Modelling Obsolescence Resolution Strategies at Thales Hengelo

Master Thesis Industrial Engineering and Management

Chiel Nijhuis
July 2023

Master Thesis Industrial Engineering and Management

Specialisation: Production and Logistics Management

Modelling Obsolescence Resolution Strategies at Thales Hengelo

Author:
C.G. Nijhuis (Chiel)
chielnijhuis@live.nl

Thales Hengelo
Zuidelijke Havenweg 40
7554 RR Hengelo
074 248 811

University of Twente
Drienerlolaan 5
7522 NB Enschede
053 489 9111

Supervisors Thales Hengelo
W. Reimert (Wouter)
R. Ypma (Rindert)

Supervisors University of Twente
Dr. M. van der Heijden (Matthieu)
Dr. E. Topan (Engin)

July 2023
1^{st} Edition, 67 Pages, 8 Appendices

Acknowledgements

Dear reader,

With the delivery of this thesis, I finalise my master Industrial Engineering and Management at the University of Twente. After enjoying my bachelors of the same study, the choice to continue with the master program with a specialisation in Production & Logistics Management was easily made. During my studies, I became specifically interested in optimisation of business processes through operations research techniques. I really enjoyed applying the theoretical knowledge from my studies in a practical setting and discussing all the issues and hiccups along the way with intelligent and experienced professionals of Thales.

More specifically, I would like to thank my company supervisors Wouter Reimert and Rindert Ypma. I was warmly welcomed into the supportability engineering department and during the execution of the research both of them provided value feedback for practical issues and questions. Moreover, I would like to thank Mathhieu van der Heijden and Engin Topan - the university supervisors - for their theoretical contribution on the research problem and the formulated model. This greatly improved the scientific quality of the thesis.

Last, I would like to thank my family and friends for their constant support during my studies and research in the last six months. Special thanks to my friend Laurens Kok, for providing feedback on the thesis frequently and providing useful tips during the execution of the research.

I hope you - the reader - enjoys reading the thesis!

Chiel Nijhuis
Wierden, July 2023

Management summary

Thales Hengelo is a worldwide leader in innovative radar systems used by naval ships and other military systems. Since an increasing part of production for these systems is outsourced and life-cycle duration of items decreases, items within radar systems are subject to turn obsolete. In the past, obsolescence issues of customers were dealt with case-by-case. Currently, Thales sees a shift of customer requirements when managing obsolescence, where performance based logistics contracts are established. Within these contracts, Thales is responsible for keeping radar systems operational and penalties occur in case contractual agreements for spare part availability are not met. Since Thales wants to offer cost-effective obsolescence management for customers with such a contract, the following research goal was defined:

"Provide a method for the obsolescence department of Thales which provides insights into the obsolescence management costs for part of a system's lifecycle."

Currently, Thales carries out obsolescence scans to solve obsolescence issues for radar systems. In case an end of life notice is received from a supplier, an obsolescence resolution strategy is implemented. For most issues, a simple resolution can be initiated (e.g. form-fit-function replacement). For some however, more expensive resolutions have to be used. Choosing the most cost-effective resolution from the various expensive resolutions (e.g. a last time buy or redesign) is difficult. This is caused by various unkown and uncertain item parameters which influence the resolution's cost.

After analysing how obsolescence issues are resolved at Thales, literature was reviewed on obsolescence management modelling and costing. Most optimisation models in literature focus on component level resolutions. These models are inapplicable for this research, since we focus on obsolescence costing at part and product level at the bidding stage of a contract. The logic used within the mitigation of obsolescence cost analysis methodology of Singh and Sandborn (2006) is used for the model formulated in this research: During the whole contracted period, obsolescence issues have to be resolved. This is the case for performance based logistics contracts at Thales, where penalty costs have to be paid in case a radar system does not meet availability requirements.

A mathematical model is formulated which makes decisions on what obsolescence resolutions to implement for spare parts turning obsolete. Decision are based on one of five policies that can be selected by the model user:

1. The current policy: For electronic items turning obsolete, a last time buy is performed. For mechanical items, a redesign is initiated and a last time buy is performed for the redesign lead time.
2. Performing last time buys: For all items turning obsolete, a last time buy is performed. This makes sure redesigns do not have to be performed.
3. Initiating a redesign: For all items turning obsolete, a redesign is initiated in combination with a last time buy for the redesign lead time.
4. Suggested policy 1: In case multiple obsolescence resolutions could be implemented, a heuristic is used to determine what obsolescence resolutions to implement. This heuristic analyses the costs of several resolutions based on expected parameter values and implements the resolution with the lowest calculated costs.

5. Suggested policy 2: Similarly to suggested policy 1, this policy determines what resolution to implement based on a heuristic. This policy analyses a different subset of possible resolutions compared to suggested policy 1.

The two "suggested" policies have been developed specifically for this research. We argue these are most logical to use when determining obsolescence management costs, as they take into account essential item characteristics when determining the obsolescence resolution to implement. The model consists of various stochastic parameters (e.g. redesign costs and available period after redesign) and variables (e.g. number of required spare parts, successful repairs). Monte Carlo simulation is consequently used to analyse the uncertain output of the model.

We carry out experiments for one of the radar system Thales offers to its customers. From these experiments, we conclude that the two suggested policies performed best overall with regards to costs. Moreover, the obsolescence management costs, which is the most important output of the model, has a high standard deviation due to the uncertain parameters (e.g. redesign costs) and variables (e.g. number of failed spare parts) used. Moreover, the sensitivity analysis carried out on uncertain parameters showed that likely changes in parameter data results in significant cost changes.

We draw the following conclusions from the conducted research: First, the implemented model can be used by Thales to determine obsolescence management costs for part of a system's lifecycle. Experimentation showed the model can provide a lower estimate for the costs than the current method used internally. Second, the model provides useful insights in what obsolescence resolutions are smart to implement for various line-replaceable units within radar systems. For example, for 42% of the units a last time buy is performed until the end of the contracted period when using one of the two suggested policies. Third, we conclude that providing an accurate estimate that can be used within performance-based logistics contracts is not possible due to the high standard deviation of the resulting cost estimate (±10% of the expected costs). Besides determining obsolescence management costs for part of a system's lifecycle, we provide several recommendations for Thales based on this research:

- Use the implemented simulation model when determining obsolescence management costs for performance based logistics contracts.

- Do not exclusively use the estimated cost price for obsolescence management within performance based logistics contracts from the model, as the actual costs in practice likely vary substantially due to uncertainty. Thales could include risk factors or make agreements with customers how to deal with this issue. For example, Thales could use the 80th percentile of the obsolescence management costs from the simulation runs within the contract.

- Use one of the two suggested policies when making obsolescence resolution decisions in practice. These policies make a clear trade-off between the resulting costs and take into account important spare part characteristics that influence the optimal obsolescence resolution.

- Investigate whether it is possible to extend the repair time frame of spare parts if this results in significant obsolescence cost reductions.

