mentioned strategies can be formulated and modelled to create more alignment between the different mitigation and resolution strategies. Furthermore, the repair option should be incorporated, and the performance measures should be determined. Finally, we should study how uncertainty/variation in installed base development and the probability of obsolescence could be incorporated in our model.

# 3. Literature study

In this chapter, we describe the performed literature study to create more insights about obsolescence related topics that should be incorporated in the model. We start by describing the subject of obsolescence monitoring in Section 3.1. In Section 3.2., the final order quantity problem will be discussed. The redesign process is emphasized on in Section 3.3. Thereafter, Section 3.4 describes how the repair process can be used as additional source of supply. Finally, the role of uncertainty and how to deal with this is the subject of Section 3.5.

## 3.1 Obsolescence monitoring

Obsolescence monitoring involves tracking items and their manufacturers, to determine the item's current availability status and, where possible, when the item will become obsolete. The degree to which obsolescence monitoring is required and which obsolescence management approach should be used is based on the obsolescence risk assessment, as described in the international standard concerning obsolescence management (IEC 62402, 2019) that Thales uses. For a large subset of electronic items commercial databases are used and the data is frequently analysed at Thales. Effective monitoring requires accurate data. One form of monitoring is based on notices of obsolescence. These notices can be in many forms depending on the technology and the organization's processes. Careful review of the manufacturer's notification documentation, including 'errata', may be necessary. The title of the notification does not always reflect its meaning and may require obsolescence activities. As within the industry of Thales, the electronics industry normally issues a Product Discontinuous Notice (PDN) to indicate the items for which the production will end after a specified LTB date.

In case the available information is not sufficient to facilitate monitoring and surveillance, which is often the case with many Commercial Of-The-Shelf (COTS) items and non-electronic items, monitoring can be achieved by using direct contact with the manufacturers (IEC 62402, 2019). The customer/manufacturer relationship should be leveraged to allow for the exchange of timely information about obsolescence. If applicable, contractual arrangements between organizations should be used to ensure that obsolescence information is actively monitored in the supply chain by the manufacturer, in order to provide an appropriate and timely response by all the affected levels in the supply chain. Some research can directly be done by assessing the manufacturer's website while other manufacturers need to be contacted. The data that should be collected includes planned item upgrades (obtain information on new features, versions, add-ons, functionality), updated item support information (vulnerability updates, end of support), assessment of manufacturer stability, and upcoming releases and related items. For complex and expensive items, direct contact with manufacturers is therefore required at Thales since the impact of missing a PDN can be high.

## 3.2 Final order quantity problem

The final order quantity problem is concerned with the last order that is placed at the supplier. Once the manufacturer of an item announces discontinuance of production, often a last opportunity to place an order is offered. The LTB option can be used to procure enough items to fulfil demand for the entire remaining life of the item, or until a redesign is finished, and therefore maintaining the availability at system level. This is categorized as a reactive approach. The LTB quantity if often relatively high to attain a high service level, which also yields high inventory levels at the end of the service period. Therefore, companies try to mitigate these risks and the costs involved by considering alternative sourcing options. Literature elaborates on multiple sourcing options such as repair of failed parts, retrieve parts from dismantling, perform extra production runs, or use external markets.

A key advantage of using such alternative supply options is that the decision to supply parts from alternative options can be postponed, thereby reducing the level of uncertainty. As concluded in Section 2.7., the repair of failed items from the field is an additional source of supply for Thales. Relating to the final order quantity problem, we incorporate the possibility to perform a Risk Mitigation Buy (RMB) in our model. An RMB, also referred to as All Time Buy (ATB) or a life of need buy in literature, means the procurement of items sufficient to support the product throughout its life cycle, or until the next planned technology upgrade. The difference with an LTB is that the item is not announced obsolete yet and this approach is categorized as proactive.

In literature, multiple scientific papers study the LTB decision with the repair option. Van Kooten and Tan (2009) study the LTB decision with the repair option as alternative. They aim to find the LTB quantity to avoid reaching the maximum number of allowed backorders in the system. In their research, a transient markovian model is built to represent the problem for a repairable spare part with a certain repair probability and repair lead time. Van Kooten and Tan (2009) assume that repair is always preferred over LTB (if repair is feasible). Furthermore, they consider a push repair policy which means that all the failed parts are repaired immediately. An approximate method is developed by Krikke and van der Laan (2011) to find a near-optimal LTB quantity while satisfying a maximum stock-out probability just before a phase-out occurs. They include the repair of failed parts, among others, as additional source of supply. Only at points in time where phase-out returns occur, decisions on using the repair option can be made. In our case, parts of the system that have failed can (and should be) directly repaired. Furthermore, Behfard et al. (2015) constructed an approximate method to find the near-optimal LTB quantity, and to determine a near-optimal repair policy. They use a Stochastic Dynamic Programming (SDP) approach and an approximate method by assuming a base stock policy for the repair decision. Based on the conclusions from Chapter 2, we focus on a push policy for the repair decision which means that the repair of failed parts is not a decision. Hellegers (2017) uses the above-described method, in combination with a modification strategy, which we will discuss in Section 3.3.

When considering the final order quantity problem, the risks associated with long term storage of the item along with risks such as the possibility of loss or damage should be considered in conjunction with the usage rate. The appropriate storage conditions should therefore be analysed to achieve successful storage, as some items may require special storage conditions. Some items might require periodic inspection, analysis, and testing to ensure their suitability for usage (IEC 62402, 2019). Ignoring these aspects, could result in high value inventory that is useless, and another resolution is required with extra costs. Concerning the costs of a final order, Teunter and Fortuin (1999) incorporate various cost factors of the total life cycle cost of an item. Commonly used cost factors are procurement costs, inventory costs, disposal costs, and penalty costs. A final order should be considered when:

- there is a known, or forecast of, the obsolescence date
- the life expectancy or production of an item is short and/or there is low demand
- an item is procured to satisfy an urgent operational need
- difficulties caused by future design changes of the item need to be avoided
- there is enough storage capacity
- items' shelf-life allow long term storage
- to avoid difficulties caused by sub item design changes by its manufacturer, resulting in subtle changes in the construction of items

Most of the above-mentioned aspects are, depending on the item/system, applicable for Thales.

## 3.3 Redesign process

In the redesign strategy, the part in consideration is slightly modified in order to replace the obsolete component with a new technology. This new technology will perform the same task but is probably more advanced (e.g., better functionality, lower failure rate). By redesigning (part of) the system, one avoids making difficult decisions regarding LTB quantities. A disadvantage is that redesign programs for defence systems need to go through time and costs consuming qualifications/certifications that make the entire process of redesign extremely expensive (Solomon, Sandborn, & Pecht, 2000). Most of the literature emphasizes on using a design refresh planning (referred to as 'technology upgrade' within Thales) method to minimize the life cycle sustainment costs of products. Singh and Sandborn (2006) describe a method that determines optimum points during the product's support life at which the design of all, or parts, of the system should be updated and (future) obsolete items should be replaced. Their methodology minimizes the total life cycle cost by determining the optimum combination of design refresh schedule for the system (i.e.,, when to refresh the design) and the design refresh content for each of the scheduled design refreshes. Such analysis methodology can be used to generate application-specific economic justifications for design refresh approaches to obsolescence management. The key input that enables refresh planning is obsolescence forecasting (Singh and Sandborn, 2006).

Kumar & Saranga (2010) argue that the decision to replace an obsolete sub-system/part with one incorporating the latest technology is driven by many factors and requires careful analysis. For example, system integration issues may force a major redesign of the LRU in which the obsolete part is embedded. In such cases, it may be convenient to choose an LTB strategy for the obsolete part. The research of Kumar & Saranga (2010) focuses on an LTB strategy, redesign strategy, and the combination of the LTB and redesign strategies. A restless bandit model is constructed for the selection of the optimal strategy, where the decision maker chooses (1) to procure parts required for the current period only, or (2) to redesign the part during a period. They conclude that the main advantage of the bandit process approach is that the model allows the decision maker to update the model parameters when we transfer from one interval to the next. Furthermore, the above-described research suggests that the part characteristics before and after redesign are different.

The research of Hellegers (2017) considers the maritime sector, in which Thales also operates, and focuses next to the LTB with repair strategy also on a modification strategy. By modifying the system, the difficult decision regarding LTB quantities is avoided since parts are widely available again after modification. In order to optimize the timing of modification, Hellegers (2017) constructed a combination model that includes both strategies. The modification strategy is optimized using Renewal theory, for which multiple forms of maintenance costs are incorporated. As performance indicators, Hellegers (2017) uses the availability level and total relevant costs.

## 3.4 Repair process

As already mentioned, repairing failed items from the field is a valuable additional source of supply. Behfard et al. (2015) state that using repair as alternative option is worth considering even when it costs considerably more than buying a new item. Especially once a final order should be placed, since the decision about the quantity and the timing of repairs is based on an explicit cost trade-off (compared to buying a new part at the beginning) and the evolution of the system over the life cycle. The general repair process, as visualized in Figure 3, consists of multiple parts. At the start of each interval (1) a number of successfully repaired ready-to-use items arrive, (2) a number of ready-to-repair items that failed have been returned from the field, (3) the current inventory position is registered, and (4) a decision should be made on the quantity of parts to repair.

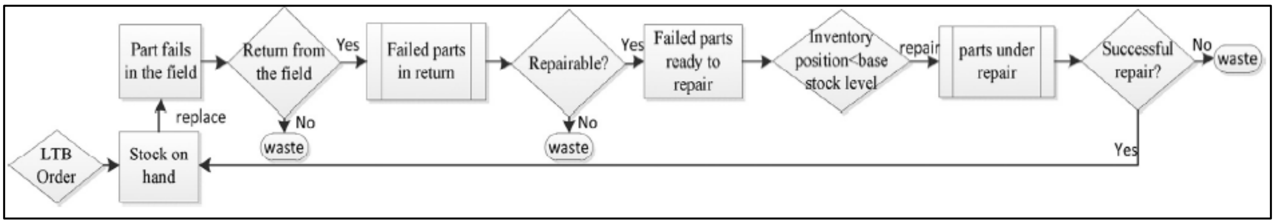


*Figure 3: General repair process (source: Behfard et al. (2015))*

In the LTB with repair model of Behfard et al. (2015), this process is used to calculate how many items should be ordered in the final order option. Some important characteristics of the repair process should be considered:

- there is a certain return yield of failed items from the installed base, which refers to the percentage of failed items that is send back for repair
- there is a certain repair yield, which is the probability of individually repairs being successful
- there is a certain return lead time for failed items from the field
- there is a certain repair lead time for each individual repair

In order to incorporate the repair option into a mathematical model, multiple ways to determine the number of successfully repaired parts are available. Behfard et al. (2015) model this as a random number, depending on the number of initiated repairs. The binomial distribution is used by Hellegers (2017) to indicate the probability of having a specific number of successfully repaired parts since using a Binomial distribution over a random number represents the situation more realistically, because it is based on the ready-to-repair inventory and the current inventory position.

## 3.5 Incorporating uncertainty

In the strategies and corresponding parameters that we should incorporate in our model, multiple forms of uncertainty and variation can be recognized. Some forms of uncertainty are the uncertainty in obsolescence forecasting, the future sales/installed base development, and the initial (non-recurring) redesign costs. Solomon et al. (2000) use Monte Carlo simulation to cope with uncertainties in the input for the cost analysis, their simulation focuses for example on the re-qualification costs associated with a particular type of qualification test. Monte Carlo simulation is a technique that simulates a physical process a specified number of times, where each simulation run is started with different start conditions. The result of this collection of simulation runs is a distribution of all possible model outcomes. To perform as Monte Carlo simulation, for each input variable a mean value, variation around that value, and a probability distribution should be derived. The latter point can be problematic, especially for the obsolescence forecast. By performing a high number of simulation runs, probability distributions, maximal, minimal, average values can be obtained. This simulation technique could be used to analyse the uncertainty in the number of future sales / installed base development and the obsolescence forecasting (moment when the part becomes obsolete). For the spare part demand and repair process, we incorporate probability distributions (Poisson and Binomial) and a discrete event simulation can be used to model the uncertainty/variation during the model life cycle.

## 3.6 Conclusion

In this chapter we reviewed relevant literature regarding our research. With respect to the subject of obsolescence monitoring, we conclude that the degree of monitoring depends on the obsolescence risk assessment that is currently under improvement at Thales. All available data should be analysed and whenever data is incomplete, Thales should have more intensive supplier contact. Both aspects will result in management costs.

Concerning the strategies that we want to incorporate in our model, multiple conducted research studies have focused on the individual strategies. Table 4 summarizes the literature and supply options that we considered during the literature study.

*Table 4: Overview of reviewed literature on obsolescence strategies.*

| Literature | LTB | Repair of failed parts | Redesign |
|---|---|---|---|
| Van Kooten & Tan (2009) | X | X | |
| Krikke and van der Laan (2011) | X | X | |
| Behfard et al. (2015) | X | X | |
| Hellegers (2017) | X | X | X |
| Teunter and Fortuin (1999) | X | | |
| Solomon, Sandborn and Pecht (2000) | | | X |
| Kumar and Saranga (2010) | X | | X |

To the best of our knowledge, there is no existing model that compares an RMB strategy, LTB strategy, and redesign strategy in order to indicate the policy that could be used during a specified life cycle. We conclude that most existing literature focuses on parts that are already obsolete (or will be on short notice), while we focus also on the years before obsolescence is expected. Therefore, we need to incorporate the obsolescence status of the part in our model. On the other hand, we conclude that some characteristics, especially about the redesign strategy and repair process, should be simplified in order to create a suitable model for Thales. To incorporate the repair process in our model, we conclude that the Binomial distribution is applicable. Using repairs as additional source of supply can decrease the impact and resolution strategies when obsolescence occurs. Based on the current situation at Thales, we conclude that some simplifications of the repair process are possible, meaning that all failed parts are directly repaired, the return yield is 100%, and the return lead time is negligible. We conclude that the following cost factors should be incorporated in the model: purchase costs, holding costs, repair costs, (un)planned redesign costs, disposal costs, backorder costs, and obsolescence monitoring costs. We conclude that we should conduct further research to determine the appropriate values for the last two cost factors since these two are currently not directly used at Thales. For the backorder costs we should look at the relation between the holding costs and the required service level since Thales does not directly incurs backorder costs (unless it is contracted). Regarding the obsolescence monitoring costs, this cost factor is not yet reviewed in comparing strategies.

Relating the analysis of the impact and consequences of uncertainty/variation we conclude that we have to incorporate multiple aspects. Based on the sensitivity analysis, it could be possible to perform an impact analysis related to the future sales / installed base size and the obsolescence forecasting. A discrete event simulation can be used to model the variation in spare part demand and repair process.

# 4. Model development

In this chapter, we develop a model which can be used to determine and analyse multiple obsolescence strategies for LRU's over (part of) the life cycle. We will start with a model introduction in Section 4.1. In Section 4.2, we give the assumptions regarding the model. The model construction method is subject of Section 4.3. In Section 4.4, we give the model input parameters and variables. Thereafter, the mathematical model formulation and expressions will be described in Section 4.5.

## 4.1 Model introduction

The model constructed during this research should determine which strategy concerning obsolescence should be followed during the life cycle under different circumstances. As concluded in Section 2.7., the three strategies that we focus on are: perform a Risk Mitigation Buy (RMB) at the start of the life cycle, monitor the LRU status and (re)act when obsolescence occurs, or include the LRU in planned redesign(s). First, we describe the general model and the strategies with corresponding scenarios. Thereafter, we describe an additional source of supply by repairing failed LRU's and how this is incorporated in the model. Finally, we describe which Key Performance Indicators (KPIs) are used to compare the strategies.

The model analyses a predetermined part of the life cycle of an LRU and consists of several intervals, each representing one year. From the start of the life cycle, an order can be placed in each interval at the supplier as long as the LRU is not obsolete. At the start of the life cycle, there is an expected Years Till End Of Life (YTEOL) concerning the LRU. Each time an order is placed at the supplier, next to the purchase price per part, fixed order costs (internal costs for preparing and performing an order) are incurred. The supplier might require a Minimum Order Quantity (MOQ) and after the specified order lead time, the order is received and put in inventory. The YTEOL indicates the number of years after which the LRU is expected to become obsolete. Depending on the strategy, the obsolescence status should be monitored and managed during (part of) the life cycle. Based on the installed base development, each interval a certain demand should be met. The expected demand per interval consists of two parts. The first part represents the LRU's that are required to produce new systems and initial spare parts. The second part is the expected demand for the replenishment of failed LRU's (spare parts) from the installed base. Once the LRU is announced obsolete and the expected future demand cannot be fulfilled, a redesign must be initiated to modify the design of the LRU. Once a redesign is started, initial redesign costs are incurred and after a certain lead time, the LRU is available again for ordering. As we will describe later in this section, repairing failed LRU's is possible from the start of the life cycle until a maximum of five years after the LRU is announced obsolete.

**Strategy 1: risk mitigation buy / all time buy at the start of the life cycle**.
In this strategy the total expected demand over the analysed life cycle is purchased with one single order from the supplier at the start of the analysed life cycle, although the LRU is not subject to obsolescence yet (i.e., YTEOL is a positive number). The ordered quantity is put in inventory and is used to fulfill demand during the life cycle. Holding costs are incurred per ready-to-use LRU in inventory at the end of each interval. Due to uncertainty in the expected demand, the inventory might not be sufficient over the analysed life cycle. Whenever TNL is not able to fulfill demand from stock, backorder costs are incurred if contractual obligations and corresponding penalties are defined. Only a small subset of projects has such contractual obligations, which TNL refers to as Performance Based Logistics (PBL). Although TNL has often no obligation to fulfill demand directly in case there is no service contract, the replenishment demand should be fulfilled at some point in time. Therefore, additional measures should be taken whenever the initial ATB quantity is (probably) not sufficient for the remaining life cycle and/or the obsolescence notification is received. As Figure 4 shows, we recognize two possible scenarios.

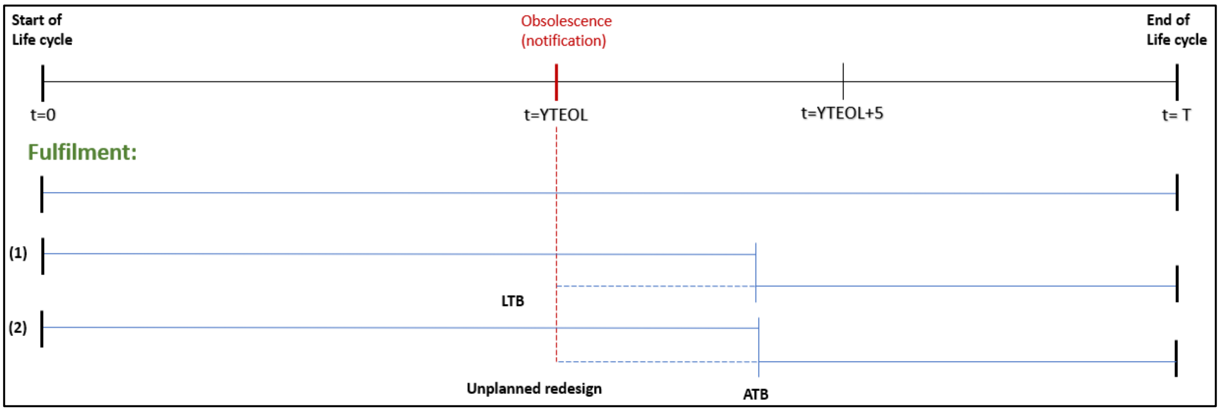


*Figure 4: Strategy 1 and scenarios*

In scenario 1 (1), once the expected YTEOL have passed and the LRU is announced obsolete, an additional Last Time Buy (LTB) is performed at the supplier to cope with future demand if necessary (i.e., if the ATB quantity turns out to be insufficient). Scenario 2 (2) means that an unplanned redesign is started to change the LRU design and resolve obsolescence, again only if this is necessary. Initiating a redesign results in initial non-recurring redesign costs (costs for engineering, testing, etc.) and after a specified redesign lead time, the LRU is available for ordering/production again. Since we follow an ATB strategy, again an ATB for the remaining expected demand is performed once the redesign is finished. Depending on the supplier reliability there might be a situation where the LRU is already obsolete when an additional LTB is required. In such cases, the supplier did not inform TNL and an unplanned redesign is the only possible resolution.

One advantage of this strategy is the fact that the fixed order costs are only incurred a limited number of times. Secondly, monitoring the LRU status regarding obsolescence is not necessary since the expected required LRU's are already stored in warehouses. Furthermore, the risk of having shortages because the LRU is obsolete without TNL knowing it (i.e., PDN is not received) is lower since (part of) the expected demand is already purchased. On the other hand, a disadvantage of this strategy is the potentially high salvage value of remaining inventory due to uncertainty in demand. This uncertainty might also result in shortages and additional resolution(s) with higher costs. The relatively high holding costs is also a disadvantage of this strategy.

**Strategy 2: monitor the LRU status and (re)act when obsolescence occurs.**
In this strategy we monitor the status of the LRU regarding obsolescence from the start of the life cycle ($t = 0$). At a predetermined frequency (e.g., quarterly), available data from the databases about the LRU is analysed. Additional information is requested from suppliers if required. At some point of the life cycle, the obsolescence notification is received ($t = YTEOL$). There are two possible scenarios, as visualized in Figure 5. Scenario 1 (1) means performing an LTB once the obsolescence notification is received to build enough inventory to cope with the remaining expected demand. Scenario 2 (2) is related to an unplanned redesign regarding the LRU. From the moment the unplanned redesign is finished on, periodic replenishment orders can be performed again until the analysed life cycle ends or until a new obsolescence notification is received. Note that after the completion of a redesign, obsolescence monitoring is required again and the YTEOL is equal to a positive number.