List of abbreviations

AMB	Authorised aftermarket buy
COTS	Commercial off-the-shelf
DoD	Department of Defense
EOL	End of life
ERP	Enterprise resource planning
FFF	Form-fit-function
ISS	In service support (type of contract)
LTB	Last time buy
LRU	Line-replaceable unit
MDP	Markov decision process
MOCA	Mitigation of obsolescence cost analysis
MoD	Ministry of Defense
MOQ	Minimum order quantity
MSI	Maintenance significant item
MTBF	Mean time between failure
OEM	Original equipment manufacturer
OMP	Obsolescence management plan
PBL	Performance based logistics
PCB	Printed circuit board
RA	Risk assessment
RMB	Risk mitigation buy
SLA	Service level agreement
WACC	Weighted-average cost of capital

Contents

1 Introduction

This chapter introduces the research which is conducted at Thales Hengelo. After shortly introducing the company where the research is conducted and providing motivation for the research, a concise research plan is formulated which describes the context of the problem shortly, states the research goal and outlines the research questions. Thereafter, the research scope and approach are discussed.

1.1 Company description

Thales Group is a global technology leader with more than 81,000 employees. The Group invests in digital and “deep tech” innovations. With its high-tech solutions, Thales aims to help companies, organisations and governments achieve their goals along one of its five vertical markets:

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

For the defence and security market, Thales equips more than 50 land forces and over 40 navies. Moreover, it has sold more than 1,200 air defence radars in 26 countries (Thales Group, 2023). Thales Hengelo is part of the Dutch division of Thales Group, employing around 1,500 people. From the five markets, Thales Hengelo focuses on Defence and security: They are a worldwide leader in innovative radar technologies and radar systems used by naval ships and other military systems. Next to supplying customers with its products, Thales offers various services such as the supply and repair of spare parts, as well as obsolescence management. The radar systems Thales offers are highly complex and during the lifecycle of the systems, several items within the system may need a repair or replacement. During the life-cycle of the system, several items may become obsolete, meaning that manufacturers of the items are no longer able to deliver the item in accordance with its original specification (International Electrotechnical Comission, 2019).

By providing active obsolescence management to its customers, Thales aims to pick the best obsolescence strategies for items that become obsolete during the system’s lifecycle. Customers can establish various contracts with Thales to get obsolescence support. In a performance based logistics contracts (PBL), Thales is responsible for the system’s availability. Within these contracts, penalty costs are incurred if uptime requirements are not met. In most cases, other in service support (ISS) contracts are used by customers, where Thales provides an obsolescence management plan (OMP) and obsolescence reports for products operational at the customer site. Based on this, customers can decide how they want to deal with upcoming obsolescence issues. Various proactive and reactive obsolescence strategies are used to solve obsolescence issues. The most common ones are listed below:

- Finding an alternative item: A different item can substitute the obsolete item within the system, since the item characteristics are the same. The substitute item can be exactly the same, which is referred to as a form-fit-function (FFF) replacement. Sometimes, a substitute can alternate slightly from the original item, which requires testing for compatibility.

- Last Time Buy (LTB) / Risk Mitigation Buy (RMB): Whenever alternative items are not available or not considered as a valid option to replace the obsolete item, an LTB can be considered. In this resolution, a sufficient amount of items are procured to support the remaining lifecycle of the system until the next planned redesign. This is similar to an RMB, where the buy is the result of proactive obsolescence mitigation.

- Authorised aftermarket buy: For some items unforeseen future demand arises (e.g. additional radar systems are sold to customers or the item is also used in a new system design entering the market). For these items an authorised aftermarket buy can be considered to increase stock and prevent a redesign from occurring. Buying stock at the aftermarket is significantly more expensive than buying parts from the original manufacturer (± factor 10). This resolution is often explored if the previous strategies are not available and initiating a redesign is costly.

- Redesign: The obsolete item could also be designed out of the system. This is a time consuming and expensive process for some items, due to strict requalification requirements. Therefore, this is often used as a last resort.

Chapter 2 of the thesis provides more detailed explanation about obsolescence strategies used at Thales and differentiates between proactive and reactive strategies to manage obsolescence.

1.2 Research motivation

The obsolescence management service Thales offers to its customers is becoming increasingly more important. This is mainly caused by an increase of outsourced production. Components purchased from suppliers are subject to decreased lifecycles and higher supplier dependency, making it crucial to manage obsolescence effectively.

Previous research conducted at Thales focused on modeling obsolescence strategies and minimising the costs associated with obsolescence (Reimert, 2020). Follow-up on this research is desired by Thales to come up with a more practical decision support tool for the obsolescence management department. The tool should support the obsolescence managers in determining the costs of obsolescence management during part of a system's lifecycle. This can be used to determine the budget which Thales requires from a customer who wants to establish a PBL contract.

1.3 Research plan

1.3.1 Problem description

An increasing amount of subsystems are being outsourced and not manufactured by Thales themselves. Especially for commercial-of-the-shelf (COTS) products, suppliers often discontinue its production due to technological advancements and profitability. Within this research, we use the following definition for COTS products: A product that is commercially ready-made and available for sale to the general public. Examples of COTS items are laptops, monitors and ethernet switches. PCBs - which are not manufactured for the general public - face the same problem: PCBs often turn obsolete due to technological advancement of chips. Figure 1.1 shows that especially in the later stage of the life-cycle of systems supplied to defence, obsolescence problems have to be managed due to the long life-cycle of radar systems compared to those of electronic items.

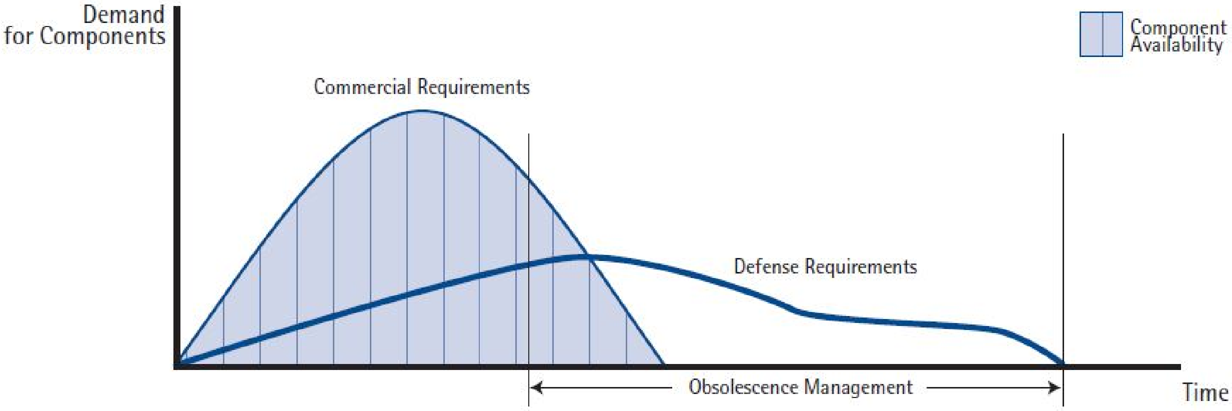


Figure 1.1: Life-cycle of electronic items and defence systems (Spectrum Signal Processing, nd)

In order to keep the system operational during its lifecycle, customers require obsolescence management from Thales to acquire cost-effective lifetime supportability for its radar systems. The trend is shifting from case-by-case obsolescence management where the customer pays for obsolescence separately per obsolescence resolution to PBL contracts, which diverts the obsolescence risk from the customer to Thales.

Whenever customers want to establish a PBL contract, a budget is required for solving all obsolescence issues for a predetermined period (e.g. 15 years). Due to the complex and uncertain environment Thales is operating in, as well as the long duration for which obsolescence should be resolved in the future, there is no effective method which can be used to determine the costs for obsolescence management in a PBL contract accurately. Previous research by Reimert (2020) identified the possible obsolescence strategies that can be used by Thales and constructed a prototype model where costs for several obsolescence strategies are calculated for maintenance significant items (MSI). An MSI is a broad term used for items where maintenance is required during the system's lifecycle. This can be preventive maintenance (e.g. lubrication) or corrective maintenance (e.g. replacement due to failure). For these items within the system, spare parts are often required. Within this research, we focus on MSIs which are replaceable by customers themselves. Further explanation about product breakdown and MSIs is provided in Section 2.3.2.