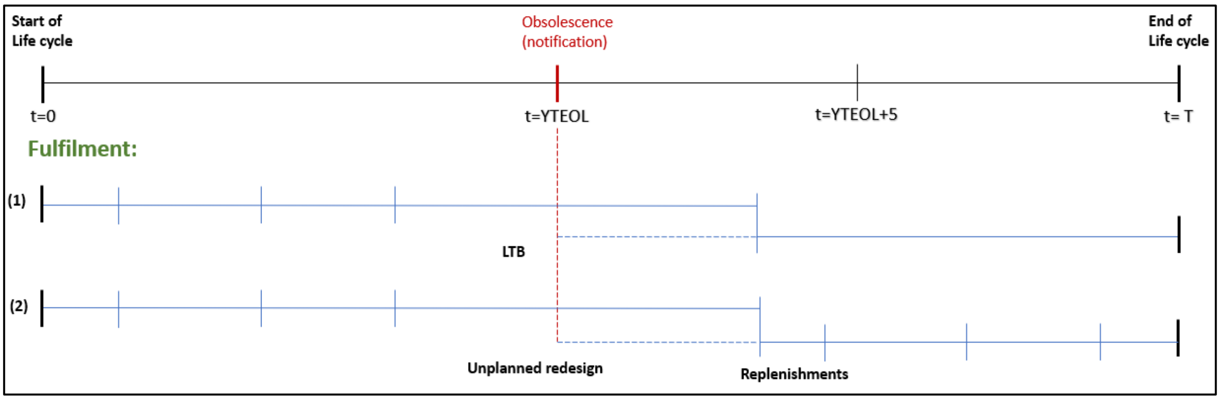


*Figure 5: Strategy 2 and scenarios*

The main advantage of a monitoring strategy and to wait until the LRU is announced obsolete before additional measures/resolutions are initiated, is the fact that uncertainty will probably be lower. As part of the life cycle has already passed, the circumstances and future developments (e.g., installed base) are less uncertain. On the other hand, if the LRU is announced obsolete at an unexpected moment, resolution(s) and corresponding costs might be higher. An advantage of performing an unplanned redesign is that the LRU will be available after the redesign lead time and can be ordered from the supplier again. This results in higher flexibility towards changes in the market such as higher demand or longer system life cycles. Whenever the LRU becomes obsolete and the remaining life cycle is short, the unplanned redesign costs might be relatively high. Finally, since the supplier reliability is not always guaranteed, there is a (small) chance that there is no LTB possibility at the interval where the LRU is expected to become obsolete $(t = YTEOL)$. This means that scenario 1 might not be an option. When this occurs, we automatically switch to an unplanned redesign (scenario 2).

**Strategy 3: include the LRU in planned redesign(s).**
In this strategy, the LRU is included in the planned redesign(s). Each product team of TNL has a policy to maintain the product for a specified life cycle, which means that planned redesigns are initiated at specified points of the life cycle. Replenishment orders can be placed at the supplier from the start of the life cycle until the planned redesign is initiated and the corresponding redesign lead time is finished. For a large subset of the LRU's (and other items/parts of the system) that are often incorporated in planned redesigns, the expected YTEOL is pretty accurate. In such cases, obsolescence might only occur after the planned redesign is (in contrary to the visualisation in Figure 6) finished and obsolescence monitoring is not required. In other cases where the obsolescence notification might be received before the redesign is finished, obsolescence monitoring is required from the start of the life cycle.

In case the obsolescence notification is received before the redesign is finished, an LTB can be performed to cope with additional expected lead time demand, see Figure 6 (scenario 1). Scenario 2 is to perform an unplanned redesign once the obsolescence notification is received and the current inventory (and additional LTB) is not sufficient to fulfill expected demand until the redesign is finished. During the redesign lead time and when an LTB is performed, obsolescence monitoring is not necessary. Depending on the type of LRU, the initial incurred redesign costs are expected to be lower than for an unplanned redesign. Especially if additional testing activities need to take place after a redesign, the marginal costs are lower when multiple parts of the product are incorporated in the redesign.

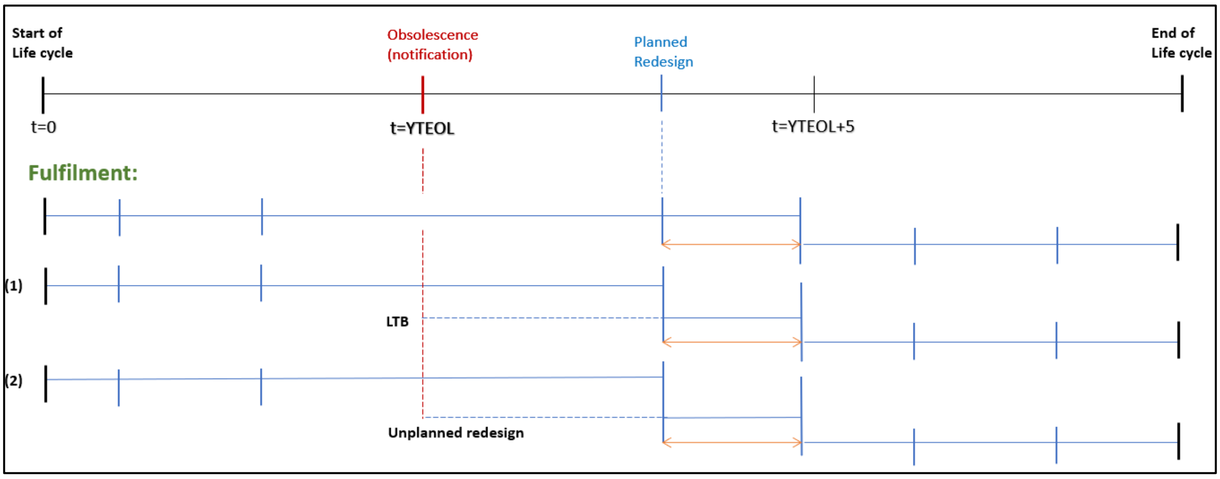


*Figure 6: Strategy 3 and scenarios*

One of the main advantages of this strategy is that, after redesigning, the LRU is expected to be available again for subsequent intervals and can be ordered/produced whenever required (so YTEOL will be positive again). Another advantage is that redesigning the LRU, together with multiple LRU's/parts, might result in improved performance and quality (against possibly lower production/operating costs). This can also result in additional future sales since part of the customers want to implement the redesign into their system. These aspects are not incorporated in our model since we focus on logistical obsolescence and not on functional obsolescence. On the other hand, initial redesign costs are often high. Due to the uncertainty in demand and other changes (internal and/or external), it might occur that an expensive redesign is performed and that the remaining demand is lower than expected (making it proportional expensive).

**Additional source of supply: repair of failed parts**
As an additional source of supply, we incorporate the repair option for LRU's in the above-described strategies. After the design phase of a system, it is defined whether an LRU is repairable or not. In case the LRU is repairable, this process can be used to increase/maintain the inventory level and to fulfill future spare part demand. Whenever possible, failed parts are always repaired since the repair costs are lower than purchasing a new LRU. Once a specific LRU is announced obsolete (so after the YTEOL have passed), the LRU can be still be repaired for five subsequent years of the analysed life cycle. This is stated by TNL since repair equipment, test equipment and professional knowledge is not maintainable for more years in practice.

Especially when the LRU is already obsolete, it might be beneficial to use this source of supply until a redesign is finished (or to avoid redesigning at all, if the remaining life cycle is short). Another advantage might be that fixed order costs are avoided, if the probably low demand is fulfilled with repaired LRU's which means that no orders need to be placed at the supplier. A disadvantage of using the repair option is the fact that not all repairs are successfully performed, but the repair costs are incurred in all cases.

**Comparison of strategies and scenarios**
In order to compare and analyse the different strategies and corresponding scenarios, the following KPI's should be analysed:

- The *Total Expected Cost (TEC)* over the analysed life cycle.

This KPI refers to the total expected costs that are incurred during the analysed life cycle. This depends on the decisions made and include: purchase order costs, obsolescence monitoring costs, holding costs, backorder costs, repair costs, redesign costs, disposal costs.

- The *cycle cervice level* $(A)$ of the LRU during the analysed life cycle.

The cycle service level refers the probability of not having a stock-out during the life cycle. This KPI indicates the probability that TNL can fulfill demand from inventory during an interval and can be used as measure to undertake action during the life cycle. By modelling this KPI over the analysed life cycle, it is possible to show the impact of different decisions and circumstances. Furthermore, the model decisions can be adjusted whenever the cycle service level drops below some specified level (e.g., 90%).

Since there is no clear restriction given by TNL whether the service level should meet a certain average cycle service level over the whole life cycle, or each interval a certain level should be attained, we focus on the first case with a minimum level of 90%. This means that the average cycle service level over the whole life cycle should attain a cycle service level of 90% or higher. Near the end of the life cycle, the service level may drop below the specified level. In such cases other resolutions (e.g., authorized aftermarket) can be used if required.

- The *risks and consequences* of uncertainty in YTEOL (obsolescence forecasting) and in installed base development (future sales).

This KPI refers to possible risks and consequences (i.e., higher TEC, lower $A$) when a specific strategy is not sufficient to fulfill all LRU demand over the life cycle, and the LRU is possibly already announced obsolete.

## 4.2 Model assumptions

In order to create a suitable model, multiple assumptions are formulated. All assumptions are described in this section.

*Assumption 1: at the start of the life cycle analysis, there might already be an installed base operational and a starting inventory of ready-to-use LRU's.*

Since we focus on one product of TNL, we assume that it is possible that there are already a specific number of LRU's operational at the start of the life cycle that will be analysed. This means that there might also be a positive inventory level of ready-to-use LRU's.

*Assumption 2: the expected demand for failed LRU's depends on the number of operational parts in the installed base and follows a Poisson distribution that is proportional with the number of operational LRU's in the installed base.*

Based on the sales forecast, an indication of the development of the installed base is available. Depending on the number of operational LRU's during each interval, the demand rate for the replenishment of LRU's is calculated and depends on the failure rate. Since the model focuses on electronical LRU's, we assume that the Poisson distribution is suitable for the failure rate. As described by multiple literature sources, the memoryless property of the inter arrival times is suitable for electronic parts.

*Assumption 3: the Minimum Order Quantity (MOQ), purchase price and order lead time from the supplier are constant over the life cycle.*

We assume that the supplier maintains the same purchase order conditions over the life cycle, independently of the order size or whether it is an LTB or regular replenishment order.

*Assumption 4: the characteristics of an existing and redesigned LRU are equal.*

Although the characteristics (e.g., purchase price, failure rate) of an LRU might change after a redesign, we assume that the characteristics are equal. Reason for this is the fact that the redesigned LRU should perform the same activities and improved functionalities/capabilities are not within the scope of the model.

*Assumption 5: the costs of monitoring and managing the obsolescence status of a LRU during an interval depend on whether the LRU is produced by TNL or a supplier and is constant over the life cycle.*

Although the frequency of analysing the status of an LRU might differ per individual customer, we assume that these costs are fixed per interval and constant over the life cycle. Furthermore, there is a difference in monitoring costs that depends on whether the LRU is produced by TNL or a supplier.

*Assumption 6: remaining inventory at the end of the analysed life cycle should be discarded, against a salvage value.*

We assume that LRU's which are kept in inventory for multiple years cannot be used for other purposes and need to be discarded at the end of the analysed life cycle. Discarding LRU's will result in extra costs that should be incorporated. Furthermore, remaining inventory after the completion of a redesign can still be used due to the fact that we focus on LRU level and spare parts can therefore still be used in operational systems.

*Assumption 7: the return yield of failed LRU's from the installed base is constant and 100%.*

The return yield refers to the percentage of failed LRU's that is sent back to TNL for repair. Since the purchase price of LRU's than can be repaired is relatively high in general (>€5.000), we assume that LRU's are always returned for repair when a failure occurs.

*Assumption 8: the repair yield is constant over the life cycle of the LRU.*

We assume that each individual repair has a specific probability of being successful. In addition, the number of successful repairs is determined based on the Binomial distribution and a standard repair yield of 90% is assumed.

*Assumption 9: the return lead time of failed LRU's from the installed base is negligible.*

We assume that failed LRU's are directly sent back to TNL when a failure occurs. Since we analyse intervals of one year, the time before the failed LRU is received is assumed to be negligible.

*Assumption 10: the repair lead time is equal to one interval.*

The process from receiving a failed LRU until the repair is finished can take up to one year, we therefore assume that the repair lead time is equal to one interval.

*Assumption 11: whether an LRU is repairable or not is specified and all failed LRU's from the installed base are repaired in the subsequent interval.*

The design department of TNL specifies if an LRU is repairable or not. The repair costs play a role in this determination, since LRU's are assumed to be beyond economic repair whenever the repair costs are equal to, or greater than 60% of the LRU purchase price. Furthermore, all ready-to-repair LRU's are directly repaired in the subsequent interval after they are received.

*Assumption 12: all lead times are deterministic and equal to an integer number of intervals.*

We assume that all incorporated lead times are deterministic and known at the start of the life cycle. Furthermore, the lead times are assumed to be equal to an integer number of intervals.

*Assumption 13: the obsolescence notification is always received.*

We assume that TNL is always notified by the supplier when the supply of the existing LRU's will end in the near future and the LRU becomes therefore obsolete. For relatively complex and expensive items the relationship with the supplier and the reliability is good. However, in some situations (especially for cheaper items) the supplier reliability is not guaranteed and TNL might not be notified about obsolescence. We assume that an expectation about the years until obsolescence (YTEOL) is available. Once a redesign is finished, we assume that the YTEOL is equal to the original estimation again.

*Assumption 14: the lead time in order to perform a redesign once it is initiated is equal to one interval.*

For this research we assume that the lead time for performing a redesign is limited to one interval. In practice, this could be equal to multiple intervals but since we assume that the obsolescence notification is always received (assumption 13), this would result in initiating the redesign in an earlier stage of the life cycle or ordering a higher last time buy quantity to cope with demand during lead time.

*Assumption 15: whenever a planned redesign strategy is followed (strategy 3), the LRU is incorporated in the redesigns that are initiated at a predetermined frequency (i.e., number of intervals before planned redesign is initiated).*

Each product team has a technology roadmap that states the future planned redesign(s) regarding the product life cycle. The whole process of investigating if enough stakeholders (i.e., customers) want to acquire the redesign, together which engineering and realization activities, might have a duration of multiple years. Unfortunately, it is not realistic to decide after the first intervals whether to include or exclude an LRU from the planned redesign. It is therefore assumed that if a redesign is initiated at the start of the interval where a redesign is already planned, it is categorized as 'planned redesign'. In all other cases, a redesign is categorized as 'unplanned' and is performed on the individual LRU.

## 4.3 Model construction method

As described in Section 4.1., at the start of each interval $t$ one or multiple decisions should be made. At the start of every interval $t$, we have to decide how many LRU's should be ordered from the supplier and if we should perform redesign activities regarding the LRU. Altogether, these decisions should minimize the total expected costs and guarantee a certain cycle service level over the entire analysed life cycle from $t = 0$ until $t = T + 1$. Although the analysed life cycle ends at the end of interval $T$, we must take interval $T + 1$ into account as well. In case there is inventory left at the end of the analysed life cycle, we must discard the remaining inventory which results in additional costs.

Since there are multiple decisions, at multiple moments of the life cycle, we are dealing with a sequential optimization problem that can be categorized as dynamic programming. Since we assume that spare part demand follows a Poisson process, demand is stochastic, and we can use Stochastic Dynamic Programming (SDP) to find an exact solution. SDP is a technique that solves optimization problems that involve making a sequence of decisions when outcomes are uncertain. An SDP program consists of stages (points in time when a decision must be made), states (e.g., possible inventory levels in each stage), decisions (e.g., how many LRU's to order), reward(s)/cost(s) (each decision result in a certain reward or cost), and state transition probabilities (depending on the state and decision, there is a certain transition probability that each state is attained in the next interval).

A key characteristic of SDP is that the past does not influence the decision that has to be made at a specific point in time. The dynamic programming problem is eventually solved by backward recursion starting at the last interval. This characteristic is based on Bellman's principle of optimality which is stated as, an optimal policy has the property that, whatever the initial state and initial decisions are, the remaining decisions must constitute an optimal policy with regard to the state resulting from the first decision. SDP gives an exact solution and reality is presented by abstract mathematical formulas which allow the model to be generally applicable. A disadvantage of SDP is dimensionality because the higher the number of state variables, the longer the computation time will be. This is not a big issue, since problem instances are relatively small and therefore using such a model is not very time intensive. All analysis to complete this research may take some computational effort and time.

## 4.4 Model input parameters and variables

This section gives an overview of the required input for the model, as described in Section 4.1 and 4.2. First, we give an overview of the input parameters. Second, we give the state variables and the auxiliary variables. Finally, the required auxiliary variables and decision variables are given.

Input parameters:

| | |
|---|---|
| $T$ | life cycle length of the analysis (number of intervals). |
| $YTEOL$ | Years Till End Of Life (nr. intervals before LRU becomes obsolete). |
| $FPRD$ | frequency of initiating a planned redesign (i.e., number of intervals before initiated) |
| $\lambda$ | Spare part demand rate per interval t for one operational LRU. |
| $IB_{\mathrm{t}}$ | deterministic number of parts representing the installed base in interval t. |
| $FD_t$ | deterministic LRU demand for new production and initial spare parts in interval t. |
| $I_0$ | inventory level of ready-to-use LRU's at the start of the life cycle analysis. |
| $c_p$ | purchasing price of a new LRU. |
| $c_{fo}$ | fixed order cost for each purchase order. |
| $MOQ$ | minimum order quantity. |
| $c_h$ | holding cost per ready-to-use part at the end of each interval (% of purchase price). |
| $c_b$ | back ordering cost (in euro) per ready-to-use part at the end of the time interval |
| $v$ | salvage value per ready-to-use part at the end of analysed life cycle. |
| $c_{mon}$ | cost for monitoring the obsolescence status during interval t. |
| $c_{rd1}$ | initial redesign cost for an unplanned redesign. |
| $c_{rd2}$ | initial redesign cost for a planned redesign. |
| $c_r$ | repair cost per initiated repair. |
| $y_{rep}$ | repair yield. |
| $\beta$ | discount factor. |

State variables

$I_t$ inventory level of ready-to-use LRU's at the beginning of interval t.

$N_t$ number of ready-to-repair LRU's at the beginning of interval t.

$O_t$ whether the LRU is not obsolete (0) or obsolete (1) at the beginning of interval t.

Auxiliary variables

$D_t$ stochastic LRU spare part demand in interval t.

$X_t$ upper bound for the spare part demand in interval t.

$OH_t$ on hand inventory of ready to use parts at the end of time interval t.

$BO_t$ number of backorders at the end of time interval t.

$k_t$ number of successfully executed repairs in interval t.

$m_t$ variable stating whether obsolescence monitoring is performed (1) or not (0) in interval t.

$s_t$ variable to indicate whether a redesign is planned (1) or unplanned (0).

$C_t([I_t, N_t, O_t]; [Q_t, RD_t])$ direct costs in interval $t$ for state: $[I_t, N_t, O_t]$ and decisions: $[Q_t, RD_t]$.

Performance measures

$A_t$ cycle service level over interval t.

$A$ average cycle service level of the analysed life cycle.

$TEC$ total expected costs over the analysed life cycle.

Decision variables

$Q_t$ quantity of LRU's ordered in interval t.

$RD_t$ whether to initiate a redesign on the LRU in interval t (1 = yes, 0 = no)

## 4.5 Model formulation and mathematical expressions

In this section we describe the mathematical expressions that are incorporated in the model. First, the general model formulation is given. Second, the cost expressions are formulated to calculate the total relevant cost. Thereafter, the state transition probabilities are formulated. Finally, we give the expressions to calculate the cycle service level.

### 4.5.1 Model formulation

As described in Section 4.3., we can formulate this problem as an SDP model.
**Stage:** time interval $t = 0, \dots, T+1$. At the start of each stage decisions must be made.

**State:** the model has three variables that determine the state at the start of each interval $t$: $[I_t, N_t, O_t]$.

The first state variable $I_t$ is the inventory level at the start of interval $t$. The value of this variable depends on the inventory level, the demand rate, the repair rate, and the order quantity in the previous interval $(t-1)$. The maximum inventory level is equal to the summation over the total maximum demand (both for new production and spare part demand) over the entire life cycle.

State variable $N_t$ is the number of ready-to-repair LRU's at the start of interval $t$. The maximum value of this state variable is equal to the maximum number of failed LRU's in the previous interval $(t-1)$ and depends therefore on the spare part demand.

State variable $O_t$ refers to the status of the LRU regarding obsolescence, at the start of each interval $t$ this state variable is either 0 (LRU is not obsolete) or 1 (LRU is obsolete).

**Decision:** depending on the chosen strategy and the state at the start of an interval, decisions can be made. Basically, we can make two decisions: (1) order $'Q'$ items at the supplier, which is only possible if the item is not obsolete ($O_t = 0$). The maximum order quantity is equal to the maximum inventory level minus the inventory level at the start of interval $t$ $(I_t)$ and a Minimum Order Quantity $(MOQ)$ may be required. (2) initiate a redesign $'RD = 1'$ or not $'RD = 0'$. Note that a redesign can either be planned or unplanned. An unplanned redesign can be initiated at the start of each interval, whereas a planned redesign is initiated each time a predetermined number of intervals have passed, denoted by: $FPRD$.

**Value function:** $V_t(I_t, N_t, O_t)$ is the minimum expected discounted cost during interval $t$, $t+1$, ..., $T+1$, given that interval $t$ started with state $(I_t, N_t, O_t)$. The minimum is taken, over the expected direct costs, $C_t([I_t, N_t, O_t]\,;[Q_t, RD_t])$, as a result of all decisions, that are feasible when starting interval $t$ with state $(I_t, N_t, O_t)$. In addition, we sum over the expected costs from interval $t+1$ to the end of interval $T+1$, multiplied with the state transition probability. This is the probability that decision $[Q_t, RD_t]$ in state $(I_t, N_t, O_t)$ in interval $t$, results in state $(I_{t+1}, N_{t+1}, O_{t+1})$ in interval $t+1$.