The model of Reimert (2020) is not used in practice, due to several limiting factors. First of all, there is limited data available about several parameters used within the model (e.g. number of future system sales, spare part demand). Therefore, various future scenarios have to be analysed and compared for the model to be used effectively. This process is too time costly with the prototype model. Second, the model is used for the analysis of one MSI at a time. In practice, a tool is desired at product level where costs can be analysed for all MSIs within a product simultaneously, since radar systems contain ± 400 MSIs.

1.3.2 Research goal

In order to contribute to the problem defined in the previous section, the following research goal is formulated:

"Provide a method for the obsolescence department of Thales which provides insights into the obsolescence management costs for part of a system's lifecycle."

Calculating the obsolescence costs for a predetermined period is hard to determine accurately upfront. For example, it is difficult to determine what obsolescence strategies are most cost effective and variables required to determine costs are often uncertain or unknown. Therefore, the solution to the problem requires the possibility to analyse several scenarios which could occur during a system's lifecycle, depending on the many uncertain variables (e.g. future sales, redesign costs).

The deliverable of this research is a simulation model implemented in *Python* which can be used to analyse obsolescence costs during a system's lifecycle for PBL contracts. The tool determines which obsolescence resolution approach to use for an MSI when it turns obsolete (e.g. perform an LTB). An important aspect of the deliverable is its practicality for Thales, since this was the major limitation of the resulting tool in previous research. Hence, the tool is able to perform sensitivity analyses and take into account the stochastic nature of parameters which results in many different product lifecycle scenarios. Next to the software tool, this thesis is the deliverable where conclusions on the research questions and recommendations for the company can be found.

1.3.3 Research questions

The following research questions are formulated to attain the research goal:

1. How are obsolescence issues resolved for radar systems produced by Thales?
    - What does the obsolescence management process look like?
    - What obsolescence mitigation and resolution strategies are used for MSIs?
    - What MSI parameters and characteristics affect the obsolescence strategies being implemented?
    - What are the costs of obsolescence strategies being implemented and how are these costs determined?
2. What methods does literature provide for analysing and modeling obsolescence management costs at product level?
3. How can a model for obsolescence management costs at product level be constructed for Thales?
4. How can the constructed model be applied for products sold within a PBL contract?
5. How can the constructed model be implemented successfully at Thales?
6. What conclusions and recommendations can be drawn from the research?

1.3.4 Research approach

Within the first research question, the current context regarding obsolescence is described. Process documentation is available about the obsolescence management process and current shortcomings within the company. This documentation is reviewed and used for describing the current obsolescence management process within the company. Similarly, past obsolescence resolutions are documented in Thales' product lifecycle management system. Since some process information might be outdated or incomplete, experts within the company are consulted to validate the information provided in this chapter.

A literature study is performed to answer the second research question. This literature study focuses on solution approaches applicable for the context of Thales. Previous literature has been studied during a master thesis assignment regarding obsolescence within Thales (Reimert, 2020). Based on this literature, a broader literature study is performed regarding models at product level specifically. Within this chapter, solution approaches are described and their applicability to the case of Thales Hengelo is discussed.

For the third research question, an appropriate modeling technique resulting from the literature study and context analysis is used to model obsolescence costs at product level. Similarly to the first research question, the model is constructed, reviewed and validated in collaboration with obsolescence experts within Thales.

In the next chapter, experiments are carried out with the model for a possible future PBL contract. Currently, 2/3 clients are interested in establishing a PBL contract for a predetermined period. In order to use the implemented model, data is collected from databases and ERP systems. If necessary, assumptions about data are made in collaboration with experts at Thales. After outlining which experiments are carried out with the model, results and useful insights are discussed.

The fifth research question describes what steps have to be taken by Thales to implement the model successfully and make using the model practical and valuable.

Within the final chapter of the thesis, the main conclusions of the research are outlined and a look is taken to what extend the research goal has been achieved. Next, recommendations are provided based on the main findings within the research. Last, limitations and the theoretical contribution of the research are discussed.

1.3.5 Scope

Several aspects of obsolescence management at Thales Hengelo are not taken into consideration within this research. First, our study focuses on obsolescence costs related to logistical obsolescence. This obsolescence type deals with items becoming unavailable during the lifecycle of a system. Whenever systems become unavailable due to system requirements changing during the lifecycle is not the focus of this research, since this is highly dependent on other departments within Thales. This is also known as functional obsolescence and is not taken into account within PBL contracts.

Second, the research focuses specifically on determining obsolescence lifecycle costs within PBL contracts. Thales is responsible for the operational availability of the radar systems within these contracts and they can receive penalties when stated targets are not met. MSIs are also present in systems not in a PBL contract. Decisions for MSIs should always be taken at product level within the research, since this results in the optimal obsolescence resolutions for the installed base and future sales expectation of an MSI. Hence, the model incorporates the installed base and future sales data of MSIs.

Third, the research focuses on hardware obsolescence specifically. This type of obsolescence deals with components on MSIs becoming obsolete, requiring a resolution therefor. In practice, parts of the system might become obsolete due to other causes as well: For example, due to the obsolescence of software. Since the obsolescence costs of these causes are currently hard to determine, they are out of scope for this research.

2 Context analysis

This chapter answers the following research question:

"How are obsolescence issues resolved for radar systems produced by Thales?"

This is done by answering the following sub-questions:

- Section 2.1: What does the obsolescence management process look like?
- Section 2.2 & 2.3: What obsolescence mitigation and resolution strategies are used for MSIs?
- Section 2.4: What MSI parameters and characteristics affect the obsolescence strategies being implemented?
- Section 2.5: What are the costs of obsolescence strategies being implemented and how are these costs determined?

Conclusions are provided in the final section of this chapter.

2.1 Obsolescence management processes

There are two main reasons for the increasing emphasis being put on obsolescence management within Thales: First, the decreasing lifetime of COTS items and chips increases the number of obsolescence issues to be resolved. Second, radar systems manufactured by Thales are becoming increasingly more complex. These two reasons cause there to be a large number of components and subsystems for which obsolescence has to be managed. In order to manage the obsolescence for its customers, Thales regularly performs two processes for its products: A risk assessment (RA) and an obsolescence scan.

2.1.1 Risk Assessment

The first process Thales regularly carries out for its radar systems is a risk assessment. This process provides guidance on how to manage different items based on the magnitude of obsolescence risk. The magnitude is determined by three factors:

1. Operational impact: This indicates the potential loss of availability or capability of the radar system in case an item is not usable.
2. Probability of obsolescence issues: Some items likely turn obsolete in the near future .
3. Resolution costs for solving obsolescence issues.

Currently, Thales is running a pilot in this process to make sure it can be carried out in the same effective manner for different products. Several databases are used as input for the RA. Based on various parameters and calculations, items within a product can fall into one of three categories: low, medium, or high risk. For the high and medium risk categories, mitigation strategies can be used. Contrary to obsolescence resolution strategies, mitigation strategies are proactive: Strategies are implemented before the department receives an end of life (EOL) notice, meaning the item will turn obsolete in the short term. Section 2.2 describes various obsolescence mitigation strategies. For items falling into the low risk category, no mitigation strategies are used and obsolescence is solved reactively.