The state space of the inventory level in interval $t+1$ $(I_{t+1})$ is given below and lays between two boundaries. The left side represents the minimum possible inventory level in interval $t+1$, which is determined by the inventory level, order quantity, fixed demand, and upper bound for spare part demand in interval $t$. The right side is the maximum possible inventory level in interval $t+1$, which is determined by the inventory level, number of ready-to-repair LRU's, order quantity, and fixed demand in interval $t$.

$$I_t + Q_t - FD_t - X_t \leq I_{t+1} \leq I_t + N_t + Q_t - FD_t$$

The state space of the number of ready − to − repair LRU's in interval $t+1$ $(N_{t+1})$ has a minimum of zero, and the maximum number of ready-to-repair LRU's in interval $t+1$ is equal to the upper bound for spare part demand in interval $t$ $(X_t)$.

$$0 \leq N_{t+1} \leq X_t$$

The obsolescence state in interval $t+1$ $(O_{t+1})$ can either be 0 (not obsolete) or 1 (obsolete), but never 0 and 1 at the same time. Therefore, we use the exclusive disjunction operator ($\veebar$) to indicate that the obsolescence state in interval $t+1$ is either 0 or 1.

$$O_{t+1} = 0 \veebar 1$$

For the last interval, after the last interval of the life cycle, $T+1$, we have to include the salvage value in case there is inventory left at the end of the life cycle. The remaining inventory at the end of the life cycle needs to be discarded (see expression 2).

$$V_t(I_t, N_t, O_t) = \min_{Q_t, RD_t \in (I_t, N_t, O_t)} \{C_t([I_t, N_t, O_t]; [Q_t, RD_t]) + \beta * \sum_{\substack{I_{t+1} \\ N_{t+1} \\ O_{t+1}}} p_t([I_{t+1}, N_{t+1}, O_{t+1}] | [I_t, N_t, O_t]; [Q_t, RD_t]) * V_{t+1}(I_{t+1}, N_{t+1}, O_{t+1})\} \quad (1)$$

$$V_{T+1}(I_{T+1}, N_{T+1}, O_{T+1}) = -v * E[\max\{I_{T+1}, 0\}] \quad (2)$$

$$\beta = \frac{1}{1 + interest\ rate} \quad (3)$$

Beta $(\beta)$ is the discount factor that is used to take the future value of money into account and is calculated by the expression 3.

### 4.5.2 Cost expressions

As described in Section 4.1, the total expected cost is one of the KPI's that should be calculated for the analysis. The direct costs that can be incurred during an interval consists of eight cost factors, which we describe below:

**Purchase costs**

The purchase costs during an interval are only incurred if at least one item is ordered and consist of fixed order costs (internal costs for preparing and performing an order), denoted as $c_{fo}$, together with the cost price per part $(c_p)$ multiplied with the number of parts ordered $(Q_t)$. Since an MOQ can be required, a restriction is needed to state that the order quantity should at least as high as the MOQ $(Q_t \geq MOQ)$.

$$c_{fo} + Q_t * c_p, if\ Q_t > 0 \quad (4)$$

$$0, if\ Q_t = 0 \quad (5)$$

**Holding costs**

In case we have a positive inventory level at the end of an interval, holding costs $(c_h)$ are incurred per ready-to-use LRU. This depends on the number of LRU's in inventory at the beginning of an interval, the number of ordered/purchased items and the demand during the interval. Since the spare part demand for failed LRU's is a stochastic variable, we should calculate an upper bound to bound the model calculations. This upper bound is denoted by $X_t$, and this variable represents the maximum expected number of spare parts demand for which a cumulative Poisson probability of some specified level (e.g., 99,9%) is attained. The upper bound is equal to the smallest value of $X_t$ that satisfies the following inequality:

$$min \sum_{i=0}^{X_t} \frac{(\lambda * IB_t)^i * \ e^{-(\lambda * IB_t)}}{i!} > 0.999 \ \ (6)$$

This means that, given an average demand per interval, the cumulative Poisson distribution should be greater than 99,9%. So, there is only a small chance of 0,1% that the expected spare part demand is one part higher ($X_t + 1$) than accounted for in the model. Note that there are no costs involved in holding LRU's that are in repair during a specific interval. TNL states that these costs are incorporated in the repair costs. The expected on-hand inventory is calculated as follows:

$$E[OH_t] = \sum_{i=\,0}^{X_t} \max\{(I_t - i - FD_t), 0\} * \frac{(\lambda * IB_t)^i * \ e^{-(\lambda * IB_t)}}{i!} \ \ (7)$$

The holding cost per ready-to-use LRU is a fraction of the initial purchase price. The holding costs are than calculated by the following expression:

$$E[OH_t] * \ c_h * c_p \ (8)$$

**Backorder costs**

In case TNL is dealing with contractual obligations and demand for spare parts cannot be fulfilled from inventory, backorder costs ($c_b$) are incurred. The expected backorder at the end of an interval is calculated as follows:

$$E[BO_t] = \sum_{i=\,0}^{X_t} \max\{(i - I_t + FD_t), 0\} * \frac{(\lambda * IB_t)^i * \ e^{-(\lambda * IB_t)}}{i!} \ \ (9)$$

Then, the expected backorders are multiplied with the backorder cost per LRU:

$$E[BO_t] * \ c_b \ \ (10)$$

In Appendix 1, we describe how we find an approximate value for the backorder costs. Note that the backorder costs are used to create a suitable model, but these costs are not directly incurred in practice.

**Repair costs**

For each repair that is initiated, repair costs are incurred. As described in Section 4.2., all ready-to-repair parts at the start of an interval are repaired. The number of repairs $N_t$ is equal to the realized spare part demand $D_{t-1}$ in the previous interval. Whenever there is already an installed base at the start of the life cycle, we can start repairing from the start of interval $t = 1$. In case the installed base at interval $t = 0$ is zero, the first repairs can be initiated after the first operational LRU's have failed (so from $t = 2$). The last interval in which repairs are initiated is $T - 1$, since these repaired LRU's are added to stock at the beginning of interval $T$ and can still be used to fulfill demand in the last interval. Starting repairs at the beginning of interval $T$ would suggest that the repaired LRU's need to be discarded. The repair costs are calculated by the following expression:

$$N_t * c_r \ \ (11)$$

**Obsolescence monitoring costs**

The obsolescence monitoring costs ($c_{mon}$) for the LRU, per interval $t$, is expressed as the costs to monitor over the entire operational installed base. Whether obsolescence monitoring is performed ($m_t = 1$) or not ($m_t = 0$) depends on the strategy and decisions as described in Section 4.1. Obsolescence monitoring is performed in all strategies from the start of the life cycle until the LRU becomes obsolete, except for the RMB strategy since all demand is already purchased and obsolescence monitoring is not required. In case the LRU is obsolete, and a redesign is initiated ($RD_t = 1$), obsolescence monitoring is required again from the first interval after completing the redesign.

In case a LRU is designed and produced by TNL, the annual monitoring costs are estimated at €1.200 per interval. Such LRU's consists of multiple buy parts (e.g., 100 parts) that need to be monitored and analysed. LRU's that are produced by a supplier exist in general of one buy part and require less effort since only information from one individual supplier should be analysed. Based on an example offer from a supplier, the approximate annual costs to monitor a buy-part are estimated to be €120 per interval for the operational installed base.

$$c_{mon}\,, \qquad if\ m_t = 1 \quad (12)$$

$$0\,, \qquad if\ m_t = 0 \quad (13)$$

**Redesign costs**

Once a redesign is initiated ($RD_t = 1$), the non-recurring engineering costs are incurred. Since the costs for an unplanned redesign ($c_{rd1}$) are higher than the costs of a planned redesign ($c_{rd2}$), an auxiliary variable ($s_t$) is used to determine the appropriate category.

In case the redesign is not initiated in the same interval as the planned redesign is initiated ($s_t \neq FPRD$), the redesign is categorized as unplanned and the costs are given by expression 14.

$$c_{rd1}\,, \qquad if\ RD_t = 1\ and\ s_t \neq FPRD \quad (14)$$

In case the LRU is included in the planned redesign ($s_t = FPRD$), expression 15 is used.

$$c_{rd2}\,, \qquad if\ RD_t = 1\ and\ s_t = FPRD \quad (15)$$

The redesign costs are zero if no redesign is initiated ($RD_t = 0$).

$$0\,, \qquad if\ RD_t = 0 \qquad\qquad (16)$$

**Disposal costs**

As already mentioned, remaining inventory at the end of the analysed life cycle should be discarded against a negative salvage value. The disposal costs are calculated by the following expression and these costs are incurred in interval T + 1:

$$-v * E[\max\{I_{T+1}, 0\}] \quad (17)$$

**Final cost expression**

All expressions together, (4) till (17), result in direct costs $C_t(I_t, N_t, O_t)$ that are incurred if the state is $(I_t, N_t, O_t)$ at the start of interval t when the decision is $[Q_t, RD_t]$:

$$C_t([I_t, N_t, O_t]; [Q_t, RD_t]) = \{expression\ 4, \dots, 17\}$$

### 4.5.3 State transition probabilities

In this section, we formulate the state transition probabilities and corresponding expressions. The state transition probabilities, which are given by: $p_t([I_{t+1}, N_{t+1}, O_{t+1}]|[I_t, N_t, O_t]; [Q_t, RD_t]$, indicate the probability that decision $[Q_t, RD_t]$ in state $(I_t, N_t, O_t)$ in interval $t$, result in state $(I_{t+1}, N_{t+1}, O_{t+1})$ in interval $t+1$. As formulated in the optimal value function, we sum over all the states that can be attained in interval $t+1$ for all possible decisions. The state transition probabilities depend on three factors. The first factor is the spare part demand $(D_t)$, which is determined by the Poisson distribution. The second factor is the number of successful repairs $(k_t)$, which is determined by the Binomial distribution. The third factor is related to whether the LRU becomes obsolete or not, which depends on the Years Till End Of Life (YTEOL) of the LRU and is deterministic.

The inventory level at the start of interval $t+1$ is given by: $I_{t+1} = I_t + Q_t - FD_t - d + \kappa$. With inventory level $(I_t)$, order quantity $(Q_t)$, fixed demand $(FD_t)$, spare part demand $(d = realization\ of\ D_t)$, and the number of successful repairs $(\kappa = realization\ of\ k_t)$ in interval $t$. Keeping in mind that $Q_t$ is a decision variable, a specific number of successful repairs $(\kappa)$ should be realized to attain a specific inventory level in interval $t+1$. This number is found by rewriting the expression for the inventory level and is given by: $\kappa = I_{t+1} - I_t - Q_t + FD_t + d$. The maximum number of successful repairs in interval $t$ can never exceed the number of ready-to-repair LRU's $(N_t)$, which means that the following restriction applies: $0 \leq \kappa \leq N_t$.

The number of ready-to-repair LRU's at the start of interval $t+1$ is equal to the realization of the stochastic spare part demand $(D_t)$ in interval $t$, and is given by: $N_{t=1} = d$.

The obsolescence state at the start of interval $t+1$ can either be not obsolete $(O_{t+1} = 0)$ or obsolete $(O_{t+1} = 1)$. In case a redesign is initiated $(RD_t = 1)$, the LRU will be not obsolete in interval $t+1$ since the lead time to perform the redesign is equal to one interval. Whenever a redesign is not initiated $(RD_t = 0)$, the LRU becomes obsolete if interval $t$ is equal to the $YTEOL$ (i.e., if the $YTEOL = 5$, and we are at the start of interval 5, the obsolescence state in interval $t+1$ will be obsolete $(O_{t+1} = 1)$. Note that the last time buy option is at the start of interval $t = YTEOL$. In all situations where interval $t$ is not equal to the $YTEOL$ $(t \neq YTEOL)$, the LRU will not become obsolete in interval $t+1$ since the obsolescence state is a deterministic variable.

First, there are multiple scenarios where the state transition probability is equal to zero:

1. In case the LRU is not obsolete $(O_t = 0)$, and a redesign is initiated $(RD_t = 1)$, the chance that the LRU is obsolete $(O_{t+1} = 1)$ in interval $t+1$ is zero.
2. In case the LRU is not obsolete $(O_t = 0)$, no redesign is initiated $(RD_t = 0)$, and $t \neq YTEOL$, the chance that the LRU is obsolete $(O_{t=1} = 1)$ is zero.
3. In case the LRU is obsolete $(O_t = 1)$, and no redesign is initiated $(RD_t = 0)$, the chance that the LRU is not obsolete $(O_{t+1} = 0)$ in interval $t+1$ is zero.
4. In case the LRU is obsolete $(O_t = 1)$, and a redesign is initiated $(RD_t = 1)$, the chance that the LRU is obsolete $(O_{t+1} = 1)$ in interval $t+1$ is zero.
5. The number of required successful repairs is higher than the number of ready-to-repair LRU's $(\kappa > N_t)$. This means that even if all initiated repairs are successful, the inventory level cannot be attained, and the state transition probability is zero.

The first four scenarios are related to the obsolescence state and since this state variable is deterministic, it depends on the redesign decision. The fifth scenario is related to the restriction concerning the maximum number of successful repairs that is possible.

The state transition probabilities for all other scenarios are determined by multiplying the Poisson probability with the Binomial probability and is given by expression 18.

$$p_t([I_{t+1}, N_{t+1}, O_{t+1}] | [I_t, N_t, O_t]; [Q_t, RD_t]) = \frac{(\lambda * IB_t)^{N_{t+1}} * e^{-(\lambda * IB_t)}}{N_{t+1}!} * \left( \binom{N_t}{\kappa} * {y_{rep}}^{\kappa} * \left(1 - y_{rep}\right)^{(N_t - \kappa)} \right) \quad (18)$$

In order to illustrate the general expression (18), we give an example. The parameter values are given in Table 5.

*Table 5: State transition probability example.*

| | | | | |
|---|---|---|---|---|
| $I_t$= 5 (parts) | $N_t$= 2 (parts) | $O_t$ = 0 | $I_{t+1}$ = 5 (parts) | $N_{t+1}$= 1 (parts) |
| $O_{t+1}$= 0 | $Q_t$ = 1 (parts) | $RD_t$ = 0 | $\lambda$ = 0.04 (part) | $IB_t$= 25 (parts) |
| $\kappa$ = 2 (parts) | $y_{rep}$ = 0.9 (90%) | $d$ = 1 (part) | $FD_t$ = 2 (parts) | |
| $p_t([5,1,0] \| [5,2,0]; [0,0]) = \frac{(0.04 * 25)^1 * e^{-(0.04*25)}}{1!} * \left( \binom{2}{2} * 0.9^2 * (1 - 0.9)^{(2-2)} \right) = 0.38 * 0.81 = 0{,}298\ (29{,}8\%)$ <br> Where: $I_{t+1} = 5 + 1 - 2 - 1 + 2 = 5\ (parts)$, and $\kappa = 5 - 5 - 1 + 2 + 1 = 2\ (parts)$ | | | | |

From the example in Table 5 we conclude that the state transition probability for this specific problem instance is 29,8%. Both repairs must be successful to reach the specific state in interval $t$ if the order quantity is one. Note that in case the actual number of required successful repairs ($\kappa$) is higher than the number of ready-to-repair parts ($N_t$) at the start of interval $t$ to attain a specific state in interval $t + 1$, the Binomial probability is equal to zero and the state transition probability is also zero (scenario 5).

Finally, the model calculates all combinations of possible state transitions with corresponding expected costs to find the optimal decisions.

### 4.5.4 Cycle service level

As described in Section 4.1., the cycle service level $(A_t)$ of the LRU over the entire life cycle is a performance indicator that should be analysed. This performance measure states the probability that there is no stock-out. Basically, the calculation of this performance measure consists of two parts. First, for a given inventory level $I_t$ the probability $\alpha_t(I_t)$ that no stock-out will occur is equal to the probability that the inventory level is sufficient to cover the total demand $D_t + FD_t$ in interval $t$:

$$\alpha_t(I_t) = P\{I_t - d - FD_t \geq 0\} = P\{d \leq I_t - FD_t\} = e^{-(\lambda * IB_t)} * \sum_{d=0}^{I_t - FD_t} \frac{(\lambda * IB_t)^d}{d!} \quad (19)$$

Subsequently, this probability is multiplied with the probability of being in that specific state (inventory level $I_t$, ready-to-repair $N_t$) at the start of interval $t$. This probability is denoted by $Prob_t(I_t, N_t)$ and depends on the parameters and variables in interval $t-1$. The state of the inventory level at the start of interval $t$ is given by: $I_t = \{I_{t-1} - FD_{t-1} - d + Q_{t-1} + \kappa\}$. The parameter and variables that determine the inventory level are: fixed demand $FD_{t-1}$, the spare part demand $d$ (as we describe below: $d = N_t$), the ordered quantity $Q_{t-1}$, and the number of successful repairs $\kappa$ in interval $t-1$. The number of ready-to-repair parts $N_t$ at the start of interval $t$, is equal to the spare part demands $(d)$ in interval $t-1$. Furthermore, we recall that $X_{t-2}$ is the upper bound value for the maximum spare part demand. The upper bound value of interval $t-2$ is used since this value determines the number of ready-to-repair parts in interval $t-1$. The number of required successful repairs in interval $t-1$ is determined by: $\kappa = \{I_t - I_{t-1} + FD_{t-1} + d - Q_{t-1}\}$. These probabilities are very similar to the state transition probabilities described in Section 4.5.3. and we must sum over all combinations regarding the spare part demand (Poisson) and number of successful repairs (Binomial) since these variables are both stochastic. Instead of solving this by backward recursion, it is solved by forward recursion. The following expression (20) is used to determine the probability that we are in a specific state at the start of interval $t$:

$$Prob_t(I_t, N_t) = \frac{(\lambda * IB_{t-1})^{N_t} * e^{-(\lambda * IB_{t-1})}}{N_t!} * \sum_{i=0}^{X_{t-2}} \sum_{\kappa=0}^{i} Prob_{t-1}(I_t + FD_{t-1} - \kappa + N_t, i) * \left( \binom{i}{\kappa} * y_{rep}{}^{\kappa} * (1 - y_{rep})^{i-\kappa} \right) \quad (20)$$

By calculating the matrix with probabilities for all possible states in all stages, subsequently the probabilities of having no stock-out in a specific interval $t$ are multiplied with the probability of being in each specific state. This results in the cycle service level per interval, and the overall cycle service level can be determined. Note that the inventory position cannot be negative, because then there is an out-of-stock situation.

Now, the probability of no stock-out in each time interval is calculated by:

$$A_t = \sum_{N_t=0}^{N_t} \sum_{I_t=0}^{I_t} \alpha_t(I_t) * Prob_t(I_t, N_t) \quad (21)$$

Finally, the average cycle service level $(A)$ is calculated by taking the average over all intervals of the life cycle:

$$A = \frac{\sum_{t=1}^{T} A_t}{T} \quad (22)$$

## 4.6 Conclusion

In this chapter, we constructed a model which is able to determine the expected outcome of the defined obsolescence strategies. Depending on the model input, the optimal order quantities and redesign decisions can be found in order to minimize the total expected cost over the analysed life cycle. The incorporated cost factors include: purchase costs, holding costs, backorder costs, repair costs, obsolescence monitoring costs, (un)planned redesign costs, and disposal costs. The backorder costs are estimated in order to analyse the trade-off between inventory, backorders and attaining a specified cycle service level. Subsequently, the cycle service level is calculated by using forward recursion. At the start of each interval of the life cycle, decisions must be made. Which decisions can be made, depends on the model state variable regarding obsolescence. Stochastic dynamic programming is used to formulate and solve the optimization problem.

In order to create model output for the individual defined strategies, we conclude that we can restrict the decisions that can be made during the life cycle (e.g., in a risk mitigation buy it is only possible the order a certain quantity at the start of the life cycle. In this way we are able to make analyse the strategies individually and compare all strategies.

# 5. Model validation and analysis

In this chapter we first describe the validation and verification of the model. Second, the results of the performed case study on two LRU's will be given to show the outcome of the constructed model and to show the impact of variation. Finally, the performed sensitivity analysis to gain managerial insights will be discussed.

## 5.1 Validation and verification of the model

The model as described in Chapter 4, is implemented in Microsoft Excel with the use of Visual Basic for Applications (VBA). The constructed model is new and cannot be checked, verified, and validated by comparing it to an existing model or system. However, to increase validity and credibility of the constructed model, we have used several techniques during the construction of the model and to verify the model, as adduced by Law (2015).

In order to validate the model, first some qualitative techniques are used. During the research study and the construction of the model, we had regular contact with relevant stakeholders within Thales Hengelo and we consulted multiple experts of the supportability engineering department. Due to some limitations in data availability, assumptions and estimations regarding input parameters are acquired and discussed with the relevant departments. After the model construction was finalized and the first numerical analysis were performed, the model and corresponding results are presented and discussed within Thales. The results and model output are obtained by performing a case study, which we will discuss in Section 5.2. Based on these techniques we can examine if our approach coincides with the business at Thales Hengelo.

For the model verification, we implemented the formulated SDP model piece wise in Microsoft Excel and we debugged the constructed VBA code to make sure that the output is correct. Multiple parts of the problem instances are checked by running the code separately to ensure that the evaluation method is correct. Furthermore, we used a discrete event simulation for the model verification. The probability distributions of the spare part demand and number of successful repairs are used in combination with a random number generator between 0 and 1 to calculate the actual events during each interval of the life cycle. The maximum number of spare part demand and successful repairs is equal to the upper bound value (as described in Chapter 4). With the use of the constructed simulation approach, it is possible to simulate a high number of life cycles. Each simulation run, the required output (see Section 5.2) can be generated and can be analysed separately. Since there is a difference in model complexity whether repairing is included or not, we compared the total expected costs of the model with the simulation for both options. Each time we run a high number of life cycles for the simulation in order to get average expected output. Comparison of the total expected costs of the simulation runs with the total expected costs of the SDP model, we find no differences greater than 0,84% on average. Based on the difference, we conclude that the model is implemented properly in Microsoft Excel and gives approximately the same results as the formulated SDP model. Since the model is stochastic, in this way we can perform the required analysis in the remainder of this chapter.

## 5.2 Case study

In this section, we perform a case study on two LRU's with different characteristics. In order to create model results, the required input data is collected and estimated by experts of TNL. The input data gives an indication of LRU's with specific characteristics but may deviate in practice. Regarding the LRU's, we analyse the following general model output for the defined strategies:

- The followed strategy/decisions:
  - Expected number of replenishment orders: E[orders]
  - Expected order quantity: E[order quantity]
  - Expected interval where redesign is initiated (if applicable): E[redesign interval]
- The total expected costs over the life cycle: TEC
- The expected average cycle service level ($A$) over the life cycle: E[A]
- Additional relevant output:
  - Expected on-hand inventory: E[OH]
  - Expected backorders: E[BO]
  - Expected number of repairs: E[repairs]
  - Expected excessive stock at the end of the planning horizon: E[excessive stock]

Furthermore, we analyse the impact of variation in installed base development and YTEOL on the strategies and the corresponding total expected costs and cycle service level. In Appendix 2, we describe the main design of the Microsoft Excel model in order to obtain the required model output.

As described in Chapter 4.1, we analyse the following strategies:

1. Risk mitigation buy at the start of the life cycle (RMB)
2. Monitoring obsolescence status and react when obsolescence occurs:
   1. Scenario 1: perform an LTB (Monitor + LTB)
   2. Scenario 2: Initiate an unplanned redesign (Monitor + redesign)
3. Incorporate LRU in planned redesign(s) (Planned redesign)

In the remainder of this section, we first introduce the selected LRU's for the case study. Secondly, we describe the general input values. Thereafter, the case study results for the individual LRU's are discussed.

### 5.2.1. Introduction to the selected LRU's

In this case study we focus on LRU's that are incorporated in the SMART-L Multi Mission radar system of Thales Hengelo. The SMART-L (see Figure 7) is a next generation long range radar for air and space surveillance and ballistic missile detection. This system can detect a very wide variety of air and space objects including stealth and short up to long range ballistic missiles. The applied high-end techniques result in a radar with an unrivalled long-range performance of up to 2.000 km.

*Figure 7: SMART-L Multi Mission radar system of Thales Hengelo.*

The first LRU that we analyse is the 'waveform generator', which is visualized in Figure 8[3]. This LRU is a complex electronic board which is special developed for the SMART-L system. The function of the waveform generator is to generate base waveforms in order to broadcast signals. This LRU is supplied by a sister company of Thales Hengelo and is therefore categorized as 'buy-part'. Although this supplier is reliable, resupplying new parts can sometimes be time consuming. Thales depends on this supplier regarding information related to obsolescence. There is a limited option to procure components of this LRU in a last time buy, and since this is a high value LRU, managing this LRU is important.

The second LRU is the 'relay' (see Figure 9), which turns the tension on and off. This is a relatively low value LRU and is also categorized as 'buy-part'. It is a Commercial Off-The-Shelf (COTS), which means the there are multiple suppliers of this part available. In case this type of LRU's becomes obsolete, the internal change process towards another supplier results in costs and actions in order to make sure that the alternative LRU is well integrated in the system.

*Figure 8: Representation of the waveform generator*

*Figure 9: Representation of the relay*

[3] Figure 8 and 9 give an indication what the LRU's look like but are not the actual representations.

### 5.2.2. General input data

For a subset of the input parameters the values are the same for the analysed LRU's. In this section we shortly describe how the values for these input parameters are obtained. It concerns the following parameters:

- Installed base development
- Life cycle analysis length
- Fixed order costs
- Holding costs
- Disposal costs
- Repair yield
- Discount factor

The total expected future sales for the next 15 years are given in Table 6. SMART-L systems can either be installed at land (landbased) or on board of a frigate (marine). In case a system is landbased the system is constant operational (i.e., 24/7, so 8.760 hours per year) and systems for the marine have 2.000 operational hours per year. In 2019 the installed base contains 12 landbased systems and 24 marine systems. The product team of the SMART-L system indicated a rough forecast of expected future sales. The minimum expected number of systems is 18, the mean is 72 and the maximum expected number is 150. Since there is no information whether these systems will be landbased or marine, we assume that two-third of the future sales will be marine as it is for the currently installed number of systems. Furthermore, we assume that the number of future sales is evenly distributed over the years since there is no forecast available for individual years. This means that if the future sales are for example 72, five systems are added to the installed base in the first 12 years of the life cycle and four systems in the last three years. In case of 150 future sales, each interval 10 systems are added to the installed base. Subsequently, two-third of the future sales are marine (e.g., 24 or 50) and one-third are land based (e.g., 48 or 100). The same approach is used for the annual operational hours to determine the spare part demand rate per interval ($\lambda$). This means that the annual operational hours per LRU is equal to 4.254,33 hours ($\frac{1}{3} * 8760 + \frac{2}{3} * 2000$), and divided by the Mean Time Between Failures (MTBF) to find $\lambda$.

*Table 6: Installed base development SMART-L radar system (CONFIDENTIAL[4]).*

| | | Future sales | | |
|---|---|---|---|---|
| | **Installed** | **Minimum** | **Mean** | **Maximum** |
| **Land based** | 12 | 6 | 24 | 50 |
| **Marine** | 24 | 12 | 48 | 100 |
| **Total** | 36 | 18 | 72 | 150 |

Table 7 shows the values of five other general input parameters. We analyse a life cycle length ($T$) of 15 years since the circumstances and developments for this period are already uncertain. Looking a longer period ahead is therefore not necessarily practical, although we will do this during the sensitivity analysis. The fixed internal order costs ($c_{fo}$) are €2.500. These costs include the hours that multiple departments spend on the process of establishing, preparing, and performing an actual order at a supplier. The annual holding cost rate ($c_h$) is 11,6% of the purchase price. This represents the material handling charges (e.g., purchase rate, aging rate) for manufacturing services that is used within the inventory management department of TNL. The salvage value ($v$) of any part/LRU is

[4] Installed base/future sales information is confidential and a certain factor is used to scale this information.

assumed to be -€100, since there is an external company that takes care of the discard process of excessive stock. The repair yield ($y_{rep}$) is expected to be 90% in all cases. Although there is no data available, TNL assumes that this is a practical value in general and is based on the experience of experts. Finally, the discount factor ($\beta$) is set equal to 1 in the analysis since there is no reliable interest rate available.

*Table 7: General input parameters values*

| **Input parameter** | **Value** |
|---|---|
| $T$ | 15 year |
| $c_{fo}$ | €2.500 |
| $c_h$ | 11,6% |
| $v$ | €-100 |
| $y_{rep}$ | 90% |
| $\beta$ | 1 |

### 5.2.2. LRU 1: Waveform generator

The input values for the waveform generator are given in Table 8. The multiplicity of the waveform generator per system is 1 and for each system one initial spare part is required in general.

*Table 8: Input parameter data for the waveform generator.*

| **Input parameter** | **Value** |
|---|---|
| $c_p$ | €16.873 |
| $\lambda$ | 0.0467 part per year |
| $IB_t$ | {36,41,46,51,56,61,66,71,76,81,86,91,96,100,104,108} parts per interval |
| $I_0$ | 0 parts |
| $MOQ$ | 0 parts |
| $c_b$ | €101.238 |
| $c_{mon}$ | €120 |
| $c_{rd1}$ | €300.000 |
| $c_{rd2}$ | €200.000 |
| $FPRD$ | 15 year |
| $YTEOL$ | 5 year |
| $c_r$ | €10.000 |

The waveform generator is characterized by a relatively high purchase price and the failure rate is relatively high. There is no starting inventory ($I_0 = 0$) and no Minimum Order Quantity (MOQ). The backorder costs are approximately €101.000 (see Appendix 1 for more details). The obsolescence monitoring costs are €120 per interval for the installed base. Since this LRU is categorized as a buy-part, only one item needs to be monitored and TNL is partly dependent on supplier information. From an historical offer from a supplier, the approximate annual costs to monitor a buy-part is estimated to be €120. The redesign impact is high, which means that the redesign costs are respectively €300.000 and €200.000 for each unplanned redesign or planned redesign (technology upgrade). Any (unplanned) redesign on an individual LRU is expected to have higher costs since the marginal costs (e.g., testing) are higher, based on expert opinions this is a factor 1.5 higher. The planned redesign strategy is not an option since the frequency of planned redesigns ($FPRD$) is 15 years, we will analyse this in the sensitivity analysis. Furthermore, the expected YTEOL is 5 and this LRU is repairable. Each initiated repair has a cost of €10.000.

### Mean input values for future sales and YTEOL

Table 9 shows the main output of the analysis.

*Table 9: Results of the analysis of the waveform generator.*

| Strategy | RMB | Monitor+LTB | Monitor+redesign |
|---|---|---|---|
| E[orders] | 1,0 | 6,0 | 10,7 |
| E[total order quantity] | 28,0 | 28,5 | 30,9 |
| E[redesign interval] | 0,0 | 0,0 | 5,0 |
| TEC | € 859.704,5 | € 702.301,3 | € 969.983,7 |
| E[A] | 91,1% | 90,7% | 92,9% |
| E[OH] | 11,4 | 5,4 | 2,4 |
| E[BO] | 0,2 | 0,1 | 0,0 |
| E[repairs] | 5,1 | 4,9 | 4,9 |
| E[excessive stock] | 1,5 | 0,8 | 1,9 |

From Table 9 we can see that a monitor + LTB strategy results in the lowest TEC of €702.301,3. The cost breakdown of each strategy is given in Table 10. The holding costs for a RMB strategy are in relation to the monitor + LTB strategy, more than twice as high and since the fixed order costs are not significant it is beneficial to order at the start of multiple intervals. In case a monitor + redesign strategy is followed, a redesign is initiated once the LRU becomes obsolete and due to the redesign costs of €300.000, the TEC is higher. The average on-hand inventory is only 2,4 parts per interval since orders can be placed during the entire life cycle. It becomes also clear that the monitoring costs for obsolescence are a small fraction of the total costs. Furthermore, the disposal costs are negligible. The fact that the E[A] is highest for the monitor + redesign strategy, is due to the fact that near the end of the life cycle an additional order quantity is placed (which is not possible for the other strategies) to avoid higher expected backorders. Due to the relatively low spare part demand rate, the E[A] is either below 90% (e.g., 89,4%) or above the desired level of 90%. Although this results in a higher TEC (especially higher purchase costs of approximately €43.000), this is required to create a fair comparison and the difference between the strategies remains still significant.

*Table 10: Cost breakdown for the waveform generator.*

| Strategy | RMB | Monitor+LTB | Monitor+redesign |
|---|---|---|---|
| Fixed order costs | € 2.500,0 | € 14.991,7 | € 26.680,0 |
| Part purchase costs | € 472.444,0 | € 480.093,1 | € 521.094,5 |
| Holding costs | € 333.543,8 | € 156.987,5 | € 71.561,2 |
| Repair costs | € 51.066,7 | € 49.433,3 | € 48.533,3 |
| Redesign costs | € - | € - | € 300.000,0 |
| Disposal costs | € 150,0 | € 75,7 | € 194,7 |
| Monitoring costs | € - | € 720,0 | € 1.920,0 |

The cycle service level over the analysed life cycle is given in Figure 10. As we can see, the cycle service level remains well above 90% in the first 11 intervals for the RMB and monitor + LTB strategies, while it is more fluctuating between 90% and 99% for the monitor + redesign strategy. In the last 4 intervals, the cycle service level drops significant towards a value of approximately 50% for the RMB and monitor + LTB strategy. This is due to the fact that no orders can be placed anymore, and repairing is only possible until interval 10. For the monitor + redesign strategy, the drop in service level is less significant since an additional quantity is ordered in interval 10. The RMB strategy results in an E[A] of 91,1%, the monitor + LTB strategy in 90,7%, and the monitor + redesign strategy in 92,9%. In Section 5.3., we analyse the impact of attaining a cycle service level of 90% during each interval of the life cycle ($A_t \geq 90\%$).

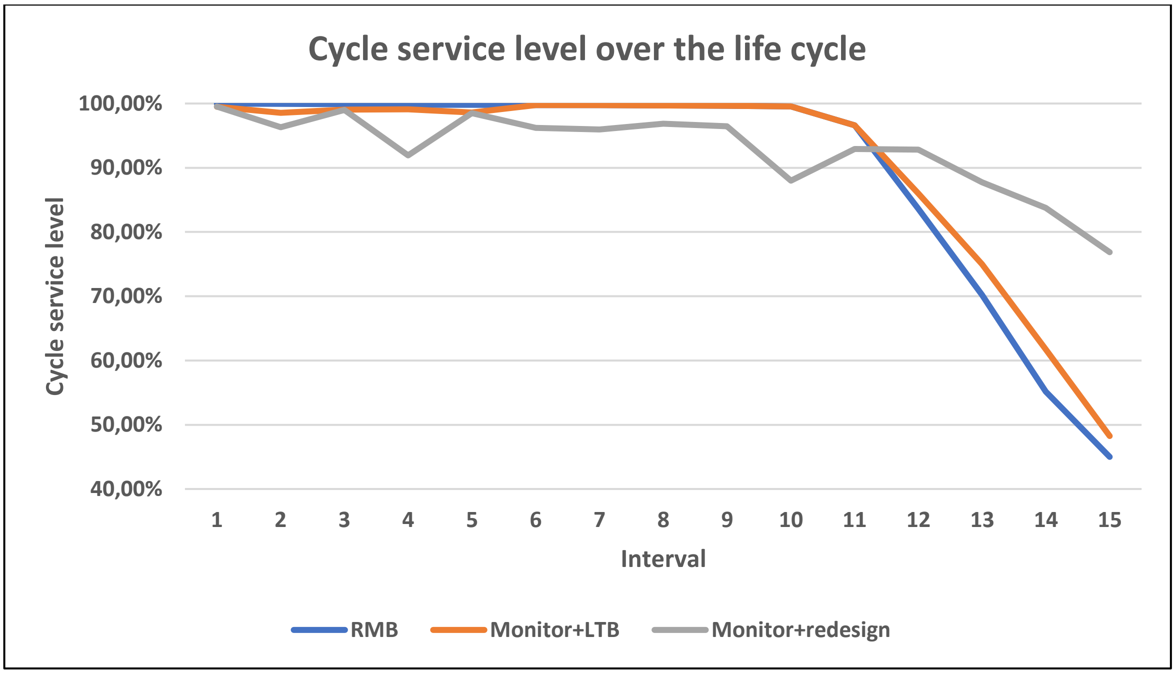


*Figure 10: Cycle service level for the waveform generator over the life cycle ($A_t$).*

## Impact analysis of variation in installed base development

In order to analyse the impact and consequences of variation in the installed base development during the life cycle, we run the model again for a lower and higher number of future sales. As stated in Table 6, there is a minimum and maximum number of expected future sales and we analyse multiple points within this range. The main goal of this is to analyse the impact of a higher actual installed base development which deviates from the mean expectation and a certain strategy is chosen at the start of the life cycle. The initial decisions under the mean forecasted installed base development are fixed for the first intervals. We include two scenarios in this analysis to show the importance of managing the installed base development during the life cycle. In scenario A the decisions can be changed after 5 years onwards, meaning that an LTB is not possible. In scenario B the decisions can be changed after the first 2 years[5], which means that an LTB is possible since the LRU is expected to become obsolete after 5 years. After some years of the life cycle, more accurate information about the actual development (i.e., number of future sales) is expected to be available and the decisions in the remaining intervals are changed. In Appendix 2, we describe this approach in more detail.

Table 11 gives an overview of the impact of future sales variation on the E[A] when the initial strategy and decisions are unchanged, and the TEC in order to modify the strategy to attain an E[A] of 90%. For more details see Appendix 4. As for the mean input values, there is some variation in the E[A] of each strategy after it is adapted (comparable ratio as for mean input). This means that the difference in the TEC for the monitor + LTB and monitor + redesign strategy can be somewhat different, but this would also mean that the E[A] of the monitor + redesign strategy is below 90% which is not desired for comparison.

[5] The uncertainty about installed base may still be significant after 2 years, but this value is used to show the importance of having more accurate future sales information before obsolescence occurs (so before the expected YTEOL have passed).

*Table 11: Impact of future sales variation on E[A] and TEC for waveform generator.*

| | Impact on E[A] | | Impact on TEC | |
|---|---|---|---|---|
| Future sales | 18-60 | 84-150 | 18-60 | 84-150 |
| | | | | |
| Strategy | Scenario A | | | |
| RMB | 99,6% | 49,4% | € 1.133.407 | € 1.369.794 |
| Monitor+LTB | 94,8% | 15,8% | € 844.333 | € 1.331.459 |
| Monitor+redesign | 98,0% | 24,0% | € 861.861 | € 1.254.139 |
| | Scenario B | | | |
| RMB | 99,6% | 49,5% | € 1.133.677 | € 1.278.067 |
| Monitor+LTB | 93,7% | 16,5% | € 481.779 | € 1.265.429 |
| Monitor+redesign | 98,2% | 23,5% | € 532.215 | € 1.202.714 |

From Table 11, we see that the E[A] is well above the required 90% in case the future sales are lower than expected, resulting in higher inventory levels and excessive stock. Especially for the RMB strategy, the expected holding costs increase to €550.000. The impact on the TEC is lowest for the monitor + LTB strategy, especially in scenario B since the LTB is limited and redesigning is avoided. For higher future sales, the cycle service level drops significantly in the last intervals. The RMB strategy still has a high cycle service level in the first intervals, resulting in an E[A] equal to 49,4%. Initiating a redesign is required in scenario A and an LTB can be performed in scenario B, although the holding costs are lower in scenario A, the redesign costs of €300.000 result in a higher TEC of approximately €90.000.

For the monitor + LTB strategy, lower actual future sales would also mean that the holding costs increase since the LTB is already performed in scenario A. The LTB can be avoided in scenario B, which means that less LRU's are ordered and the TEC is €362.554 lower. In case the future sales are higher, a redesign is required in scenario A and a higher LTB quantity is sufficient in scenario B. The TEC is approximately €66.000 higher for scenario A.

Regarding the monitor + redesign strategy, in case the future sales is limited to 18 systems this would mean that redesigning is only avoided in scenario B. In scenario A, the order quantity in the remaining intervals is limited but the redesign costs are incurred which results in a higher TEC. In case the future sales are between 48 and 150, the total order quantity in the remaining periods after the redesign is lower in case of lower actual future sales. Logically, the total order quantity is higher in case of higher future sales.

Based on the average TEC when the actual number of sales deviates from the expectation, we conclude that the impact on the TEC is lowest for the monitor + LTB strategy. Especially if the actual future sales are lower, the TEC in scenario A is approximately 75% higher than in scenario B. This means that updating the expected installed base development, before obsolescence occurs, results in a significant lower TEC. In case the actual future sales are higher, a monitor + redesign strategy results in a slightly lower TEC since multiple orders can be placed over the whole life cycle and therefore lowering the holding costs.

### Impact analysis of variation in YTEOL

The same approach as for the installed base development is used for variation in the actual YTEOL of the LRU. Although it is expected that the LRU becomes obsolete after 5 years, it is also possible that obsolescence occurs at an earlier / later stage of the life cycle. We analyse the impact of an actual YTEOL between 2 and 8 years. We analyse two scenarios. In scenario A, obsolescence monitoring is not applied. This means that whenever the LRU becomes obsolete before the initial expected interval, an LTB is not possible, and the decisions can only be changed after the actual interval where the LRU becomes obsolete. On the other hand, if the actual YTEOL is higher than expected, all decisions until the actual YTEOL are fixed. In scenario B, obsolescence monitoring is applied from the start of the life cycle. This means that if the LRU becomes obsolete in an earlier stage, an LTB is possible. In case the actual YTEOL is higher, some decisions (i.e., performing an LTB, or initiating a redesign) can be postponed.

Table 12 gives an overview of the impact of YTEOL variation on the E[A] and TEC for both scenarios. Note that obsolescence monitoring is not actually incorporated in scenario A. First, we conclude that variation in the actual YTEOL has no significant impact on the RMB strategy, since all expected demand is already ordered at the start of the life cycle. The repair fractions and order quantity are slightly different in case the YTEOL deviates from the expectation.

*Table 12: Impact of YTEOL variation on E[A] and TEC for waveform generator.*

| | Impact on E[A] | | Impact on TEC | |
|---|---|---|---|---|
| YTEOL | 2-4 | 6-8 | 2-4 | 6-8 |
| | | | | |
| Strategy | Scenario A | | | |
| RMB | 91,1% | 91,1% | € 963.247 | € 962.664 |
| Monitor+LTB | 68,4% | 92,7% | € 969.333 | € 970.815 |
| Monitor+redesign | 83,1% | 91,7% | € 947.443 | € 1.152.919 |
| | Scenario B | | | |
| RMB | 91,1% | 91,1% | € 964.849 | € 964.906 |
| Monitor+LTB | 91,8% | 91,0% | € 892.236 | € 870.310 |
| Monitor+redesign | 93,2% | 91,2% | € 871.658 | € 1.001.387 |

For the other two strategies, the E[A] will be lower in scenario A if obsolescence occurs in an earlier interval since an LTB is not possible. In this situation a redesign is required (in an earlier stage), but the average inventory level will be lower since orders can be placed at the supplier after the redesign is finished. In case the actual YTEOL is higher, the LTB is already performed since obsolescence was not monitored. In case we apply obsolescence monitoring (scenario B), the E[A] is more constant since strategic changes can be made at the appropriate intervals. An LTB is performed in an earlier stage in the monitoring + LTB strategy and thus avoiding redesign activities. For the monitor + redesign strategy, the redesign is initiated in an earlier stage. Whenever the YTEOL is higher than expected, we can postpone the LTB decision in the monitor + LTB strategy and an LTB is not required in the monitor + redesign strategy. From Table 12 we conclude that if obsolescence monitoring is not applied, the RMB strategy will result in a slightly lower TEC of 0,8% compared to the monitor + LTB strategy. In case obsolescence monitoring is applied, the TEC in case of YTEOL variation is lowest for the monitor + LTB strategy. The RMB strategy and monitor + redesign strategies will result in a higher TEC of approximately 10% and 15%. Furthermore, obsolescence monitoring will result in a lower TEC of 11,5% on average, compared to scenario A where obsolescence in not monitored.

### 5.2.3. LRU 2: Relay

The input values for the relay are given in Table 13. The multiplicity of this LRU per system is 2 and for each system one initial spare part is required in general.