2.1.2 Obsolescence scan

The second process Thales carries out to mitigate risk is an obsolescence scan. For every product Thales manufactures, an obsolescence scan is carried out once or twice a year. The main input for these scans is lifecycle information of system components. External information from market databases and internal information from the ERP system and component information system are used. A bill of materials (BOM) of a specific product is uploaded into the database and filled with all relevant lifecycle information. Whenever information is unavailable, it is added manually if applicable or possible.

After the obsolescence scan is finalised, an obsolescence analysis is carried out. During this analysis, components with an EOL in the near future are examined to see if the obsolescence is being managed already. When no actions have been implemented for these items, an obsolescence mitigation or resolution is usually initiated.

2.2 Obsolescence mitigation strategies

A list is provided of the proactive / mitigation strategies Thales implements for items with medium / high obsolescence risk as indicated by the RA. These strategies are also noted in Thales' obsolescence manual (TNL NAVAL, 2023):

- RMB: A risk mitigation buy can be performed, where enough stock is purchased to meet the expected future demand. This is an attractive option for items with a low cost price. The amount of items to purchase is determined in a similar way to an LTB quantity, which is explained in Section 2.5.1.
- Service level agreement (SLA): In an SLA, agreements can be made with suppliers to lower obsolescence risk. There are two requirements in SLAs which are of interest for the obsolescence department: Obliging the supplier to offer an LTB option or obliging the supplier to introduce an FFF replacement.
- Authorised continuing manufacture: A formal agreement with an original manufacturer or authorised aftermarket party is developed to continue the production of the soon to be obsolete part. This is a way to push the EOL date into the future.

There are also mitigation strategies which are implemented for all low risk items. These strategies are therefore not the result of the RA:

- Supplier contracting: The general terms and conditions of a purchase include the obligation of suppliers to notify Thales 12 months before a discontinuance. In practice this does not always happen.
- Planned technology upgrades: Part of a radar system might also be redesigned during the lifecycle. The redesign can include new parts (which resolve obsolete parts) and often increase functionality / performance of the subsystem. This strategy is also referred to as design refresh planning. By redesigning part of a radar, obsolete items can be designed out of the product.

The proactive obsolescence strategies used by Thales are formulated in the TNL NAVAL (2023). The literature review of Romero Rojo et al. (2009b) mentions similar proactive strategies which can be implemented. However, planned technology upgrades are not actively used as a mitigation strategy within Thales. Three technology roadmaps of different products have been examined to see to what extend refreshment planning is used for subsystems within the product. This examination showed that the roadmaps only include redesigns currently being undertaken or from the past. Future upgrades are generally only planned for subsystems with obsolescence issues. This issue has been discussed and confirmed by the obsolescence and design engineering department.

2.3 Obsolescence resolution strategies

In order to solve obsolescence problems for its customer, Thales reactively implements resolution strategies to ensure the systems of its customers can stay operational. Different resolutions can be initiated depending on the context (TNL NAVAL, 2023):

- Existing stock: In case there is sufficient stock of the item available (e.g. after an RMB) for future project usage, no solution has to be implemented.
- Equivalent: An item which is functionally, parametrically and technically interchangeable is used in the future (also referred to as FFF replacement).
- Alternative: An item which is functionally, parametrically or technically slightly different is used. Since they are different from the original item, minor requalification testing is required to ensure compatibility.
- Reclamation/cannibalisation: The use of an item found in surplus equipment or equipment beyond economical repair. This option is currently used seldomly. This option can be used in case similar systems are known to be around the end of its lifecycle at other clients. Moreover, customers do not like second-hand items within their systems and therefore only want to use this resolution if cost savings are high.
- Emulation: A manufacturing process that produces a re-engineered substitute FFF item for the unobtainable item. This can be performed by Thales or a supplier in case required data is available. Moreover, requalification testing is required for this resolution and is therefore often expensive.
- Last Time Buy: Buy a sufficient amount of the item to support the remaining lifecycle of the product or until the next planned technology upgrade (in which the item is redesigned).
- Authorised aftermarket: The item is available on the market but not from the original manufacturer. It is important to note that these suppliers require to be licensed sources. This resolution can be used when an initial LTB quantity turned out to be insufficient and is usually used as a backup by Thales. Moreover, prices of items procured on the authorised aftermarket are often inflated.
- Redesign: Creating a new design of a subsystem which alternates from the original design and does not include the obsolete item in its design. For this resolution, the impact and costs are highly dependent on the scope of the redesign. Some redesigns are small and relatively cheap (e.g. €20,000). Some are major and therefore quite expensive (e.g. €500,000).

2.3.1 Obsolescence decision tree for resolution strategies

Although the obsolescence resolution process involves many internal stakeholders and might deviate in practice, a simplified decision-tree diagram can be used for determining the obsolescence resolution. Figure 2.1 shows this simplified process. An obsolescence resolution is only picked for items where not enough stock is available for the required future sales and installed base (including necessary repairs). First, FFF-items and alternative items are examined (with minor requalification requirements). In case these are available, they are always picked as the resolution as the other possible resolutions are more costly.

Whenever substitutes are unavailable, the possibility for an LTB is examined. When this is possible, Thales will order sufficient stock to support the installed base as well as futures sales until the next redesign or until the end of the system's lifecycle. An LTB calculation is performed to determine the ordering quantity. This is explained in Section 2.5.1. In practice, it might occur that an obsolescence trigger starts the resolution picking process, but the supplier has not notified Thales about the discontinuation of production. For these cases (or cases where not enough items were ordered at an LTB), the authorised aftermarket can be a promising solution. Thales currently has a list of parties that might have stock of items although they are obsolete. Items from these parties might have a purchase price of around factor 10, but this might still be cheaper than initiating a redesign. Whenever an aftermarket buy is not possible, the possibility of a redesign is investigated with the required stakeholders (e.g. design engineers).

For customers where Thales operates under a Performance Based Logistic (PBL) contract, Thales is responsible for the system availability. Consequently, if an item is obsolete and no stock is present, a redesign is unavoidable, since costs are incurred if requirements within the contract are not met. For customers where Thales is not operating under an ISS contract, a redesign can only be initiated with consent (and indirect payment) of the customer.