*Table 13: Input parameter values for relay.*

| Input parameter | Value |
|---|---|
| $c_p$ | €76 |
| $\lambda$ | 0.0008 part per year |
| $IB_t$ | {72,82,92,102,112,122,132,142,152,162,172,182,192,200,208,216} parts per interval |
| $I_0$ | 0 units |
| $MOQ$ | 10 units |
| $c_b$ | €76 |
| $c_{mon}$ | €120 |
| $c_{rd1}$ | €22.500 |
| $c_{rd2}$ | €15.000 |
| $FPRD$ | 15 year |
| $YTEOL$ | 8 year |

From Table 13 we can see that this is a relatively low price LRU with a very low failure rate. There is no starting inventory ($I_0 = 0$) and the MOQ is 10 units. The backorder costs are €76. The obsolescence monitoring costs are €120 per interval for the installed base. Furthermore, the redesign impact is generally low for this LRU which means that incorporating this LRU in a planned redesign (technology upgrade) costs €15.000. Any (unplanned) redesign on an individual LRU is expected to cost more since the marginal costs (e.g., testing) are higher, based on expert opinions this is a factor 1.5 higher. Since the frequency of planned redesigns ($FPRD$) is 10 year for this LRU. Finally, the expected Years Till End Of Life ($YTEOL$) is 8 year and failed LRU's cannot be repaired.

#### Mean input values for future sales and YTEOL

In Table 14, the results of the analysis are summarized.

*Table 14: Results of the analysis for the relay.*

| Strategy | RMB | Monitor+LTB | Monitor+redesign | Planned redesign |
|---|---|---|---|---|
| E[orders] | 1,0 | 3,0 | 3,0 | 3,0 |
| E[total order quantity] | 38,0 | 37,5 | 37,8 | 37,8 |
| E[redesign interval] | 0,0 | 0,0 | 8,0 | 10,0 |
| TEC | € 7.355,0 | € 12.039,6 | € 35.443,3 | € 27.693,0 |
| E[A] | 94,8% | 90,1% | 90,4% | 91,0% |
| E[OH] | 14,4 | 4,3 | 4,4 | 4,3 |
| E[BO] | 0,1 | 0,1 | 0,1 | 0,1 |
| E[repairs] | 0,0 | 0,0 | 0,0 | 0,0 |
| E[excessive stock] | 0,6 | 0,4 | 0,4 | 0,4 |

From Table 14 we see that an RMB strategy at the start of the life cycle, results in the lowest TEC of €7.355,0. This means that only one quantity is ordered to cope with the total expected demand. In Table 15, an overview of the cost breakdown is given. Although the average on-hand inventory is higher than it is for other strategies, the holding costs are relatively low compared to the fixed order costs. Using multiple orders in combination with obsolescence monitoring and/or redesigning will lead to a significant higher TEC.

*Table 15: Cost breakdown for the relay.*

| Strategy | RMB | Monitor+LTB | Monitor+redesign | Planned redesign |
|---|---|---|---|---|
| Fixed order costs | € 2.500,0 | € 7.500,0 | € 7.533,0 | € 7.535,0 |
| Part purchase costs | € 2.888,0 | € 2.852,3 | € 2.871,3 | € 2.872,0 |
| Holding costs | € 1.909,0 | € 570,3 | € 575,0 | € 563,9 |
| Repair costs | € - | € - | € - | € - |
| Redesign costs | € - | € - | € 22.500,0 | € 15.000,0 |
| Disposal costs | € 58,0 | € 37,0 | € 44,0 | € 42,0 |
| Monitoring costs | € - | € 1.080,0 | € 1.920,0 | € 1.680,0 |

Figure 11 visualizes the expected cycle service level in each interval of the life cycle. The cycle service level in in the first intervals is approximately 99,9%. In interval 8 we see a drop towards 85,5%, this is due to the fact that the LRU becomes obsolete and an LTB is performed to increase the inventory level. Towards the end of the life cycle, the cycle service level drops towards 75% for the RMB strategy and towards 60% for the other strategies. Due to the low demand rate, the E[A] is 94,8% for the RMB strategy and approximately 90% for the other strategies.

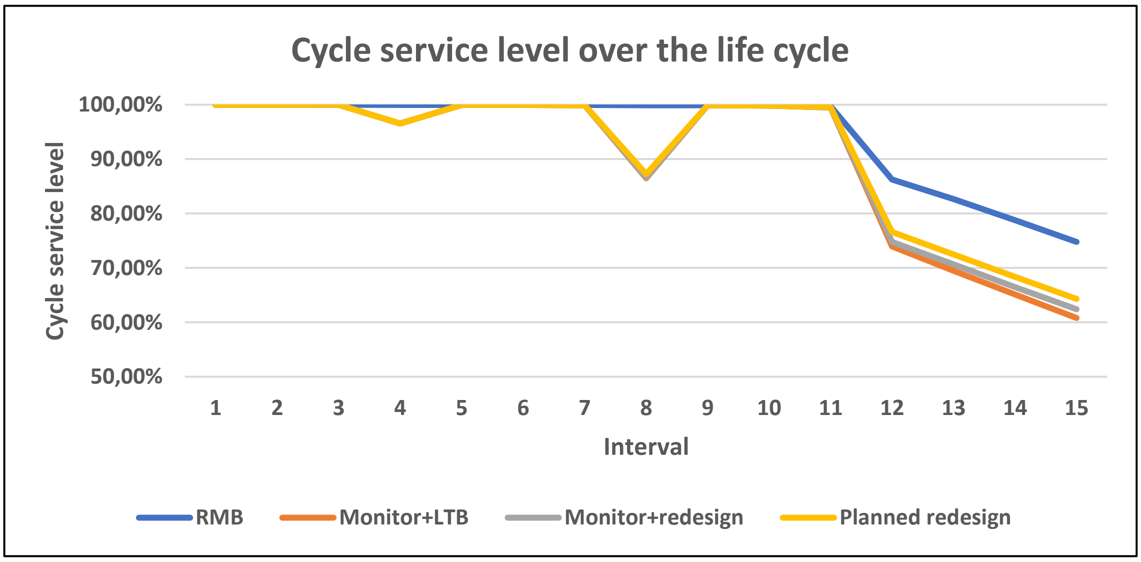


*Figure 11: Cycle service level for the relay over the life cycle ($A_t$).*

## Impact analysis of variation in installed base development

In order to analyse the impact and consequences of variation in the installed base development, we follow the same approach as we did in Section 5.2.2. Table 16 shows the impact of variation on the E[A], when the initial strategy and decisions are unchanged, and the TEC in order to modify the strategy to attain a minimum E[A] of 90%.

Based on the results we conclude that the impact of future sales variation is the lowest for the RMB strategy. The differences between scenario A and B are small, since this LRU is expected to become obsolete after 8 years. In case the future sales are lower, the holding costs are higher and the E[A] is 99,9%. Whenever the future sales are higher, the E[A] is approximately 54% and an additional order is required which results in extra fixed order costs. Furthermore, a redesign can be avoided in case the future sales are lower. The redesign is initiated in an earlier stage and/or the LTB quantity is higher in case the future sales are higher than expected.

*Table 16: Impact of future sales variation on E[A] and TEC for relay.*

| | Impact on E[A] | | Impact on TEC | |
|---|---|---|---|---|
| Future sales | 18-60 | 84-150 | 18-60 | 84-150 |
| | | | | |
| Strategy | Scenario A | | | |
| RMB | 99,9% | 52,4% | € 10.098 | € 13.881 |
| Monitor+LTB | 99,9% | 36,5% | € 9.634 | € 16.571 |
| Monitor+redesign | 99,9% | 37,1% | € 9.667 | € 35.435 |
| Planned redesign | 99,8% | 39,0% | € 9.699 | € 32.481 |
| | Scenario B | | | |
| RMB | 99,9% | 56,3% | € 10.128 | € 14.049 |
| Monitor+LTB | 99,9% | 34,8% | € 9.117 | € 15.076 |
| Monitor+redesign | 99,9% | 37,2% | € 9.478 | € 34.413 |
| Planned redesign | 99,9% | 37,2% | € 9.679 | € 32.368 |

## Impact analysis of variation in YTEOL

The expected YTEOL for the relay is 8 years, in order to analyse the impact of variation we will vary the YTEOL within a range of 4 and 12 years. Table 17 shows the impact of variation in YTEOL on the E[A] and the TEC.

*Table 17: Impact of YTEOL variation on E[A] and TEC for relay.*

| | Impact on E[A] | | Impact on TEC | |
|---|---|---|---|---|
| YTEOL | 2-6 | 10-14 | 2-6 | 10-14 |
| | | | | |
| Strategy | Scenario A | | | |
| RMB | 94,8% | 94,8% | € 7.383 | € 7.383 |
| Monitor+LTB | 56,4% | 95,4% | € 32.283 | € 11.154 |
| Monitor+redesign | 68,3% | 95,1% | € 31.467 | € 13.599 |
| Planned redesign | 75,8% | 95,1% | € 40.195 | € 14.412 |
| | Scenario B | | | |
| RMB | 94,8% | 94,8% | € 8.439 | € 8.439 |
| Monitor+LTB | 90,7% | 92,8% | € 11.447 | € 11.458 |
| Monitor+redesign | 92,0% | 91,5% | € 11.775 | € 11.813 |
| Planned redesign | 92,0% | 92,7% | € 11.864 | € 11.940 |

The impact on the RMB strategy is negligible, the only difference is that obsolescence monitoring costs of approximately €1.000 are incurred if obsolescence is monitored (scenario B). For the other strategies, the impact of YTEOL variation is higher. In case the YTEOL is lower than expected, an LTB is not possible and an unplanned redesign is required for the monitor + LTB strategy and planned redesign strategy, resulting in an average TEC of €34.648, which is more than four times as high as for the RMB strategy. In case obsolescence monitoring is applied (scenario B), an LTB is used instead of initiating a redesign. The TEC in scenario B is approximately 40% lower if we compare the RMB strategy with the other strategies. Based on this we conclude that the RMB strategy is the most robust strategy to deal with YTEOL variation, and obsolescence monitoring means that the TEC for the other strategies is a factor three lower in case obsolescence occurs at an earlier stage of the life cycle and obsolescence monitoring is applied.

## 5.3 Sensitivity analysis

In this section, we describe the results of the performed sensitivity analysis (SA) to investigate the properties and sensitivity of the model output. The model output that is analysed is equal to Section 5.2. The input parameters that are expected to have significant impact and have degree of uncertainty are described below:

- **Life cycle length of the analysis ($T$)**
  Systems that Thales produces can have a life cycle of 30 years or longer. The fact that some LRU's are incorporated in multiple types of systems means that the LRU's need to be available for a long period of time. As we described before, the installed base development is very uncertain and an indication for the future sales for the next 15 years is available. To show the impact of a longer life cycle, we analyse a life cycle length of 20 to 30 years. We assume that the YTEOL, after redesigning, is set equal to 10 years in order to analyse this.
- **Future sales (FS)**
  As given in Table 6, there is an indication for the expected total future sales for the next 15 years. At the start of the life cycle analysis, a specific number of systems is already operational. Furthermore, there is a forecasted number of systems (both landbased and marine) that are expected to be become operational in future years. Since the forecasting of future sales is very difficult/uncertain, the actual demand for a LRU can vary. For this reason, we incorporate the installed base development in the sensitivity analysis. Based on an indication for the relevant product team, we analyse the minimum number of systems of 18 and the maximum number of systems which is 150.
- **Years Till End Of Life (YTEOL)**
  The YTEOL is an indication for the expected stage of the life cycle where the LRU becomes obsolete. For each LRU, there is in general some data and knowledge available to use in the analysis. Since the forecasting of the YTEOL is very difficult and uncertain, the actual moment in time where the LRU becomes obsolete can be earlier or later than expected. Therefore, we analyse the effect if the LRU becomes a few years earlier/later obsolete.
- **Fixed order costs ($c_{fo}$)**
  The fixed order costs are the internal incurred costs each time a replenishment order is placed at the supplier. Experts of TNL indicate that the fixed order costs are approximately € 2.500. Depending on the characteristics of the LRU, these costs can play a significant role.
- **Redesign costs ($c_{rd1}$)**
  The redesign costs are a rough indication of the non-recurring engineering costs related to the redesign process of an individual LRU. Since a high uncertainty in the actual redesign costs is expected, we analyse what the impact of lower/higher redesign costs will be. Only unplanned redesign costs are considered.
- **Holding costs ($c_h$)**
  The holding costs are calculated as a fraction of the LRU purchase price. Depending on the purchase price, the holding costs can have a certain degree of significance. Based on input from the inventory management department, a standard fraction of 11,6% of the purchase price is used in the case study. Since this is a total material handling rate, and therefore incorporates multiple aspects, we analyse two cases where the holding cost rate is 5% and 20% to show the impact on the optimal strategy.
- **Frequency of planned redesign (FPRD)**
  For each LRU, a rough estimation for the frequency of initiating planned redesigns (technology upgrades) is analysed. Since the frequency can be low (e.g., each 10 or 15 years), this strategy is often not an optimal or even considered at all. Therefore, we analyse the

impact on the optimal strategy by changing the frequency of planned redesign to 5 or 10 years for the waveform generator.

- **Cycle service level** $(A \text{ and } A_t)$
As described in Section 4.1., we analyse a cycle service level over the life cycle and the average cycle service level over all years should attain a minimum level of 90%. The result of this is that the cycle service level will significantly decrease as we reach the end of the life cycle. Although, it is expected that alternative sourcing options can be used in such cases, we will analyse the impact of attaining a service level of 90% in each individual interval ($A_t \geq 90\%$). Furthermore, we set the minimum average cycle service level equal to 95% ($A \geq 95\%$) to indicate the impact of maintaining a higher cycle service level.

Since not all input parameters have significant impact on different types of LRU's, in the remainder of this section we describe the significant parameters for each LRU. For more details about the results concerning the sensitivity analysis we refer to Appendix 5.

### 5.3.1. LRU 1: Waveform generator

Table 18 gives an overview of the key results of the sensitivity analysis for the waveform generator.

*Table 18: Overview of sensitivity analysis results for waveform generator.*

| Parameter | Value | Optimal strategy | E[orders] | E[order quantity] | E[redesign interval] | TEC |
|---|---|---|---|---|---|---|
| T | 20 years | Monitor+LTB | 5 | 43 | - | € 1.192.692 |
| | 25 years | Monitor+redesign | 6 | 60 | 5 | € 1.655.993 |
| | 30 years | Monitor+redesign | 6 | 77 | 5 &17 | € 2.266.570 |
| FS | 18 systems | Monitor+LTB | 3 | 9 | - | € 251.989 |
| | 150 systems | Monitor+LTB | 6 | 55 | - | € 1.285.234 |
| YTEOL | 3 years | Monitor+LTB | 3 | 30 | - | € 805.739 |
| | 7 years | Monitor+LTB | 9 | 28 | - | € 658.307 |
| $c_{rd1}$ | € 50.000 | Monitor+redesign | 11 | 29 | 5 | € 687.798 |
| | € 75.000 | Monitor+redesign | 10 | 28 | 5 | € 689.163 |
| | € 100.000 | Monitor+LTB | 6 | 28 | - | € 711.641 |
| $c_h$ | 5% | Monitor+LTB | 5 | 29 | - | € 621.295 |
| | 20% | Monitor+LTB | 6 | 28 | - | € 838.645 |
| FPRD | 5 years | Monitor+LTB | 6 | 29 | - | € 702.931 |
| | 10 years | Monitor+LTB | 6 | 29 | - | € 704.314 |
| CSL | $A_t \geq 90\%$ | Monitor+LTB | 6 | 32 | - | € 959.991 |
| | $A > 95\%$ | Monitor+LTB | 6 | 30 | - | € 893.805 |

From the sensitivity analysis we conclude that the optimal strategy for the waveform generator only changes if the life cycle length is longer or when the redesign costs are lower than €100.000. In all other cases, a monitor + LTB strategy is optimal and results in the lowest total expected costs. In case the life cycle length ($T$) is equal to 25 or 30 years, the optimal strategy is to initiate a redesign once the LRU becomes obsolete after 5 years. After the redesign is finished, regular orders are performed until the redesigned LRU becomes obsolete. For a life cycle length of 25 years, an LTB is performed in year 16 to cope with the remaining expected demand. The monitor + redesign strategy results in 11,6% lower costs than a monitor + LTB strategy. A second redesign is not optimal, since the costs would be 3,8% higher in relation to the monitor + LTB strategy. For a life cycle length of 30 years, the optimal strategy is to initiate a redesign at the start of year 5 and year 17, resulting in lower expected total costs of 10%. Furthermore, the second redesign can be replaced by performing an LTB in year 16, resulting in 6% extra cost savings. Although, this would result in a less flexible process since the installed base variation is highly uncertain over a long period of time.

TNL expects that the incorporated value of €300.000 for redesign costs ($c_{rd1}$) is case dependent, and possibly even higher in practice. From the performed analysis we conclude that the monitor + redesign strategy is only optimal if the redesign costs are lower than €100.000. Since the expected demand is rather low, redesign costs are highly significant. The total expected costs are, in relation to the monitor + LTB strategy, approximately 2,4% and 0,84% lower when the redesign costs are €50.000 and €75.000. As the redesign costs increase, the marginal difference between both strategies increases. Since the frequency of planned redesigns (technology upgrades) for this LRU is 15 year, we also analysed a frequency of 5 and 10 years but this has no impact on the optimal strategy.

Finally, we emphasize on the required cycle service level. For the case study, we analysed the scenario where the average cycle service level over the life cycle is set at a minimum of 90%. In case a cycle service level of 90% should be attained in each interval ($A_t$), we conclude that the total order quantity increases with 4 parts to 32. This results in higher costs of approximately €250.000, due to procurement costs and higher holding costs. In case an average cycle service level ($A$) of 95% should be attained, 30 parts are ordered over the life cycle. The total costs are approximately €190.000. The optimal strategy does not change in both cases. Although the sensitivity regarding the repair process is not within the focus of this research, extending the number of years the LRU is repairable could be a value source of supply to cope with spare part demand in the last years of the life cycle. Whenever the repair process will be extended for 5 more years (so until 10 years after obsolescence), the (final) order quantity can be lower since the actual repair costs are lower than the extra costs purchase costs and holding costs.

### 5.3.2. LRU 2: Relay

Table 19 gives an overview of the key results of the sensitivity analysis for the relay.

*Table 19: Overview of sensitivity analysis results for relay.*

| Parameter | Value | Optimal strategy | E[orders] | E[order quantity] | E[redesign interval] | TEC |
|---|---|---|---|---|---|---|
| T | 20 years | RMB | 1 | 52 | - | € 9.849 |
| | 25 years | RMB | 1 | 66 | - | € 11.655 |
| | 30 years | RMB | 1 | 80 | - | € 13.916 |
| FS | 18 systems | RMB | 1 | 11 | - | € 3.652 |
| | 150 systems | RMB | 1 | 76 | - | € 12.267 |
| YTEOL | 4 years | RMB | 1 | 38 | - | € 7.536 |
| | 12 years | RMB | 1 | 38 | - | € 7.217 |
| $c_{fo}$ | € 100 | RMB | 1 | 38 | - | € 3.863 |
| | € 1.000 | RMB | 1 | 38 | - | € 4.826 |
| $c_h$ | 5% | RMB | 1 | 38 | - | € 5.845 |
| | 20% | RMB | 1 | 38 | - | € 8.792 |
| CSL | $A_t \geq 90\%$ | RMB | 1 | 39 | - | € 7.663 |
| | $A > 95\%$ | RMB | 1 | 39 | - | € 7.543 |

As we can see in Table 19, the optimal strategy is always to perform an RMB at the start of the life cycle. Since the relay is a low value LRU, with a low demand rate, the holding costs are not significant. The fixed order costs of €2.500 are significant, but since there is a Minimum Order Quantity of 10 units for this LRU, there is no change in strategy if the fixed order costs are reduced. Furthermore, ignoring the MOQ will also not change to optimal strategy. Attaining a higher (average) service level can be achieved by ordering one additional part, the impact of total expected costs is relatively small.

## 5.4 Conclusion

Based on the performed analysis, we conclude that different types of LRU's require different strategies to cope with obsolescence over the life cycle. We formulated the following conclusions:

- For low value LRU's, an RMB at the start of the life cycle is optimal. Due to low demand rates, cost factors such as redesign costs and fixed order costs result in a substantial higher TEC for the other strategies. The impact of variation in YTEOL and future sales is relatively small for the RMB strategy and we conclude that this strategy is most robust. Based on the sensitivity analysis we conclude that no change in optimal strategy occurs for the analysed instances.
- For high value LRU's, an obsolescence monitoring with LTB strategy is optimal. Due to the relatively high holding costs, the RMB strategy will result in a TEC which is 22,41% higher. The redesign costs are also significant, and an obsolescence monitoring with redesign strategy will result in a higher TEC of 38,12%. The impact of variation in YTEOL and future sales can be significant for high value LRU's. In case the actual future sales are higher (17% till 208%), or the actual YTEOL is lower (20% till 60%), than expected, a redesign instead of an LTB will result in a slightly lower TEC of respectively 4,96% and 2,31%. Whenever the actual future sales are lower (17% till 75%), or the actual YTEOL is higher (20% till 60%), the obsolescence monitoring with LTB strategy is most robust and results in a lower TEC of respectively 9,48% and 13,09% compared to using a redesign. From the performed sensitivity analysis, we conclude that the optimal strategy changes only changes towards an obsolescence monitoring with redesign strategy if the life cycle length is 25 years or longer, or if the redesign costs are significant lower (<€100.000).
- Based on the impact analysis of future sales variation we conclude that updating the installed base development at an early stage, at least before the YTEOL have passed, results in a substantial lower TEC compared to when this is noticed at a later stage when the LRU is already obsolete. Especially, for the obsolescence monitoring with LTB or redesign strategy, this results in an average lower TEC of 40,59% if the actual future sales are lower. For higher actual future sales, the average TEC is 4,53% lower.
- From the impact analysis of YTEOL variation we conclude that obsolescence monitoring can reduce the TEC for high value LRU's with approximately 8,6% in case obsolescence occurs in an earlier stage of the life cycle (20% till 60% earlier than expected). In case obsolescence occurs at a later stage, obsolescence monitoring results in a lower TEC of 11,5% compared to when obsolescence is not monitored. We conclude that although the monitoring costs are relatively low, the potential savings can be significant since LTB and redesign decisions can be adjusted according to the actual developments.
- In order to attain a higher (average) cycle service level, we conclude that ordering a few extra parts can be sufficient but will also result in a higher TEC (especially increased holding costs, 44,21% for $A_t \geq 90\%$ and 13,87% for $A \geq 95\%$). We conclude that extending the repair option for a longer period, can also be used as flexible source of supply near the end of the life cycle.

# 6. Conclusions and recommendations

In this chapter we describe the conclusions and recommendations. We start with the main conclusions of the study. Thereafter, the research limitations will be discussed. Finally, the recommendations for further research and possible model extensions at Thales are formulated.

## 6.1 Conclusions

This research is performed at Thales Hengelo to determine which obsolescence strategy should be used to manage obsolescence from the start of the life cycle. Thales Hengelo has already knowledge about available obsolescence management strategies. Since the comparison between multiple strategies is not available, the goal of this research is formulated as follows:

*"Construct a model to assess the differences and impact of obsolescence strategies related to maintenance significant items, after the design phase at Thales Hengelo in order to create a guideline on how to manage and to decrease the impact of obsolescence over the system life cycle".*

In order to complete this goal, multiple research questions are formulated and answered. First, we reviewed the current obsolescence strategies. Whenever an item is announced obsolete, and a substitute item is not available, a Last Time Buy (LTB) is considered. In case the LTB is not possible, or sufficient, a redesign is used to modify a product. Obsolescence monitoring is applied to all systems of Thales Hengelo and the intensity depends on customer agreements. Furthermore, planned redesigns (technology upgrades) are used to redesign specific parts of a product and in some cases a Risk Mitigation Buy (RMB) is performed to minimize the impact of obsolescence in advance.

From the literature study we conclude that there are multiple models available that incorporate specific strategies such as performing an LTB, (planned) redesigns, and repairing failed parts from the field. Since the literature incorporates certain details that are not relevant for Thales, and the fact that obsolescence monitoring is not incorporated in either of them, we constructed a model that focuses on three strategies: (1) an RMB at the start of the life cycle, (2) obsolescence monitoring and either perform an LTB and/or initiate a redesign when obsolescence occurs, or (3) include the LRU in planned redesign(s). The repair option is included in all strategies (if applicable). The following cost factors are incorporated:

- Purchase costs (part price and fixed order costs)
- Holding costs
- Backorder costs
- Repair costs
- Obsolescence monitoring costs
- (un)planned redesign costs
- Disposal costs

The model that we constructed should determine which obsolescence strategy results in minimum TEC, while attaining a specified cycle service level (i.e., no-stockout probability) over the analysed life cycle. At the start of every interval of the life cycle, decisions regarding the order quantity and redesign activities should be made and this depends on the obsolescence state. For this reason, this problem is categorized as a sequential optimization problem. Next to the fixed demand for new production, we incorporate the spare part demand. Since we focus on electronical items, for which a Poisson distribution is applicable, the constructed model is based on Stochastic Dynamic Programming (SDP). For the repair process, a Binomial distribution is used to model the number of successfully executed repairs (if applicable). Furthermore, the cycle service level is found by using forward recursion, to determine the probability of no-stockout during each interval of the life cycle.

The model is validated by consulting experts of Thales Hengelo concerning different relevant assumptions, limitations, and model considerations. In order to verify the model and to obtain model output for analysis, we constructed a simulation model which uses the random number generator in combination with the demand distribution and repair distribution, to simulate the actual demand and repair process over multiple life cycles.

Based on the performed analysis, we conclude that an obsolescence monitoring with LTB strategy is optimal and most robust for high value LRU's (that can be repaired). The other strategies result in a substantial higher TEC of 22,41% (€157.403) for the RMB strategy, 38,12% (€267.682) for the obsolescence monitoring with redesign strategy, and 27,12% (€190.464) for the planned redesign strategy. Sensitivity analysis shows that the optimal strategy only changes to an obsolescence monitor with redesign strategy if the life cycle length increases, or the non-recurring engineering costs related to redesigning are significantly lower (<€100.00) than estimated (€300.000). We conclude that the impact of variation is lowest for the optimal strategy, only for higher actual future sales or lower actual YTEOL, an obsolescence monitoring with redesign strategy will result in a slightly lower TEC. For low value LRU's, an RMB strategy is optimal and most robust against variation under all analysed instances. Since the impact of fixed order costs and redesign costs are relatively high for low value LRU's, the other strategies result in a substantial higher TEC (of €4.685 for the monitor with LTB strategy, €28.087 for the obsolescence monitoring with redesign strategy, and €20.338 for the planned redesign strategy). The impact of variation on the RMB strategy is relatively small.

Based on the impact analysis of future sales variation we conclude that updating the installed base development at an early stage, at least before the YTEOL have passed, results in a substantial lower TEC compared to when this is noticed at a later stage when the LRU is already obsolete. Especially, for the obsolescence monitoring with LTB or redesign strategy, this results in an average lower TEC of 40,59% if the actual future sales are lower. For higher actual future sales, the average TEC is 4,53% lower. Regarding the variation in YTEOL, we conclude that obsolescence monitoring can reduce the TEC with approximately 8,6% in case obsolescence occurs in an earlier stage of the life cycle, and approximately 11,5% if obsolescence occurs in a later stage than expected. We conclude that this is due to the fact that LTB decisions and redesign decisions can be adjusted accordingly the actual developments.

Finally, we conclude that as the life cycle reaches its end, the cycle service level drops significantly but still remains above the required average level of 90%. Although Thales assumes that the authorized aftermarket might be used in case a demand occurs at the end of the life cycle, a higher cycle service level can be attained by either buying few extra parts (resulting in higher holding costs of 44,21% for $A_t \geq 90\%$ and 13,87% for $A \geq 95\%$) or extending the repair option for a longer period.

## 6.2 Research limitations

During the research we encountered multiple limitations and restrictions. The main limitations are summarized below:

- The data availability in order to create input values for the model was limited. For the model analysis data for multiple LRU's is gathered by using experience and knowledge of the logistic engineering department. This results in the fact that some input data values are a rough approximation/indication. Since historic data about followed strategies is not available, we were not able to compare the model output with actual used strategies at Thales Hengelo.
- Due to time restrictions and mathematical complexity, not all factors are incorporated in the comparison of the obsolescence strategies. For example, we included the obsolescence state as state variable, but there is no probability distribution incorporated for the probability regarding obsolescence over the life cycle (the LRU becomes either obsolete or not during an interval of the life cycle).
- We assume that obsolescence is always notified in advance. Generally, this might be true since the data availability for simple/cheap LRU's is often good and for complex/expensive LRU's Thales may maintain intensive supplier contact/agreements. But there will also be cases in which Thales is not notified once obsolescence occurs and it is only detected once new demand arises. We analysed this partly by looking at deviating YTEOL values, and the effect of following a specific strategy while obsolescence occurs earlier/later in the life cycle.
- The lead times of different processes (e.g., replenishment order at supplier, repair, redesign) are limited to an integer number of intervals (years). In practice the lead time could be equal to multiple intervals or a fraction of (an) interval(s). This could lead to somewhat different model output, but this would also increase the mathematical and model complexity.
- Concerning the redesign process, we did not incorporate details about possibly changing LRU characteristics. Furthermore, we assumed that the planned redesigns/updates are initiated at predetermined points of the life cycle. Although these parts were not within the scope of our research, these aspects could result in a shift of adapting the strategy at some point during the life cycle.

## 6.3 Recommendations for Thales Hengelo

Based on the conclusions and findings of our research, we formulate multiple recommendations for Thales Hengelo concerning future research. First, we describe the formulated recommendations that are related to future research on obsolescence management. Thereafter, we describe possibly valuable model extensions.

The following recommendations for future research at Thales Hengelo in general are formulated:

- Additional research on the topic of obsolescence forecasting will contribute to improved obsolescence management and strategies at Thales Hengelo. Since there is a lot of uncertainty about the point in time where a part will become obsolete, it is crucial to have information about this in order to deal with obsolescence in a correct manner. Multiple research studies related to obsolescence forecasting are conducted, but since these studies include many attributes it is not direct applicable for Thales Hengelo. Furthermore, it could be beneficial to improve supplier relationships for some type of parts to make sure that obsolescence is communicated in in all cases.
- In our research we used a rough indication of the installed base development, which is provided by the responsible product team. Although the market sector in which Thales operates is categorized by high uncertainties, extra research into the future sales/installed base development over the life cycle of an LRU and the corresponding system can have significant value since the demand for new parts (initial production and spare part packages) has a higher significance than the replenishment of spare parts during the life cycle. In order to incorporate the spare part demand, we used the theoretical failure rate. Thales Hengelo is currently working on a project to create a more reliable spare part forecasts, which is based on historical data. Eventually the results of that project could be used for obsolescence management as well.
- In this research, we focused on LRU's of one type of system of Thales Hengelo. Further research can be performed on how multiple types of systems, that contain the same (subset of) LRU's, can be combined in order to create more alignment and benefits from the used obsolescence strategies.
- It is expected that Performance Based Logistics (PBL) will take an increased role in the environment of Thales in the next decades, leading to an increased importance of obsolescence management. This means that backorder costs, or monetary fines, will be incurred if a certain service level is not attained. In this research, we used backorder costs to create the trade-off between holding costs and the cycle service level. In order to incorporate PBL in the future, the actual backorder costs should be determined and possibly other PBL related aspects should be researched.
- This research analysed two different types of LRU's, and we concluded which obsolescence strategy is optimal for which type of LRU. Further research could be performed to establish thresholds for certain parameters (e.g., demand, item value) and when a change in optimal strategy occurs.

Regarding the model that we constructed, we first of all recommend Thales Hengelo to implement the model design/approach in order to improve the current obsolescence management. This research delivers a prototype model in Microsoft Excel. In order to implement and use the constructed model, multiple recommendations for possible valuable model extensions are formulated:

- We included a state variable for whether a LRU is obsolete or not and based on an indication of the expected years until obsolescence occurs, we performed analysis on the impact of variation regarding this parameter. Once a more reliable forecast is available, this could be included as probability distribution to model the obsolescence state variable in the model. Since obsolescence is already incorporated as state variable and our model is based on stochastic dynamic programming, this could relatively easily be implemented.
- Once the forecasted installed base development is more accurate and reliable, this could be incorporated into the model to create more reliable output and to cope with potential change more in advance. In our research we assumed a deterministic installed base development, but it is possible to incorporate the future sales of systems as stochastic variable in the same way as we did for spare part demand.
- For the redesign process, only a lead time equal to 1 interval is analysed. In general, a large subset of LRU's have a redesign lead time that is equal to multiple intervals. Extending the model to cope with this will result in a more general applicable model for Thales. Since we assumed that a last time buy is always possible this would mean that if the redesign lead time is higher, we either initiate the redesign in an earlier interval, or the last time buy quantity would be higher to cope with the expected demand during the redesign lead time. The model that we constructed is based on backwards recursion where we start in the last interval and solve the model by optimizing the decisions each time a transition from interval $t$ to interval $t + 1$ is made. This means that a redesign of multiple intervals cannot be directly analysed in the current model formulation. Further research is therefore required to determine how a longer redesign lead time could be analysed.
- Regarding the repair process of failed spare parts, we modelled this as fixed input and all ready-to-repair LRU's are repaired in the subsequent time interval. Future research can be performed on incorporating the repair process as decision variable. Although Thales states that repairing failed parts in not a decision (exceptions excluded), multiple literature sources state that as the life cycle progresses it could be beneficial to only start repair activities under specific circumstances. Furthermore, extending the repair process for a longer period can result in a flexible source of supply near the end of the life cycle.

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# Appendix 1: Backorder costs determination

In this section we describe how the values for the backorder costs are determined. Since we concluded that Thales does not always directly faces backorder costs, we reviewed multiple equivalence relations regarding backorder costs and service levels. Such equivalence relations incorporate the trade-off between holding costs, backorder costs, and service levels.

We analyse the cycle service level as performance measure, we restrict ourselves to the equivalence relation that focus on the cycle service level. In literature we found the following method (Silver, Pyke, & Thomas, 2017):

- Fractional shortage costs per unit per unit $B_2$ is equivalent to cycle service level $P_1$

$$P_1 = 1 - \frac{Q * r}{D * B_2}$$

Where:

- Q is the lot size
- r is the holding cost rate per period
- D is the demand per period

This relation is often used in (s,Q) inventory systems with a normal distributions for demand characteristics. In a (s,Q) system, a certain reorder point is calculated and whenever the inventory drops below this reorder level quantity Q is ordered. Although the demand at Thales is not normally distributed, we can use the relationship in order to create a starting point for the backorder costs. By solving the equivalence relationship, we find the value for $B_2$ which is the fractional shortage costs of the LRU purchase price. In order to include this in the model, the equivalence relation is solved by using the Microsoft Excel Solver function.

In order to find a suitable value for different LRU's, we conducted experimental analysis to see which $B_2$ value results in a certain cycle service level. The results are summarized in Table 20.

*Table 20: Experimental results of B2 factor for backorder costs.*

| **$B_2$ factor** | **$P_1$ for waveform generator** | **$B_2$ factor** | **$P_1$ for relay** |
|---|---|---|---|
| 5.5 | 88,7% | 0.5 | 89,0% |
| 6.0 | 90,0% | 1.0 | 95,3% |
| 6.5 | 90,8% | 1.5 | 96,2% |
| 7.0 | 91,4% | 2.0 | 96,8% |
| 7.5 | 91,6% | - | - |

From the experimental analysis, we conclude that we should use a fractional shortage costs of 6.0 for the waveform generator and 1.0 for the relay. Since the spare part demand for the relay is quite low, $P_1$ is either 89,0% or 95,3%. The purchase price of the Waveform generator is €16.873, which means that the backorder costs are €101.238,0. The purchase price of the relay is €76, which means that the backorder costs are equal to a value of €76.

# Appendix 2: Model analysis and simulation approach in Excel

In this section we describe the design of the model analysis and simulation approach as formulated in Microsoft Excel. We used multiple modules in Visual Basic for Applications (VBA) to implement the required code to solve and analyse the model. In the remainder of this section, we describe the main parts in general.

**Initialization of the model input**

The first step is to enter the LRU input data in a worksheet. Based on the LRU input data and installed base development, the first module initializes the input parameters and the installed base development. The expected number of future sales (systems) is evenly distributed over the whole life cycle analysis (i.e., if the expected future sales is 12 systems, and the life cycle length is 15 years, the first 12 years one system is added to the installed base for which initial parts are demanded.)

**Solving the SDP model and calculating the total expected costs**

The second step is to solve the SDP model by backward recursion and calculate the corresponding Total Expected Costs (TEC) for each state in each interval based on the expected installed base development and Years Till End Of Life (YTEOL). The output of this module is stored in separate matrices.

Since we also want to analyse the impact of variation in the installed base development and YTEOL, which we describe below, we change the input data based on the expected variation and solve the SDP again for the following scenarios:

- lower installed base development, YTEOL equal to original value
- higher installed base development, YTEOL equal to original value
- original installed base development, lower expected YTEOL
- original installed base development, higher expected YTEOL

The results of these models are stored in separate matrices and will be used to change certain decisions during the life cycle in the impact analysis concerning variation.

**Simulation design**

After the SDP model is solved, it is clear which decisions should be made in which interval and corresponding state. In order to obtain actual model output which shows the followed strategy, we simulate individual life cycles. The reason for this is the fact that SDP is based on probabilities and since decisions should be made in each interval, it is necessary to simulate the actual spare part demand process and repair process.

By using a random number generator between 0 and 1, and the relevant probability distribution (Poisson for spare part demand and Binomial for repair process) we obtain values for the actual spare part demand, number of ready-to-repair parts, and the number of successful repairs. Together with the fixed demand for new production, we subsequently loop trough the SDP matrix and all decisions are obtained by using lookup functions. Thereafter, we calculate the total costs and other relevant output is summarized (e.g., expected inventory, order quantities). The next step is to calculate the Cycle Service Level (CSL), as we describe in the last part of this section.

In order to analyse the impact and consequences of variation in the installed base development, we run the model again for a lower (3 till 11 systems) and higher (13 till 25 systems) number of future sales. The initial decisions under the mean forecasted installed base development are fixed for the first intervals. After multiple years of the life cycle, we expect that more accurate information about the actual development (i.e., number of future sales) is available and the decisions in the remaining intervals are changed. Two scenarios are analysed. In scenario A, the decisions can be changed after 5 years (so from year 6 onwards). For scenario B, the decisions can be changed after 2 years (so from year 3 onwards). Due to uncertainty, the actual installed base development can be uncertain for a longer period. Nevertheless, in this way we indicate the importance and impact of regularly updating the available installed base information.

Depending on the expected variation (i.e., ± number of systems), which is input to the analysis, the installed base development is adjusted. The difference between the mean number of systems and the variation is subtracted from specific intervals using a uniform distribution. This means that the systems are randomly subtracted or added to certain intervals of the life cycle. Hereafter, we first determine the effect on the cycle service level if variation occurs and decisions would not be changed. Subsequently we use the SDP matrix related to the specific scenario to change the decisions from interval 3 or 6 (depending on the scenario) onwards to see which changes can/should be made. Finally, the total expected costs are calculated to attain the performance measure about the cycle service level, together with the other output.

Roughly the same approach as for the installed base development is used for variation in the actual YTEOL of the LRU. Although it is expected that the LRU becomes obsolete after a specified number of years, it is also possible that obsolescence occurs at an earlier/later stage of the life cycle. We analyse the impact of an actual YTEOL between the minimum and maximum expected years. We analyse two scenarios. In scenario A, obsolescence monitoring is not applied. This means that whenever the LRU becomes obsolete before the initial expected interval, an LTB is not possible, and the decisions can only be changed after the actual interval where the LRU becomes obsolete. On the other hand, if the actual YTEOL is higher than expected, the decisions until the actual YTEOL are fixed. In scenario B, obsolescence monitoring is applied from the start of the life cycle. This means that if the LRU becomes obsolete in an earlier stage, an LTB is possible. In case the actual YTEOL is higher, some decisions (i.e., performing a last time buy, or initiating a redesign) can be postponed.

**Determine the cycle service level**

Based on the decisions that are derived in each simulation run, the order quantity in each interval is input to calculate the cycle service level. Forward recursion is used to calculate the probabilities that each state is attained in each interval. These probabilities are based on the expected demand probabilities, repair probabilities, and order quantities. The probabilities are summed over each interval to find the cycle service level per interval. Finally, the output is stored in a matrix.

# Appendix 3: Results of the model simulation evaluation

In this section we describe the results of the model simulation that is used for the model verification. In the analysis we compared the three different strategies, where strategy two has two possible scenarios. In order to compare the difference between the SDP model and the simulation model, we use the same model input as in the case study (see Section 5.2).

Since incorporating the repair option in the Microsoft Excel model is included, there is a difference in the complexity of the model construction. For this reason, we examined both LRU's of the performed case study. LRU 1 'waveform generator' can be repaired, whereas LRU 2 'relay' cannot be repaired. Table 21 gives the results of this analysis

*Table 21: Overview relative difference between SDP model costs and simulation costs.*

| LRU | Strategy | Model costs | Simulation costs | Relative difference |
|---|---|---|---|---|
| 1 | RMB | € 849.704,5 | € 859.704,5 | 1,163% |
| 2 | RMB | € 7.315,0 | € 7.335,0 | 0,273% |
| 1 | Monitor+LTB | € 696.301,3 | € 702.301,3 | 0,854% |
| 2 | Monitor+LTB | € 11.939,6 | € 12.039,6 | 0,831% |
| 1 | Monitor+redesign | € 959.973,7 | € 969.973,7 | 1,031% |
| 2 | Monitor+redesign | € 35.143,3 | € 35.443,3 | 0,846% |
| 1 | Planned redesign | € 928.703,3 | € 934.703,3 | 0,642% |
| 2 | Planned redesign | € 27.393,0 | € 27.693,0 | 1,083% |

The analysis shows that the relative difference is approximately 0,923% on average when the repair option is included and 0,758% on average when the repair option is not included. We expect that the difference is a result of the simulation where the actual demand rate is quite low since the failure rate is low. Furthermore, the fact that the difference is higher when the repair option is included is due to the number of successful repairs that we simulated.

# Appendix 4: Results of impact analysis variation

In this section we give the detailed overview of the results of the analysis regarding the impact of variation in future sales and Years Till End Of Life (YTEOL) regarding the two LRU's analysed in the case study in Section 5.2. Multiple points within certain ranges are analysed to show the impact when variation/uncertainty increases. Tables 22 till 25 show the results of the waveform generator, and tables 26 till 29 the results of the relay. The tables show the impact of variation on the expected average cycle service level (E[A]), if the strategy/decision would not be adjusted, and the impact on TEC to modify the strategy/decisions to attain a minimum E[A] of 90%.