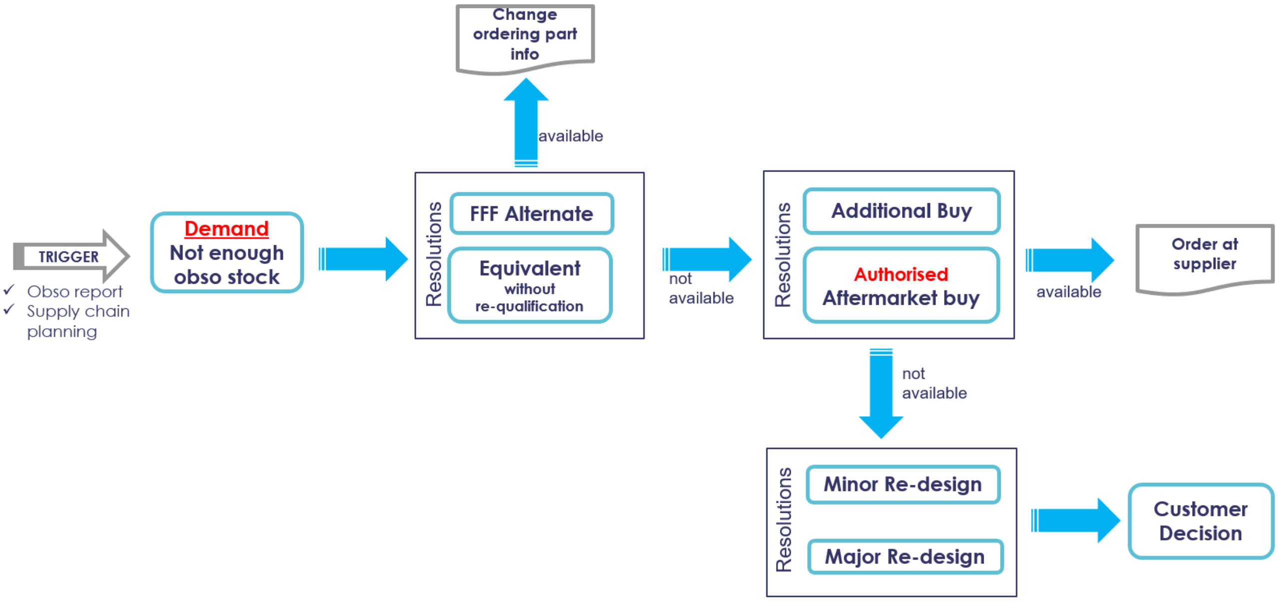


Figure 2.1: Simplified process overview for determining the obsolescence resolution strategy (TNL NAVAL, 2023)

2.3.2 Product breakdown structure

This section explains how the different levels within a product interact when solving obsolescence issues for customers. This is important to understand, as obsolescence strategies can be referred to differently depending on the indenture level of an item. Figure 2.2 shows a simplified breakdown structure of a radar system. In practice they are more complex. The level which is of interest to a customer is the Line Replaceable Unit (LRU) level. LRUs can be replaced by customers themselves when it breaks down and customers are interested if Thales can supply these items during a system's lifecycle. LRUs which require maintenance are also referred to as MSIs. However, MSIs can also be items at a lower indenture level.

At Thales, items are always scanned at the lowest possible indenture level to retrieve lifecycle information. In the example depicted in Figure 2.2, this would be all items without any underlying items. Thus, when an MSI is classified as obsolete, one of the underlying components are classified as obsolete. Moreover, when an obsolescence resolution is introduced for an obsolete component, the resolution might be referred to differently depending on the level in the product tree. For example, an obsolete component might be replaced by an alternative (and minor requalification testing is required). At component level, this is referred to as an alternative. At MSI level, this might be referred to as a (small) redesign however and the revision of the MSI has to be increased.

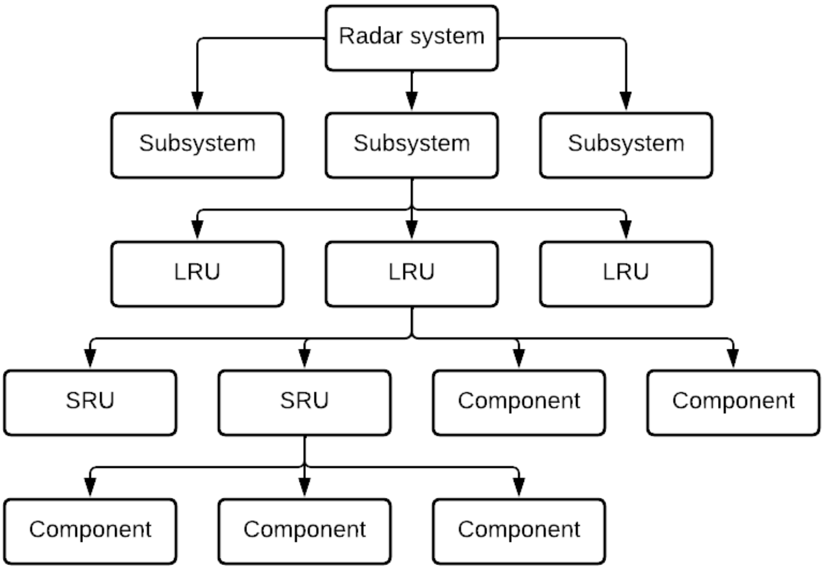


Figure 2.2: Simplified product tree of a radar system

2.4 MSI parameters & characteristics

Within a complex radar system, many different subsystems exist with different functions and items. For MSIs within a system, various characteristics influence the obsolescence mitigation or resolution strategy to be used. For example, cheap items are handled differently compared to expensive ones. Whenever an item receives an EOL notification, the obsolescence resolution process described in Section 2.3 is followed. However, when determining the future obsolescence costs within a PBL contract, the costs of all items (also those without an EOL notification in the near future) have to be estimated.

Within a radar system, there are 100 - 400 MSIs at LRU level, depending on the radar. Figure 2.3 shows examples of MSIs at this level (e.g. printed circuit boards, gearboxes and switches). Currently there is no clear process in place how to estimate the lifecycle costs for PBL contracts and this is done based on experience and common sense. This results in a situation where the obsolescence management costs are not estimated as accurately as possible, taking into account possible scenarios that an unfold due to uncertainty.

Figure 2.3: Example of MSIs within radar systems

Based on internal meetings with stakeholders, the following MSI parameters and characteristics are identified that influence the expected obsolescence costs of an MSI within a PBL contract:

- Unit cost: The price for which an item is procured from an original supplier or manufactured internally. The effort put into determining the obsolescence costs is often higher for items with a high unit cost. The unit cost is often higher for items procured from the aftermarket (see Section 2.5.2) and might be lower for items where large quantities are procured.
- Obsolescence status: When a product is sold to customers, it is possible that items within the system are obsolete already. For most of these items (or its underlying components), an LTB is performed and stock should be reserved for PBL contracts. Examples of obsolescence statuses are: obsolete - no stock; obsolete - stock for 7 years; Not obsolete.
- Stock and demand: Whenever enough stock is available to meet all future demand, no actions have to be taken. Stock can be present at Thales as well as the customer site (which might be unknown).
- Shelf life requirements: Some items cannot be stored for a long time (or need to be used at certain frequencies to not break down). Examples of such items are PC chargers. For these items, LTBs can only be performed to cover a certain time span (where maintenance during storage is required).

- Mechanical vs. electronic items: MSIs which have electrical components often have a shorter lifecycle. Therefore, the probability of having to initiate an obsolescence resolution is higher for these MSIs. Moreover, for these MSIs mean-time-between-failure (MTBF) data is used to determine the amount of spare parts necessary. For mechanical MSIs, preventive maintenance is performed and items rarely have to be replaced correctively. Therefore, the amount of spare parts necessary for a certain period are based on the preventive maintenance interval plus a risk percentage.

- Risk assessment: Although the RA is not actively used at Thales at the moment, an outcome of the RA is the risk category of an MSI. For MSIs with a medium or high risk level, mitigation strategies should be considered. Items with a low risk impact should not have any mitigation costs.

- Minimum order quantity (MOQ): For some items, an MOQ is used by the supplier. This might favor a different obsolescence resolution to be implemented, especially when the MOQ value is significantly higher than the expected future demand.

- Repairability: Some MSIs can be repaired relatively cheaply. For these items, repairing failed MSIs is worthwhile and often used by Thales. Whenever an item is repaired, the repair yield influences the obsolescence costs for these items, since lower LTB quantities are required and therefore inventory holding costs are lower. Currently, a standard repair yield of 90% is assumed, but this might vary in practice depending on the item. Items which can be repaired, can be repaired by Thales or a subcontractor. Moreover, the repair price is assumed to be x% of the LRU unit cost and repairs do not happen for cheap LRUs (items with a unit cost under €x)[1].