*Table 22: Impact of future sales variation with initial decisions on the E[A] for waveform generator.*

| | Actual number of future sales | | | | | |
|---|---|---|---|---|---|---|
| Strategy | 18 | 48 | 60 | 84 | 96 | 150 |
| RMB | 99,99% | 99,80% | 99,04% | 74,21% | 64,30% | 9,60% |
| Monitor+LTB | 99,32% | 95,09% | 90,02% | 29,01% | 16,00% | 2,50% |
| Monitor+redesign | 99,80% | 98,80% | 95,50% | 45,34% | 23,30% | 3,50% |

*Table 23: Impact of future sales variation on the TEC for waveform generator.*

| | Actual number of future sales | | | | | |
|---|---|---|---|---|---|---|
| Strategy | 18 | 48 | 60 | 84 | 96 | 150 |
| RMB | € 1.278.226 | € 1.097.758 | € 1.024.236 | € 1.186.677 | € 1.389.430 | € 1.533.276 |
| Monitor+LTB | € 538.179 | € 983.318 | € 1.011.501 | € 1.242.492 | € 1.335.556 | € 1.416.330 |
| Monitor+redesign | € 781.144 | € 842.281 | € 962.159 | € 1.109.482 | € 1.205.193 | € 1.447.743 |
| (A) After 5 years information about actual future sales | | | | | | |
| RMB | € 1.283.360 | € 1.096.403 | € 1.021.268 | € 1.102.645 | € 1.294.184 | € 1.437.371 |
| Monitor+LTB | € 376.577 | € 502.765 | € 565.995 | € 1.215.390 | € 1.214.155 | € 1.366.741 |
| Monitor+redesign | € 434.947 | € 549.670 | € 612.029 | € 1.061.955 | € 1.158.666 | € 1.387.522 |
| (B) After 2 years information about actual future sales | | | | | | |

*Table 24: Impact of YTEOL variation on the E[A] for waveform generator.*

| | Actual YTEOL | | | | | |
|---|---|---|---|---|---|---|
| Strategy | 2 | 3 | 4 | 6 | 7 | 8 |
| RMB | 91,07% | 91,06% | 91,10% | 91,08% | 91,04% | 91,06% |
| Monitor+LTB | 58,70% | 68,90% | 77,52% | 92,90% | 92,50% | 92,76% |
| Monitor+redesign | 78,59% | 84,20% | 86,42% | 91,80% | 92,20% | 91,20% |
| (A) Without obsolescence monitoring | | | | | | |
| RMB | 91,07 | 91,07% | 91,09% | 91,09% | 91,07% | 91,08% |
| Monitor+LTB | 93,94 | 90,20% | 91,33% | 90,75% | 90,12% | 92,20% |
| Monitor+redesign | 93,56 | 91,60% | 94,47% | 90,20% | 91,20% | 92,33% |
| (B) With obsolescence monitoring | | | | | | |

*Table 25: Impact of YTEOL variation on the TEC for waveform generator.*

| | Actual YTEOL | | | | | |
|---|---|---|---|---|---|---|
| Strategy | 2 | 3 | 4 | 6 | 7 | 8 |
| RMB | € 960.677 | € 962.503 | € 966.561 | € 965.659 | € 962.504 | € 959.830 |
| Monitor+LTB | € 999.844 | € 973.935 | € 934.221 | € 998.319 | € 960.538 | € 953.588 |
| Monitor+redesign | € 952.191 | € 941.293 | € 948.846 | € 1.121.434 | € 1.157.320 | € 1.180.004 |
| (A) Without obsolescence monitoring | | | | | | |
| RMB | € 968.370 | € 962.431 | € 963.747 | € 964.852 | € 963.070 | € 966.795 |
| Monitor+LTB | € 901.648 | € 870.965 | € 904.096 | € 874.418 | € 870.966 | € 865.546 |
| Monitor+redesign | € 916.321 | € 844.592 | € 854.061 | € 982.123 | € 1.012.717 | € 1.009.320 |
| (B) With obsolescence monitoring | | | | | | |

*Table 26: Impact of future sales variation with initial decisions on the E[A] for relay.*

| | Actual number of future sales | | | | | |
|---|---|---|---|---|---|---|
| Strategy | 18 | 48 | 60 | 84 | 96 | 150 |
| RMB | 99,97% | 99,93% | 99,91% | 66,57% | 58,30% | 32,22% |
| Monitor+LTB | 99,97% | 99,90% | 99,79% | 56,00% | 36,80% | 16,55% |
| Monitor+redesign | 99,99% | 99,89% | 99,79% | 55,68% | 39,05% | 16,56% |
| Planned redesign | 99,95% | 99,82% | 99,66% | 56,12% | 42,96% | 17,80% |

*Table 27: Impact of future sales variation on the TEC for relay.*

| | Actual number of future sales | | | | | |
|---|---|---|---|---|---|---|
| Strategy | 18 | 48 | 60 | 84 | 96 | 150 |
| RMB | € 12.273 | € 9.489 | € 8.533 | € 12.647 | € 13.008 | € 15.987 |
| Monitor+LTB | € 11.456 | € 8.844 | € 8.601 | € 14.896 | € 15.255 | € 19.562 |
| Monitor+redesign | € 11.505 | € 8.800 | € 8.695 | € 31.762 | € 35.820 | € 38.724 |
| Planned redesign | € 11.434 | € 8.746 | € 8.917 | € 28.566 | € 30.325 | € 38.552 |

(A) After 5 years information about actual future sales

| | | | | | | |
|---|---|---|---|---|---|---|
| RMB | € 12.206 | € 9.557 | € 8.621 | € 12.755 | € 13.288 | € 16.105 |
| Monitor+LTB | € 9.945 | € 8.677 | € 8.729 | € 14.420 | € 15.022 | € 15.785 |
| Monitor+redesign | € 11.302 | € 8.589 | € 8.544 | € 30.890 | € 35.498 | € 36.852 |
| Planned redesign | € 11.400 | € 8.742 | € 8.896 | € 28.405 | € 30.155 | € 38.545 |

(B) After 2 years information about actual future sales

*Table 28: Impact of YTEOL variation on the E[A] for relay.*

| | Actual YTEOL | | | | | |
|---|---|---|---|---|---|---|
| Strategy | 2 | 4 | 6 | 10 | 12 | 14 |
| RMB | 94,78% | 94,78% | 94,78% | 94,78% | 94,78% | 94,78% |
| Monitor+LTB | 43,88% | 59,23% | 66,20% | 95,18% | 95,89% | 95,13% |
| Monitor+redesign | 50,45% | 66,33% | 88,20% | 95,12% | 95,08% | 95,23% |
| Planned redesign | 66,36% | 76,44% | 84,54% | 94,97% | 95,71% | 94,76% |

(A) Without obsolescence monitoring

| | | | | | | |
|---|---|---|---|---|---|---|
| RMB | 94,8% | 94,78% | 94,78% | 94,78% | 94,78% | 94,78% |
| Monitor+LTB | 90,0% | 91,20% | 90,89% | 92,80% | 93,10% | 92,45% |
| Monitor+redesign | 91,9% | 92,82% | 91,45% | 90,99% | 91,80% | 91,60% |
| Planned redesign | 90,80% | 92,57% | 92,50% | 91,27% | 92,50% | 94,30% |

(B) With obsolescence monitoring

*Table 29: Impact of YTEOL variation on the TEC for relay.*

| | Actual YTEOL | | | | | |
|---|---|---|---|---|---|---|
| Strategy | 2 | 4 | 6 | 10 | 12 | 14 |
| RMB | € 7.357 | € 7.376 | € 7.416 | € 7.416 | € 7.377 | € 7.357 |
| Monitor+LTB | € 30.834 | € 33.307 | € 32.708 | € 11.170 | € 11.156 | € 11.135 |
| Monitor+redesign | € 30.838 | € 31.052 | € 32.510 | € 12.751 | € 13.025 | € 15.022 |
| Planned redesign | € 24.415 | € 27.121 | € 27.050 | € 14.522 | € 14.407 | € 14.308 |

(A) Without obsolescence monitoring

| | | | | | | |
|---|---|---|---|---|---|---|
| RMB | € 8.450 | € 8.416 | € 8.452 | € 8.452 | € 8.416 | € 8.449 |
| Monitor+LTB | € 11.856 | € 11.452 | € 11.033 | € 11.256 | € 11.023 | € 12.096 |
| Monitor+redesign | € 11.750 | € 11.652 | € 11.924 | € 11.588 | € 11.898 | € 11.952 |
| Planned redesign | € 11.887 | € 11.759 | € 11.945 | € 12.003 | € 11.762 | € 12.056 |

(B) With obsolescence monitoring

# Appendix 5: Results of the sensitivity analysis

In this section we give an overview of the model output of the sensitivity analysis as described in Section 5.3. For both LRU's of the case study, we described the main aspects that are analysed in the sensitivity analysis. Tables 30 till 36 describe the detailed model results for each analysed value of the input parameters of the waveform generator and Tables 37 till 42 for the relay. Each table gives the same model output as described in the case study. The cycle service level over the whole life cycle is not presented, since it represents the same pattern as in the case study.

*Table 30: Results of SA: life cycle length for waveform generator.*

| | T = 20 years | | | T = 25 years | | | T = 30 years | | |
|---|---|---|---|---|---|---|---|---|---|
| **Strategy** | **RMB** | **Monitor+LTB** | **Monitor+redesign** | **RMB** | **Monitor+LTB** | **Monitor+redesign** | **RMB** | **Monitor+LTB** | **Monitor+redesign** |
| E[orders] | 1,0 | 5,3 | 15,3 | 1,0 | 6,0 | 16,6 | 1,0 | 6,0 | 22,0 |
| E[order quantity] | 43,0 | 42,8 | 43,0 | 58,0 | 60,2 | 62,0 | 74,0 | 76,9 | 79,3 |
| E[redesign interval] | 0,0 | 0,0 | 5,0 | 0,0 | 0,0 | 17,7 | 0,0 | 0,0 | 17,0 |
| TEC | € 1.486.877,0 | € 1.192.691,9 | € 1.230.587,6 | € 2.060.924,7 | € 1.848.284,3 | € 1.907.992,9 | € 2.791.654,1 | € 2.501.007,0 | € 2.146.569,5 |
| E[A] | 93,6% | 92,8% | 90,0% | 91,1% | 92,2% | 90,0% | 90,0% | 91,9% | 91,1% |
| E[OH] | 18,2 | 10,4 | 2,8 | 20,6 | 15,4 | 4,8 | 24,9 | 19,1 | 3,3 |
| E[BO] | 0,1 | 0,1 | 0,0 | 0,2 | 0,0 | 0,0 | 0,4 | 0,2 | 0,0 |
| E[repairs] | 4,8 | 4,9 | 5,6 | 7,2 | 6,5 | 5,8 | 8,2 | 6,5 | 7,7 |
| E[excessive stock] | 1,8 | 2,1 | 1,3 | 0,8 | 2,8 | 2,0 | 0,8 | 2,5 | 2,5 |
| **Cost breakdown** | | | | | | | | | |
| Fixed order costs | € 2.500,0 | € 13.250,0 | € 38.255,0 | € 2.500,0 | € 15.000,0 | € 41.517,7 | € 2.500,0 | € 15.000,0 | € 55.017,0 |
| Part purchase costs | € 725.539,0 | € 722.164,4 | € 725.539,0 | € 978.634,0 | € 1.015.754,6 | € 1.046.126,0 | € 1.248.602,0 | € 1.297.533,7 | € 1.338.028,9 |
| Holding costs | € 710.658,0 | € 407.347,5 | € 108.143,6 | € 1.007.710,7 | € 751.529,7 | € 208.553,2 | € 1.458.472,1 | € 1.122.503,3 | € 193.993,6 |
| Repair costs | € 48.000,0 | € 49.000,0 | € 56.000,0 | € 72.000,0 | € 65.000,0 | € 58.000,0 | € 82.000,0 | € 65.000,0 | € 77.000,0 |
| Redesign costs | € - | € - | € 300.000,0 | € - | € - | € 300.000,0 | € - | € - | € 600.000,0 |
| Disposal costs | € 180,0 | € 210,0 | € 130,0 | € 80,0 | € 280,0 | € 200,0 | € 80,0 | € 250,0 | € 250,0 |
| Monitoring costs | € - | € 720,0 | € 2.520,0 | € - | € 720,0 | € 1.596,0 | € - | € 720,0 | € 2.280,0 |

*Table 31: Results of SA: future sales for waveform generator.*

| | Future sales = 18 systems | | | Future sales = 150 system | | |
|---|---|---|---|---|---|---|
| **Strategy** | **RMB** | **Monitor+LTB** | **Monitor+redesign** | **RMB** | **Monitor+LTB** | **Monitor+redesign** |
| E[orders] | 1,0 | 3,0 | 3,6 | 1,0 | 6,0 | 14,7 |
| E[order quantity] | 9,0 | 8,9 | 9,4 | 55,0 | 54,8 | 59,3 |
| E[redesign interval] | 0,0 | 0,0 | 5,0 | 0,0 | 0,0 | 5,0 |
| TEC | € 269.128,2 | € 251.989,1 | € 552.004,4 | € 1.663.135,7 | € 1.285.234,3 | € 1.482.247,2 |
| E[A] | 93,7% | 91,6% | 90,6% | 90,7% | 90,1% | 91,1% |
| E[OH] | 2,6 | 1,9 | 1,5 | 22,4 | 9,5 | 2,5 |
| E[BO] | 0,0 | 0,1 | 0,0 | 0,3 | 0,3 | 0,1 |
| E[repairs] | 3,7 | 3,9 | 3,9 | 7,4 | 6,6 | 7,0 |
| E[excessive stock] | 1,3 | 0,9 | 1,2 | 0,2 | 0,4 | 1,5 |
| **Cost breakdown** | | | | | | |
| Fixed order costs | € 2.500,0 | € 7.575,0 | € 8.930,0 | € 2.500,0 | € 15.000,0 | € 36.780,0 |
| Part purchase costs | € 151.857,0 | € 149.326,1 | € 158.774,9 | € 928.015,0 | € 925.315,3 | € 1.000.231,4 |
| Holding costs | € 77.343,2 | € 55.382,0 | € 43.257,4 | € 658.502,7 | € 278.064,0 | € 72.962,7 |
| Repair costs | € 37.300,0 | € 38.900,0 | € 39.000,0 | € 74.100,0 | € 66.100,0 | € 70.200,0 |
| Redesign costs | € - | € - | € 300.000,0 | € - | € - | € 300.000,0 |
| Disposal costs | € 128,0 | € 86,0 | € 122,0 | € 18,0 | € 35,0 | € 153,0 |
| Monitoring costs | € - | € 720,0 | € 1.920,0 | € - | € 720,0 | € 1.920,0 |

*Table 32: Results of SA: YTEOL for waveform generator.*

| | YTEOL = 3 | | | YTEOL = 7 | | |
|---|---|---|---|---|---|---|
| **Strategy** | **RMB** | **Monitor+LTB** | **Monitor+redesign** | **RMB** | **Monitor+LTB** | **Monitor+redesign** |
| E[orders] | 1,0 | 3,0 | 11,3 | 1,0 | 8,9 | 10,1 |
| E[order quantity] | 31,0 | 29,8 | 32,6 | 28,0 | 27,8 | 28,1 |
| E[redesign interval] | 0,0 | 0,0 | 2,0 | 0,0 | 0,0 | 8,0 |
| TEC | € 952.284,8 | € 805.739,0 | € 978.664,3 | € 891.408,4 | € 658.307,5 | € 942.453,4 |
| E[A] | 93,0% | 90,0% | 91,6% | 92,8% | 92,0% | 91,7% |
| E[OH] | 13,5 | 9,1 | 2,4 | 11,7 | 3,1 | 2,2 |
| E[BO] | 0,1 | 0,3 | 0,0 | 0,0 | 0,0 | 0,1 |
| E[repairs] | 3,0 | 2,8 | 2,8 | 7,2 | 7,5 | 7,6 |
| E[excessive stock] | 1,0 | 0,5 | 1,6 | 1,8 | 1,5 | 1,9 |
| **Cost breakdown** | | | | | | |
| Fixed order costs | € 2.500,0 | € 7.500,0 | € 28.252,0 | € 2.500,0 | € 22.350,0 | € 25.358,0 |
| Part purchase costs | € 523.063,0 | € 502.477,9 | € 549.384,9 | € 472.444,0 | € 468.563,2 | € 474.300,0 |
| Holding costs | € 397.119,8 | € 267.054,1 | € 70.948,5 | € 344.084,4 | € 91.560,3 | € 64.788,4 |
| Repair costs | € 29.500,0 | € 28.300,0 | € 28.000,0 | € 72.200,0 | € 74.600,0 | € 75.900,0 |
| Redesign costs | € - | € - | € 300.000,0 | € - | € - | € 300.000,0 |
| Disposal costs | € 102,0 | € 47,0 | € 159,0 | € 180,0 | € 154,0 | € 187,0 |
| Monitoring costs | € - | € 360,0 | € 1.920,0 | € - | € 1.080,0 | € 1.920,0 |

*Table 33: Results of SA: redesign costs for waveform generator.*

| | Redesign costs = €50.000 | | | Redesign costs = €75.000 | | | Redesign costs = €100.000 | | |
|---|---|---|---|---|---|---|---|---|---|
| **Strategy** | **RMB** | **Monitor+LTB** | **Monitor+redesign** | **RMB** | **Monitor+LTB** | **Monitor+redesign** | **RMB** | **Monitor+LTB** | **Monitor+redesign** |
| E[orders] | 1,0 | 6,0 | 11,3 | 1,0 | 5,7 | 9,7 | 1,0 | 6,0 | 10,0 |
| E[order quantity] | 29,0 | 28,0 | 29,0 | 29,0 | 27,7 | 28,0 | 29,0 | 27,7 | 28,0 |
| E[redesign interval] | 0,0 | 0,0 | 5,0 | 0,0 | 0,0 | 5,0 | 0,0 | 0,0 | 5,0 |
| TEC | € 888.443,8 | € 707.317,9 | € 687.798,3 | € 884.399,4 | € 694.945,6 | € 689.162,7 | € 888.484,5 | € 711.641,3 | € 712.977,3 |
| E[A] | 93,1% | 90,1% | 92,4% | 93,1% | 90,2% | 92,9% | 93,1% | 90,0% | 92,1% |
| E[OH] | 12,3 | 5,4 | 2,1 | 12,1 | 5,8 | 2,9 | 12,2 | 4,4 | 2,5 |
| E[BO] | 0,0 | 0,0 | 0,0 | 0,1 | 0,0 | 0,0 | 0,1 | 0,4 | 0,0 |
| E[repairs] | 3,7 | 6,0 | 6,0 | 3,7 | 3,7 | 3,0 | 4,0 | 4,0 | 4,1 |
| E[excessive stock] | 1,3 | 1,0 | 1,0 | 0,0 | 1,3 | 2,3 | 1,0 | 0,3 | 1,7 |
| **Cost breakdown** | | | | | | | | | |
| Fixed order costs | € 2.500,0 | € 15.000,0 | € 25.838,3 | € 2.500,0 | € 14.166,7 | € 24.250,0 | € 2.500,0 | € 15.000,0 | € 25.005,0 |
| Part purchase costs | € 489.317,0 | € 472.444,0 | € 489.317,0 | € 489.317,0 | € 466.819,7 | € 689.162,7 | € 489.317,0 | € 466.819,7 | € 472.444,0 |
| Holding costs | € 359.826,8 | € 159.053,9 | € 60.623,0 | € 355.915,7 | € 176.439,2 | € 85.393,7 | € 356.567,5 | € 129.068,3 | € 73.008,3 |
| Repair costs | € 36.666,7 | € 60.000,0 | € 60.000,0 | € 36.666,7 | € 36.666,7 | € 30.000,0 | € 40.000,0 | € 40.000,0 | € 40.433,3 |
| Redesign costs | € - | € - | € 50.000,0 | € - | € - | € 75.000,0 | € - | € - | € 100.000,0 |
| Disposal costs | € 133,3 | € 100,0 | € 100,0 | € - | € 133,3 | € 233,3 | € 100,0 | € 33,3 | € 166,7 |
| Monitoring costs | € - | € 720,0 | € 1.920,0 | € - | € 720,0 | € 1.920,0 | € - | € 720,0 | € 1.920,0 |

*Table 34: Results of SA: holding costs for waveform generator.*

| | Holding cost rate = 5% | | | Holding cost rate = 20% | | |
|---|---|---|---|---|---|---|
| **Strategy** | **RMB** | **Monitor+LTB** | **Monitor+redesign** | **RMB** | **Monitor+LTB** | **Monitor+redesign** |
| E[orders] | 1,0 | 5,0 | 7,3 | 1,0 | 6,0 | 12,3 |
| E[order quantity] | 29,0 | 29,0 | 30,7 | 29,0 | 28,3 | 31,0 |
| E[redesign interval] | 0,0 | 0,0 | 5,0 | 0,0 | 0,0 | 5,0 |
| TEC | € 703.774,0 | € 621.295,1 | € 916.911,5 | € 1.130.287,3 | € 838.644,7 | € 1.026.613,8 |
| E[A] | 93,1% | 91,6% | 92,3% | 93,1% | 90,3% | 92,3% |
| E[OH] | 12,0 | 5,7 | 2,8 | 11,9 | 5,9 | 2,6 |
| E[BO] | 0,1 | 0,2 | 0,1 | 0,1 | 0,0 | 0,0 |
| E[repairs] | 6,0 | 4,7 | 4,3 | 3,7 | 4,7 | 3,7 |
| E[excessive stock] | 1,0 | 1,0 | 1,7 | 0,0 | 1,0 | 2,7 |
| **Cost breakdown** | | | | | | |
| Fixed order costs | € 2.500,0 | € 12.500,0 | € 18.338,3 | € 2.500,0 | € 15.000,0 | € 30.838,3 |
| Part purchase costs | € 489.317,0 | € 489.317,0 | € 517.438,7 | € 489.317,0 | € 478.068,3 | € 523.063,0 |
| Holding costs | € 151.857,0 | € 71.991,5 | € 35.714,5 | € 601.803,7 | € 298.089,7 | € 133.859,1 |
| Repair costs | € 60.000,0 | € 46.666,7 | € 43.333,3 | € 36.666,7 | € 46.666,7 | € 36.666,7 |
| Redesign costs | € - | € - | € 300.000,0 | € - | € - | € 300.000,0 |
| Disposal costs | € 100,0 | € 100,0 | € 166,7 | € - | € 100,0 | € 266,7 |
| Monitoring costs | € - | € 720,0 | € 1.920,0 | € - | € 720,0 | € 1.920,0 |