- EOL indication: Several commercial and internal databases can give an indication on the expected EOL date for components within an MSI. For items with an EOL indication in the near future, obsolescence costs are higher in general. These are often electronic MSIs. The EOL indication databases provide are for components. For example, a PCB consists of ± 100 components and when no aftermarket options are available for an obsolete component that has insufficient stock, a redesign has to be initiated for the PCB.

- Industrial product: For some items it is relatively easy to find an FFF-replacement or alternative item. These are usually industrial products which are not specifically designed for Thales only, but are used by other businesses as well.

- Redesign impact: Redesigns for MSIs where the redesign impact is high are not desired, since they are expensive. In general, for these items a resolution is required which makes sure that no redesign needs to be initiated.

Currently only part of these characteristics are used when determining obsolescence costs for a PBL contract (e.g. unit cost, redesign impact and obsolescence status). Other characteristics are not used to the extend they could be (e.g. RA). Moreover, the uncertain nature of parameters (EOL indication, MSI demand, repairability) is not actively used to determine costs accurately. The extend to which the parameters and characteristics have been used for previous PBL contracts is described in Section 2.5.4.

---

[1] Values related to cost calculations are either multiplied by a constant factor or replaced by an x, due to the confidential nature of the data.

2.5 Costs of obsolescence strategies

Whenever a PBL contract is sold to a customer, costs for managing obsolescence are incurred. Next to standard processes used internally (performing risk assessments and obsolescence scans for products) obsolescence mitigation and resolution strategies are used to manage obsolescence. Quantification of these strategies is required within the formulated model in Chapter 4.

First, several obsolescence mitigation strategies are usually implemented within a product's lifecycle for different MSIs. Some mitigation costs are currently not taken into account when estimating the lifecycle costs of a product. Some information is listed about what strategies are included and excluded in budgeting a PBL contract:

- During previous PBL estimations, authorised continuing manufacture was not included in the cost calculations. This option is seldomly implemented in practice and is only interesting if significant holding costs can be mitigated.
- Supplier contracting is not included for the obsolescence costs, since they are found in the general terms and conditions within all contracts.
- Planned technology upgrades have to be included when determining future obsolescence costs. However, most technology roadmaps of products do only contain past upgrades and no redesigns are actively planned.
- For some MSIs, SLAs have been established with suppliers. For these MSIs, a percentage of the SLA costs is transferred to the PBL contract (e.g. €5,000 per subcontractor).
- RMBs are usually implemented for items with a low price.

Similarly to mitigation strategies, resolution strategies have to be taken into account when determining obsolescence management costs for a predetermined time span:

- Two strategies are considered out of scope when determining obsolescence costs upfront: reclamation/cannibalisation and emulation. These are rarely used in practice and when they can be used is hard to determine upfront.
- FFF or alternative items are taken into account. These are usually industrial components having multiple suppliers. Internally, no standard budget or costs are assigned to changing this information. According to an experienced engineer, the average time required for changing an item to an FFF or alternative is 2 hours.
- The costs of LTBs, redesigns and authorised aftermarket buys (AMB) play a key role. Since these resolutions are the biggest cost factor for PBL contracts, they are further explained in Sections 2.5.1 - 2.5.4.

2.5.1 LTB costs

Whenever an LTB is performed for an item, the total future demand of the item affects the LTB quantity. This demand can arise from different subsystems and products. For example, a PCB might be present in four different products or a component might be present in five different PCBs. Consequently, an LTB is not only performed for spare parts required in a PBL contract, but also for future sales and spare part demand for other systems and customers.

Before discussing the equations used to determine the LTB quantity of an item, we would like to note the limitations of these equations: Several parameters within these equations are uncertain and subject to change. According to experts within Thales, these are amongst others the demand (for items required in future systems), field data required for spare parts (MTBF data and annual operating hours) and repairability information (repair yield and repair time). Appendix A.1 confirms this belief by obsolescence managers about demand uncertainty, showing that demand changed significantly at both product as well as MSI level (100% and 300% change respectively) in only 6 months.

Moreover, current demand forecast does not take into account redesigns and technology upgrades which are already scheduled or being undertaken, forcing the obsolescence managers to change the demand forecast manually when determining the LTB quantity.

Due to the uncertain data being used for LTB calculations, several redesigns might be required at product level within a PBL contract, although this was not the chosen obsolescence resolution strategy. Since redesigns are costly, analysing and taking into account possible redesign scenarios is important when determining the obsolescence costs.

The equations used for determining the LTB quantities are explained in Appendix B. The LTB quantities calculated are used for the total installed base and future sales forecast of an item. Whenever a PBL contract is sold to a customer, stock should be reserved for this customer specifically and its corresponding purchasing, holding and disposal costs are of interest. Internally, the holding costs of items is estimated to be 15% of the unit cost per year. However, there is no consensus about the percentage to use for holding costs. The disposal costs are assumed to be €100 per MSI.

Within the current LTB calculations, there are two shortcomings with regards to repairs: First, component failure in an item is not modelled accurately when calculating the required spare parts. Currently, the logistics engineering department assumes that if a board consists of n components, the probability a failure is caused by one of the components is $\frac{1}{n}$. For items where repairs are performed, sufficient stock has to be present for components which need replacement. Whenever components are not present, repairs cannot be performed.

Second, the repair costs of items are unknown exactly and the repair yield is uncertain. When these two parameters are known more accurately, cost savings can be made: Currently, Thales assumes repair costs are x% of an items cost price and the repair yield is 90%[2]. The assumption that repair costs are x% of the cost price are quite high according to experts within Thales. When repair costs are known to be low for certain items, more effort can be put in the repair process of these failed spare parts (e.g. improving the required information systems of repairs, increasing the repair yield or increasing the time frame for which repairs can still be performed after the last production batch). This allows for significant cost savings.

---

[2] Values related to cost calculations are either multiplied by a constant factor or replaced by an x, due to the confidential nature of the data.

2.5.2 Authorised aftermarket

Whenever an item is required by Thales and cannot be bought at an original supplier, the authorised aftermarket is used to find potential stock against an increased price. Usually, LRUs are not procured directly from suppliers, but components within them are procured. Prices of components on the aftermarket can be highly inflated (e.g. factor 5). The price of components on the aftermarket compared to the original price depends on mainly two factors, according to an experienced obsolescence engineer of Thales: Scarcity on the market and the redesign impact.

When an item turns obsolete, is usually still available at aftermarket parties and therefore the prices are not highly inflated (e.g. factor 1.5). Three to five years after an item has been announced obsolete, it starts getting more difficult to find parties and the prices are therefore increasing (e.g. factor 8).

For components with a low redesign impact, prices are usually not highly inflated on the aftermarket. For these components, it is cheaper to redesign the component with relatively low engineering costs. For other items (e.g. a chip), the redesign impact can be high, for example due to software having to be programmed on the new item. For these items, redesigns are usually not initiated by Thales/suppliers and aftermarket prices can be highly inflated (e.g. factor 10).

Since the aftermarket can reduce obsolescence resolution costs, it should be used when determining obsolescence costs in a PBL contract. Thirteen different components which have been bought on the aftermarket are analysed. Figure 2.4 shows that for one of these components, the price dropped on the aftermarket. For ten of these components, the increase was between 0 - 400% and for two of the components the increase was around 900%. This confirms the statement of obsolescence engineers about component prices on the aftermarket: The increase in prices is case dependent.

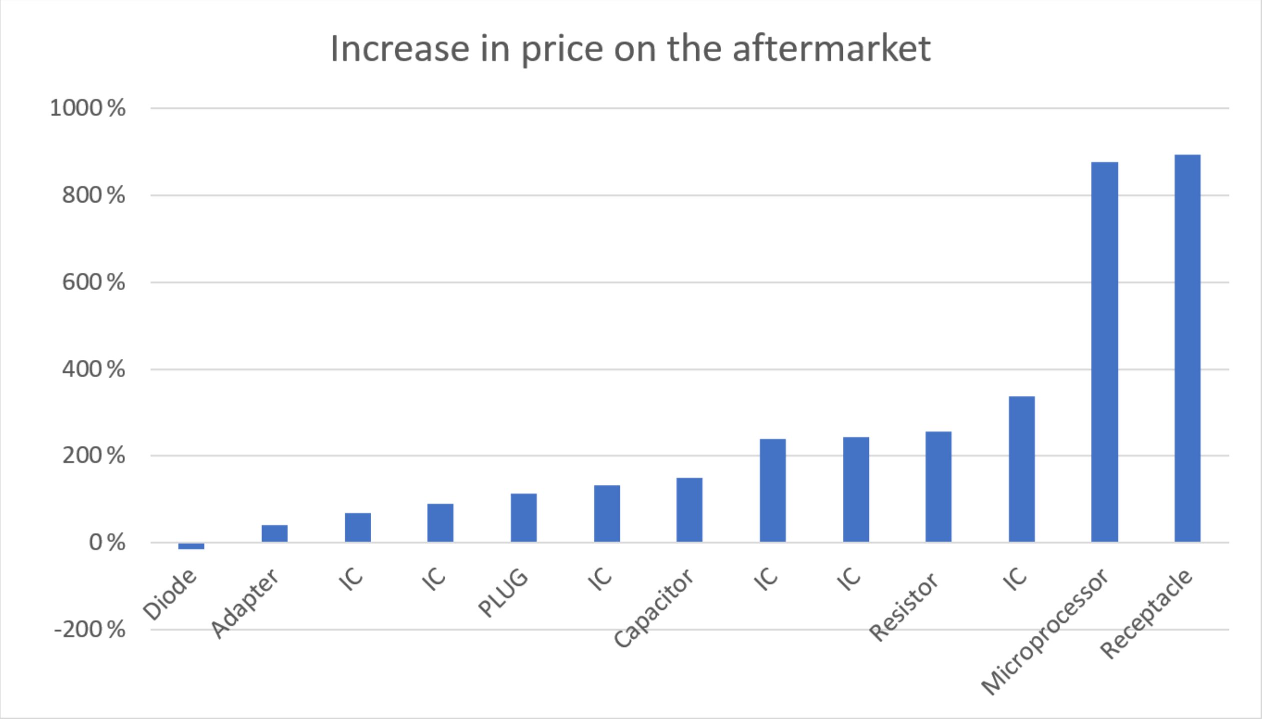


Figure 2.4: Cost comparison original supplier vs. aftermarket

2.5.3 Redesign costs

The last obsolescence resolution for which the costs heavily affect the price of the PBL contract are redesigns. Redesigns are usually required for PCBs and electronic items. This is caused by the high number of electronic components being present on these items which turn obsolete, as well as the short lifecycle of electronic items.

Within the design engineering department of Thales, a project is being undertaken to determine the redesign costs of PCBs. Currently, the costs of previous and current redesigns are not insightful. The main cost factor for redesigns are the engineering hours required (80 - 90% according to managers of the design engineering department). During redesigns, all obsolete components within a board are exchanged. Moreover, components with an EOL indication in the upcoming years are also tried to be removed from the new design.

Determining the redesign costs up front is complex: In case only three obsolete components on a PCB have to be changed, the redesign might take 3000 non-recurring engineering hours. In another case, ten obsolete components might need to be changed and this only takes 1000 hours. The outcome of the tool which is currently being constructed puts a PCB in one of three categories depicted in Table 2.1[3]. The meaning of the these categories is shortly explained: Within a minor redesign, production of the PCB can start without any additional qualification testing. For medium redesigns, a formal prototype process is followed where additional testing is required before normal production can be started. For a major redesign, the prototype process is also followed, but based on the results the redesign will be slightly altered to ensure all board requirements are met. After the alteration, an additional prototype process is followed similar to the one of a medium redesign. The classification in one of the three categories is based on a checklist which is filled in by design experts of Thales.

Table 2.1: Estimate for redesign costs of PCBs

Impact	**Likelihood**	**Non-recurring-engineering hours**	**Costs (€)**
Minor redesign	80%	x	x
Medium redesign	15%	x	x
Major redesign	5%	x	x

Next to redesign costs of PCBs, redesign costs of other items might also be incurred in PBL contracts: Computers, monitors, ethernet switches and complex mechanical items can turn obsolete as well. Usually LTBs are performed for these items, but depending on the item characteristics a redesign might be initiated.

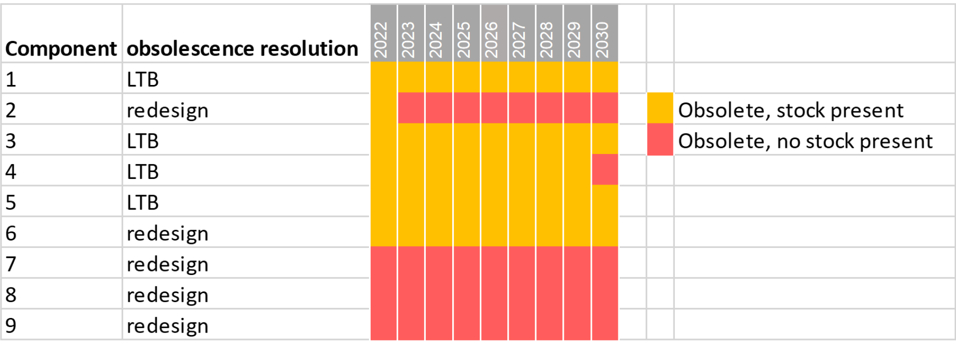
2.5.4 Case analysis: costs for lifecycle period

This subsection describes the costs that are currently made in the PBL contact that is active for one of Thales' customers. First, a redesign which took place for a PCB is discussed. This item is present in the current system of the PBL contract. Next, the budgeted costs for the PBL contract are compared to the costs which have been made this far.

---

[3] Values related to cost calculations are either multiplied by a constant factor or replaced by an x, due to the confidential nature of the data.

For one PCB, a redesign is currently undertaken due to obsolescence issues. This PCB is an LRU of the system with a PBL contract. For nine components within this PCB, no original supplier is available anymore and therefore the components are obsolete. Figure 2.5 shows that these components are obsolete and for some there is no stock. Therefore, a redesign is initiated for these components. In total, the board consists of 119 components. Some of these components have an extremely low redesign impact (e.g. an alternative supplier will be able to deliver an FFF). For others, the redesign impact is high and making sure enough stock is available is important. For the components shown in Figure 2.5, the redesign impact is high. Therefore, a redesign at board level was initiated which is costly. Redesigning a board takes around two years and for this specific board the redesign is almost finished. The exact costs are unknown exactly but are estimated to be around €200,000 - €300,000[4].