*Table 35: Results of SA: frequency planned redesign for waveform generator.*

| | FPRD = 5 year | | | | FPRD = 10 year | | | |
|---|---|---|---|---|---|---|---|---|
| **Strategy** | **RMB** | **Monitor+LTB** | **Monitor+redesign** | **Planned redesign** | **RMB** | **Monitor+LTB** | **Monitor+redesign** | **Planned redesign** |
| E[orders] | 1,0 | 6,0 | 11,0 | 10,6 | 1,0 | 6,0 | 11,2 | 7,4 |
| E[order quantity] | 29,0 | 28,8 | 30,8 | 30,2 | 29,0 | 28,6 | 31,2 | 31,0 |
| E[redesign interval] | 0,0 | 0,0 | 5,0 | 5,0 | 0,0 | 0,0 | 5,0 | 10,0 |
| TEC | € 891.655,0 | € 702.931,1 | € 969.347,6 | € 857.313,3 | € 904.852,8 | € 704.314,3 | € 985.176,9 | € 934.703,3 |
| E[A] | 93,1% | 92,3% | 92,0% | 90,8% | 93,1% | 91,5% | 92,8% | 91,1% |
| E[OH] | 12,4 | 5,4 | 2,3 | 2,5 | 12,4 | 5,5 | 2,7 | 3,1 |
| E[BO] | 0,2 | 0,2 | 0,0 | 0,0 | 0,1 | 0,3 | 0,0 | 0,4 |
| E[repairs] | 3,6 | 4,4 | 5,2 | 4,6 | 5,0 | 4,6 | 4,8 | 4,0 |
| E[excessive stock] | 1,0 | 0,4 | 1,8 | 1,8 | 0,8 | 0,6 | 2,0 | 0,2 |
| **Cost breakdown** | | | | | | | | |
| Fixed order costs | € 2.500,0 | € 15.000,0 | € 27.505,0 | € 26.510,0 | € 2.500,0 | € 15.000,0 | € 28.005,0 | € 18.508,0 |
| Part purchase costs | € 489.317,0 | € 485.942,4 | € 519.688,4 | € 509.564,6 | € 489.317,0 | € 482.567,8 | € 526.437,6 | € 523.063,0 |
| Holding costs | € 363.738,0 | € 157.228,7 | € 68.054,2 | € 73.138,7 | € 362.955,8 | € 159.966,5 | € 78.614,3 | € 151.912,3 |
| Repair costs | € 36.000,0 | € 44.000,0 | € 52.000,0 | € 46.000,0 | € 50.000,0 | € 46.000,0 | € 48.000,0 | € 40.000,0 |
| Redesign costs | € - | € - | € 300.000,0 | € 200.000,0 | € - | € - | € 300.000,0 | € 200.000,0 |
| Disposal costs | € 100,0 | € 40,0 | € 180,0 | € 180,0 | € 80,0 | € 60,0 | € 200,0 | € 20,0 |
| Monitoring costs | € - | € 720,0 | € 1.920,0 | € 1.920,0 | € - | € 720,0 | € 1.920,0 | € 1.200,0 |

*Table 36: Results of SA: higher cycle service level for waveform generator.*

| | $A_t \geq 90\%$ | | | $A \geq 95\%$ | | |
|---|---|---|---|---|---|---|
| **Strategy** | **RMB** | **Monitor+LTB** | **Monitor+redesign** | **RMB** | **Monitor+LTB** | **Monitor+redesign** |
| E[orders] | 1,0 | 6,0 | 13,3 | 1,0 | 6,0 | 12,3 |
| E[order quantity] | 32,0 | 32,3 | 33,7 | 30,0 | 30,3 | 30,3 |
| E[redesign interval] | 0,0 | 0,0 | 5,0 | 0,0 | 0,0 | 5,0 |
| TEC | € 1.013.862,3 | € 826.979,5 | € 1.071.113,9 | € 944.505,1 | € 739.764,8 | € 1.112.324,7 |
| E[A] | 97,6% | 97,7% | 98,0% | 95,5% | 96,0% | 96,1% |
| E[OH] | 14 | 7,711111111 | 3,466666667 | 13,1 | 6,1 | 4,4 |
| E[BO] | 0,0 | 0,0 | 0,0 | 0,2 | 0,1 | 0,0 |
| E[repairs] | 6,0 | 4,0 | 6,7 | 5,0 | 3,3 | 4,7 |
| E[excessive stock] | 4,0 | 4,3 | 4,3 | 2,3 | 1,3 | 5,7 |
| **Cost breakdown** | | | | | | |
| Fixed order costs | € 2.500,0 | € 15.000,0 | € 33.338,3 | € 2.500,0 | € 15.000,0 | € 30.838,3 |
| Part purchase costs | € 539.936,0 | € 544.435,5 | € 568.057,7 | € 506.190,0 | € 511.814,3 | € 511.814,3 |
| Holding costs | € 411.026,3 | € 226.390,7 | € 101.777,9 | € 385.581,8 | € 178.763,8 | € 221.598,7 |
| Repair costs | € 60.000,0 | € 40.000,0 | € 66.666,7 | € 50.000,0 | € 33.333,3 | € 46.666,7 |
| Redesign costs | € - | € - | € 300.000,0 | € - | € - | € 300.000,0 |
| Disposal costs | € 400,0 | € 433,3 | € 433,3 | € 233,3 | € 133,3 | € 566,7 |
| Monitoring costs | € - | € 720,0 | € 840,0 | € - | € 720,0 | € 840,0 |

*Table 37: Results of SA: life cycle length of relay.*

| | T = 20 years | | | | T = 25 years | | | | T = 30 years | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Strategy** | **RMB** | **Monitor+LTB** | **Monitor+redesign** | **Planned redesign** | **RMB** | **Monitor+LTB** | **Monitor+redesign** | **Planned redesign** | **RMB** | **Monitor+LTB** | **Monitor+redesign** | **Planned redesign** |
| E[orders] | 1,0 | 4,0 | 5,1 | 5,1 | 1,0 | 5,0 | 6,1 | 6,0 | 1,0 | 5,1 | 7,1 | 6,2 |
| E[order quantity] | 52,0 | 51,8 | 52,2 | 51,8 | 66,0 | 65,7 | 66,6 | 65,9 | 80,0 | 79,6 | 79,7 | 78,3 |
| E[redesign interval] | 0,0 | 0,0 | 8,0 | 10,0 | 0,0 | 0,0 | 8,0 | 20,0 | 0,0 | 0,0 | 8,0 | 20,0 |
| TEC | € 9.848,7 | € 16.234,4 | € 42.442,4 | € 34.791,2 | € 11.655,1 | € 20.090,9 | € 47.008,8 | € 37.811,3 | € 13.916,5 | € 21.561,1 | € 51.304,8 | € 39.877,2 |
| E[A] | 93,1% | 91,2% | 91,4% | 91,2% | 94,2% | 92,1% | 92,4% | 93,2% | 94,1% | 91,9% | 90,0% | 90,8% |
| E[OH] | 18,6 | 6,1 | 3,4 | 3,9 | 17,9 | 6,1 | 3,7 | 4,1 | 19,4 | 5,8 | 4,1 | 4,0 |
| E[BO] | 0,0 | 0,0 | 0,1 | 0,0 | 0,0 | 0,0 | 0,1 | 0,0 | 0,0 | 0,1 | 0,0 | 0,1 |
| E[repairs] | 0,0 | 0,0 | 0,0 | 0,0 | 0,0 | 0,0 | 0,0 | 0,0 | 0,0 | 0,0 | 0,0 | 0,0 |
| E[excessive stock] | 1,2 | 1,5 | 1,0 | 1,3 | 2,0 | 1,7 | 2,5 | 2,0 | 2,1 | 1,4 | 1,8 | 0,8 |
| **Cost breakdown** | | | | | | | | | | | | |
| Fixed order costs | € 2.500,0 | € 10.000,0 | € 12.508,0 | € 12.510,0 | € 2.500,0 | € 12.500,0 | € 15.008,0 | € 15.020,0 | € 2.500,0 | € 13.000,0 | € 17.508,0 | € 15.020,0 |
| Part purchase costs | € 3.952,0 | € 3.921,6 | € 3.876,0 | € 3.860,8 | € 5.016,0 | € 4.993,2 | € 4.962,8 | € 5.008,4 | € 6.080,0 | € 6.064,8 | € 5.996,4 | € 5.950,8 |
| Holding costs | € 3.331,3 | € 1.067,6 | € 597,2 | € 614,8 | € 3.943,5 | € 1.401,4 | € 735,5 | € 769,0 | € 5.198,7 | € 1.587,3 | € 930,2 | € 969,8 |
| Repair costs | € - | € - | € - | € - | € - | € - | € - | € - | € - | € - | € - | € - |
| Redesign costs | € - | € - | € 22.500,0 | € 15.000,0 | € - | € - | € 22.500,0 | € 30.000,0 | € - | € - | € 22.500,0 | € 30.000,0 |
| Disposal costs | € 210,0 | € 130,0 | € 100,0 | € 10,0 | € 200,0 | € 230,0 | € 100,0 | € 80,0 | € 240,0 | € 130,0 | € 140,0 | € 70,0 |
| Monitoring costs | € - | € 1.080,0 | € 2.520,0 | € 2.280,0 | € - | € 1.080,0 | € 3.120,0 | € 1.680,0 | € - | € 1.080,0 | € 3.720,0 | € 2.280,0 |

*Table 38: Results of SA: future sales for relay.*

| | Future sales = 18 systems | | | | Future sales = 150 system | | | |
|---|---|---|---|---|---|---|---|---|
| **Strategy** | **RMB** | **Monitor+LTB** | **Monitor+redesign** | **Planned redesign** | **RMB** | **Monitor+LTB** | **Monitor+redesign** | **Planned redesign** |
| E[orders] | 1,0 | 1,0 | 1,0 | 1,0 | 1,0 | 5,7 | 7,0 | 6,0 |
| E[order quantity] | 11,0 | 11,0 | 10,0 | 11,0 | 76,0 | 77,0 | 77,0 | 77,3 |
| E[redesign interval] | 0,0 | 0,0 | 8,0 | 10,0 | 0,0 | 0,0 | 8,0 | 10,0 |
| TEC | € 3.652,2 | € 4.238,1 | € 27.874,0 | € 20.452,9 | € 12.267,2 | € 21.979,5 | € 48.334,9 | € 38.160,4 |
| E[A] | 92,3% | 92,0% | 90,8% | 93,2% | 92,3% | 93,1% | 91,7% | 93,9% |
| E[OH] | 1,9 | 1,9 | 1,2 | 2,2 | 30,0 | 6,7 | 4,2 | 4,5 |
| E[BO] | 0,0 | 0,1 | 0,2 | 0,0 | 0,1 | 0,1 | 0,0 | 0,1 |
| E[repairs] | 0,0 | 0,0 | 0,0 | 0,0 | 0,0 | 0,0 | 0,0 | 0,0 |
| E[excessive stock] | 0,7 | 0,7 | 0,3 | 1,3 | 0,3 | 0,0 | 0,0 | 0,0 |
| **Cost breakdown** | | | | | | | | |
| Fixed order costs | € 2.500,0 | € 2.500,0 | € 2.508,0 | € 2.510,0 | € 2.500,0 | € 14.166,7 | € 17.508,0 | € 15.010,0 |
| Part purchase costs | € 836,0 | € 836,0 | € 760,0 | € 836,0 | € 5.776,0 | € 5.852,0 | € 5.852,0 | € 5.877,3 |
| Holding costs | € 249,6 | € 234,4 | € 152,7 | € 293,6 | € 3.957,9 | € 880,8 | € 554,9 | € 593,1 |
| Repair costs | € - | € - | € - | € - | € - | € - | € - | € - |
| Redesign costs | € - | € - | € 22.500,0 | € 15.000,0 | € - | € - | € 22.500,0 | € 15.000,0 |
| Disposal costs | € 66,7 | € 66,7 | € 33,3 | € 133,3 | € 33,3 | € - | € - | € - |
| Monitoring costs | € - | € 600,0 | € 1.920,0 | € 1.680,0 | € - | € 1.080,0 | € 1.920,0 | € 1.680,0 |

*Table 39: Results of SA: YTEOL for relay.*

| | YTEOL = 4 | | | | YTEOL = 12 | | | |
|---|---|---|---|---|---|---|---|---|
| **Strategy** | **RMB** | **Monitor+LTB** | **Monitor+redesign** | **Planned redesign** | **RMB** | **Monitor+LTB** | **Monitor+redesign** | **Planned redesign** |
| E[orders] | 1,0 | 3,0 | 3,0 | 3,0 | 1,0 | 3,0 | 3,0 | 3,0 |
| E[order quantity] | 38,0 | 39,3 | 38,3 | 38,0 | 38,0 | 37,0 | 37,3 | 37,7 |
| E[redesign interval] | 0,0 | 0,0 | 4,0 | 10,0 | 0,0 | 0,0 | 12,0 | 10,0 |
| TEC | € 7.536,6 | € 12.273,8 | € 35.562,7 | € 27.854,0 | € 7.217,2 | € 12.489,6 | € 35.384,0 | € 27.917,2 |
| E[A] | 91,1% | 92,6% | 91,2% | 91,0% | 94,8% | 90,2% | 90,5% | 91,5% |
| E[OH] | 15,0 | 8,0 | 4,7 | 8,2 | 13,8 | 4,4 | 4,4 | 4,2 |
| E[BO] | 0,0 | 0,0 | 0,0 | 0,0 | 0,2 | 0,1 | 0,1 | 0,3 |
| E[repairs] | 0,0 | 0,0 | 0,0 | 0,0 | 0,0 | 0,0 | 0,0 | 0,0 |
| E[excessive stock] | 1,7 | 1,3 | 1,0 | 1,7 | 0,0 | 0,3 | 0,3 | 0,7 |
| **Cost breakdown** | | | | | | | | |
| Fixed order costs | € 2.500,0 | € 7.500,0 | € 7.504,0 | € 7.510,0 | € 2.500,0 | € 7.500,0 | € 7.512,0 | € 7.510,0 |
| Part purchase costs | € 2.888,0 | € 2.989,3 | € 2.913,3 | € 2.888,0 | € 2.888,0 | € 2.812,0 | € 2.837,3 | € 2.862,7 |
| Holding costs | € 1.981,9 | € 1.051,1 | € 625,4 | € 1.089,3 | € 1.829,2 | € 584,3 | € 581,4 | € 557,9 |
| Repair costs | € - | € - | € - | € - | € - | € - | € - | € - |
| Redesign costs | € - | € - | € 22.500,0 | € 15.000,0 | € - | € - | € 22.500,0 | € 15.000,0 |
| Disposal costs | € 166,7 | € 133,3 | € 100,0 | € 166,7 | € - | € 33,3 | € 33,3 | € 66,7 |
| Monitoring costs | € - | € 600,0 | € 1.920,0 | € 1.200,0 | € - | € 1.560,0 | € 1.920,0 | € 1.920,0 |

*Table 40: Results of SA: fixed order costs for relay.*

| | Fixed order costs = €100 | | | | Fixed order costs = €1.000 | | | |
|---|---|---|---|---|---|---|---|---|
| **Strategy** | **RMB** | **Monitor+LTB** | **Monitor+redesign** | **Planned redesign** | **RMB** | **Monitor+LTB** | **Monitor+redesign** | **Planned redesign** |
| E[orders] | 1,0 | 3,0 | 3,1 | 3,1 | 1,0 | 3,0 | 3,0 | 3,0 |
| E[order quantity] | 38,0 | 37,5 | 37,4 | 37,7 | 38,0 | 37,6 | 37,7 | 37,3 |
| E[redesign interval] | 0,0 | 0,0 | 8,0 | 10,0 | 0,0 | 0,0 | 8,0 | 10,0 |
| TEC | € 3.862,6 | € 4.523,4 | € 27.851,7 | € 20.118,1 | € 4.826,3 | € 7.229,0 | € 30.593,0 | € 22.815,3 |
| E[A] | 94,8% | 90,1% | 90,0% | 91,0% | 94,8% | 90,5% | 91,1% | 90,0% |
| E[OH] | 14,4 | 4,3 | 4,4 | 4,2 | 14,7 | 4,3 | 4,4 | 4,4 |
| E[BO] | 0,0 | 0,1 | 0,0 | 0,2 | 0,0 | 0,0 | 0,1 | 0,1 |
| E[repairs] | 0,0 | 0,0 | 0,0 | 0,0 | 0,0 | 0,0 | 0,0 | 0,0 |
| E[excessive stock] | 0,5 | 0,5 | 0,3 | 0,2 | 1,0 | 0,5 | 0,5 | 0,4 |
| **Cost breakdown** | | | | | | | | |
| Fixed order costs | € 100,0 | € 300,0 | € 308,0 | € 310,0 | € 1.000,0 | € 3.000,0 | € 3.008,0 | € 3.010,0 |
| Part purchase costs | € 2.888,0 | € 2.852,5 | € 2.842,4 | € 2.867,7 | € 2.888,0 | € 2.857,6 | € 2.862,7 | € 2.837,3 |
| Holding costs | € 821,3 | € 244,2 | € 248,0 | € 240,4 | € 838,3 | € 244,7 | € 249,0 | € 248,0 |
| Repair costs | € - | € - | € - | € - | € - | € - | € - | € - |
| Redesign costs | € - | € - | € 22.500,0 | € 15.000,0 | € - | € - | € 22.500,0 | € 15.000,0 |
| Disposal costs | € 53,3 | € 46,7 | € 33,3 | € 20,0 | € 100,0 | € 46,7 | € 53,3 | € 40,0 |
| Monitoring costs | € - | € 1.080,0 | € 1.920,0 | € 1.680,0 | € - | € 1.080,0 | € 1.920,0 | € 1.680,0 |

*Table 41: Results of SA: holding costs for relay.*

| | Holding cost rate = 5% | | | | Holding cost rate = 20% | | | |
|---|---|---|---|---|---|---|---|---|
| **Strategy** | **RMB** | **Monitor+LTB** | **Monitor+redesign** | **Planned redesign** | **RMB** | **Monitor+LTB** | **Monitor+redesign** | **Planned redesign** |
| E[orders] | 1,0 | 3,0 | 3,0 | 3,0 | 1,0 | 3,0 | 3,0 | 3,0 |
| E[order quantity] | 38,0 | 37,5 | 37,7 | 37,4 | 38,0 | 38,5 | 38,7 | 38,7 |
| E[redesign interval] | 0,0 | 0,0 | 8,0 | 10,0 | 0,0 | 0,0 | 8,0 | 10,0 |
| TEC | € 5.844,7 | € 11.695,1 | € 35.057,4 | € 27.308,2 | € 8.792,2 | € 12.587,1 | € 35.997,8 | € 28.264,3 |
| E[A] | 94,8% | 90,0% | 90,6% | 90,1% | 94,8% | 91,2% | 91,5% | 91,4% |
| E[OH] | 14,4 | 4,2 | 4,3 | 4,3 | 14,6 | 4,4 | 4,5 | 4,5 |
| E[BO] | 0,1 | 0,1 | 0,1 | 0,1 | 0,1 | 0,0 | 0,1 | 0,1 |
| E[repairs] | 0,0 | 0,0 | 0,0 | 0,0 | 0,0 | 0,0 | 0,0 | 0,0 |
| E[excessive stock] | 0,5 | 0,3 | 0,2 | 0,3 | 0,7 | 0,7 | 1,1 | 1,0 |
| **Cost breakdown** | | | | | | | | |
| Fixed order costs | € 2.500,0 | € 7.500,0 | € 7.508,0 | € 7.510,0 | € 2.500,0 | € 7.500,0 | € 7.508,0 | € 7.510,0 |
| Part purchase costs | € 2.888,0 | € 2.847,5 | € 2.862,7 | € 2.842,4 | € 2.888,0 | € 2.923,5 | € 2.943,7 | € 2.938,7 |
| Holding costs | € 410,0 | € 240,9 | € 246,7 | € 242,4 | € 3.330,8 | € 1.010,3 | € 1.019,4 | € 1.035,6 |
| Repair costs | € - | € - | € - | € - | € - | € - | € - | € - |
| Redesign costs | € - | € - | € 22.500,0 | € 15.000,0 | € - | € - | € 22.500,0 | € 15.000,0 |
| Disposal costs | € 46,7 | € 26,7 | € 20,0 | € 33,3 | € 73,3 | € 73,3 | € 106,7 | € 100,0 |
| Monitoring costs | € - | € 1.080,0 | € 1.920,0 | € 1.680,0 | € - | € 1.080,0 | € 1.920,0 | € 1.680,0 |

*Table 42: Results of SA: higher cycle service level for relay.*

| | $A_t \geq 90\%$ | | | | $A \geq 95\%$ | | | |
|---|---|---|---|---|---|---|---|---|
| **Strategy** | **RMB** | **Monitor+LTB** | **Monitor+redesign** | **Planned redesign** | **RMB** | **Monitor+LTB** | **Monitor+redesign** | **Planned redesign** |
| E[orders] | 1,0 | 3,0 | 4,0 | 3,0 | 1,0 | 3,0 | 3,0 | 3,0 |
| E[order quantity] | 39,0 | 39,4 | 40,0 | 38,8 | 39,0 | 38,6 | 39,0 | 38,6 |
| E[redesign interval] | 0,0 | 0,0 | 8,0 | 10,0 | 0,0 | 0,0 | 8,0 | 10,0 |
| TEC | € 7.663,4 | € 12.478,5 | € 37.669,8 | € 27.425,3 | € 7.542,9 | € 12.298,3 | € 34.909,1 | € 27.373,1 |
| E[A] | 98,1% | 98,2% | 99,1% | 98,0% | 95,0% | 95,5% | 96,6% | 95,7% |
| E[OH] | 15,6 | 5,6 | 4,9 | 5,04 | 14,6 | 5,0 | 4,7 | 4,76 |
| E[BO] | 0,0 | 0,0 | 0,0 | 0,0 | 0,0 | 0,0 | 0,0 | 0,0 |
| E[repairs] | 0,0 | 0,0 | 0,0 | 0,0 | 0,0 | 0,0 | 0,0 | 0,0 |
| E[excessive stock] | 1,4 | 1,6 | 2,8 | 1,0 | 1,0 | 1,2 | 1,2 | 1,0 |
| **Cost breakdown** | | | | | | | | |
| Fixed order costs | € 2.500,0 | € 7.500,0 | € 10.008,0 | € 7.510,0 | € 2.500,0 | € 7.500,0 | € 7.508,0 | € 7.510,0 |
| Part purchase costs | € 2.964,0 | € 2.994,4 | € 3.040,0 | € 2.948,8 | € 2.964,0 | € 2.933,6 | € 2.964,0 | € 2.933,6 |
| Holding costs | € 2.059,4 | € 744,1 | € 641,8 | € 666,5 | € 1.928,9 | € 664,7 | € 617,1 | € 629,5 |
| Repair costs | € - | € - | € - | € - | € - | € - | € - | € - |
| Redesign costs | € - | € - | € 22.500,0 | € 15.000,0 | € - | € - | € 22.500,0 | € 15.000,0 |
| Disposal costs | € 140,0 | € 160,0 | € 280,0 | € 100,0 | € 150,0 | € 120,0 | € 120,0 | € 100,0 |
| Monitoring costs | € - | € 1.080,0 | € 1.200,0 | € 1.200,0 | € - | € 1.080,0 | € 1.200,0 | € 1.200,0 |