Component	obsolescence resolution	2022	2023	2024	2025	2026	2027	2028	2029	2030
1	LTB	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
2	redesign	🟨	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
3	LTB	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
4	LTB	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟥
5	LTB	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
6	redesign	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
7	redesign	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
8	redesign	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
9	redesign	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥

🟨 Obsolete, stock present
🟥 Obsolete, no stock present

Figure 2.5: Obsolescence forecast for critical components of a PCB

For the only PBL contract which is currently active, the obsolescence management costs are split in two different factors: monitoring costs and resolution costs. For the obsolescence monitoring costs, weekly hours have been estimated with relevant stakeholders (± x hours on average for the obsolescence managers, engineers as well as related departments)[4].

For the obsolescence resolution part of the obsolescence costs, the following approach is used: For all MSIs where obsolescence issues are expected to occur during the contracted period, an RMB is used to solve obsolescence at the start of the contract. For the same MSIs, the costs of performing a redesign during the contracted period have been estimated. For both strategies, the total estimated costs were similar. Hence, these costs were assumed to cover obsolescence resolution costs during the contracted period and have been used within the contract.

For the costs used in the contract, current expenditures are tracked in an application where employees register the time they spend on activities related to the PBL contract and where item purchases are registered. Unfortunately, the registration of hours related to obsolescence monitoring does not happen accurately and thus we cannot see whether the estimated hours are correct within the contract for obsolescence monitoring. For obsolescence resolutions, most costs are usually made near the end of the system's lifecycle (due to an aging system and therefore more obsolescence issues). Table 2.2 shows the estimated and current expenditures of the PBL contract[1]. Since the obsolescence monitoring activities are not registered correctly and the obsolescence resolution costs happen mostly near the end of the contracted period, we are unable to say whether the estimated costs have been correct.

---

[4] Values related to cost calculations are either multiplied by a constant factor or replaced by an x, due to the confidential nature of the data.

Table 2.2: Expenditures for the PBL contract currently undertaken

Cost factor	**Estimated expenditure (€) for a period of 15 years**	**Current expenditure (€) after 4 years**
Obsolescence monitoring	242,000	32,600
Obsolescence resolution	671,000	13,500
Total	913,000	46,100

2.6 Conclusion

Within this chapter the following research question was addressed:

"How are obsolescence issues resolved for radar systems produced by Thales?"

We draw the following conclusions:

- Product risk assessments and obsolescence scans are used to identify items for which obsolescence mitigation and resolution strategies have to be implemented. Part of the mitigation strategies are only used for items with a high obsolescence impact.
- The implementation of a technology roadmap is currently not done proactively. Therefore, the obsolescence resolution process does not clearly make a trade-off between LTBs, redesigns and AMBs.
- With the help of experts, multiple MSI characteristics and parameters are listed that influence the preferred obsolescence resolution to be used in case of obsolescence, where multiple parameters are uncertain (e.g. Repairability information and EOL indications).
- Due to uncertainty in future demand (and other parameters), RMB and LTB quantities might turn out to not be enough in practice. This might force expensive redesigns at LRU level.
- The costs incurred in the PBL contract that is currently active at Thales are based on internal meetings and expert opinion. No conclusions can be drawn about the accuracy of the cost estimate, since costs registration is not performed accurately and the contract has only been active for 4 out of 15 years.

3 Theoretical framework

This chapter answers the following research question:

"What methods does literature provide for analysing and modeling obsolescence management costs at product level?"

Section 3.1 describes models which can be used for determining obsolescence resolution costs. Next, Section 3.2 discusses cost metrics which can be applied for obsolescence resolutions used at Thales. Moreover, a process is discussed for creating reliable cost estimates. This includes information about dealing with unavailable and uncertain data. Finally, conclusions for the remainder of the research are stated in Section 3.3.

The literature review of Kapletia and Probert (2010) confirms the current situation where customers are moving from traditional contracts to availability or PBL contracts within the defence sector. This is also the case at Thales. This diverts the risk of obsolescence from the consumer to the original equipment manufacturer (OEM). In practice however, obsolescence risk is shared between both parties in accordance with the clauses agreed in the contract (Kapletia and Probert, 2010; Romero Rojo et al., 2009a). This way of contracting requires accurate estimations of obsolescence costs at the bidding stage for both parties.

3.1 Models for the obsolescence resolution process

Obsolescence issues can be resolved at component, assembly or system level. In research, most of the focus has been on component level obsolescence (Herald et al., 2008; Romero Rojo et al., 2009b). The research for Thales focuses on obsolescence at system level. When managing obsolescence at this level, data is often required to perform an accurate analysis that is not available in practice (Herald et al., 2008). Several tools exist for managing obsolescence, where only a limited amount of these tools can be applied to an analysis on system level (Romero Rojo et al., 2009b). Most models focus on optimal design refresh planning, where optimal decisions are made on which obsolescence resolution to use.

3.1.1 Porter's model

Porter (1998) created a first simple model for performing life-cycle planning associated with the trade-off between LTBs and redesigns, on which many other optimisation models are based. Although Porter's model is referred to in many academic articles, we note it is a technical white paper by Boeing and the model is therefore not peer-reviewed. Within Porter's model, an optimal date for a design refresh is determined which minimises life-cycle costs. The optimisation model is depicted in Equation (3.1). The first and second term represent the LTB and redesign costs respectively.

$$\min C_{Total} = P_0 \sum_{i=1}^{Y_R} Q_i + \frac{C_{DR_0}}{(1+r)^{Y_R}} \tag{3.1}$$

Where:

P_0 = Price of the obsolete part in the year of the LTB (year 0)
Y_R = Year of the design refresh
Q_i = Number of parts needed in year i
C_{DR_0} = Design refresh cost in year 0
r = Discount rate

The model has several limitations for the application to real systems:

- Optimal design refresh dates can only be determined on part by part basis and does not consider coupling of decisions about multiple parts.
- The model only uses LTBs and redesigns as possible resolution strategies.
- The model only considers a single design refresh at a time and cannot optimise multiple design refreshes simultaneously.

3.1.2 The MOCA methodology

The mitigation of obsolescence cost analysis (MOCA) methodology is designed to minimise the expected life-cycle costs of sustainment-dominated electronic systems. Singh and Sandborn (2006) directly address the shortcomings of Porter's model with MOCA. The methodology takes into account the treatment of data uncertainty, multiple redesigns, considers the product breakdown structure and does not focus on a single item only. Within the tool, life-cycle plans for a predetermined period are simulated and the total lifecycle costs for these plans are estimated. The tool gives the best design refresh strategy which minimises the lifecycle costs, based on simulated candidate refresh plans. Fundamentally, the methodology must incorporate "short term" and "long term" resolution strategies to make sure obsolescence is dealt with at all times. Short term strategies relate to strategies where the parts remain obsolete, but obsolescence issues are solved for the short term. For long term strategies, obsolescence is resolved by for example substitution or redesign. For these strategies, the item is therefore not obsolete anymore after initiating the strategy.

Figure 3.1 summarises the MOCA methodology. Based on various input data (e.g. obsolescence dates, part data, procurement costs of parts at a specific point in time), lifecycle costs of a selected refresh plan are determined. Based on the resulting lifecycle costs, new design refresh candidates are selected. The refresh plan with the lowest lifecycle costs is selected from the set of examined plans. Unfortunately, the algorithm that selects the next candidate refresh plan based on previous results is not provided in Singh and Sandborn (2006).

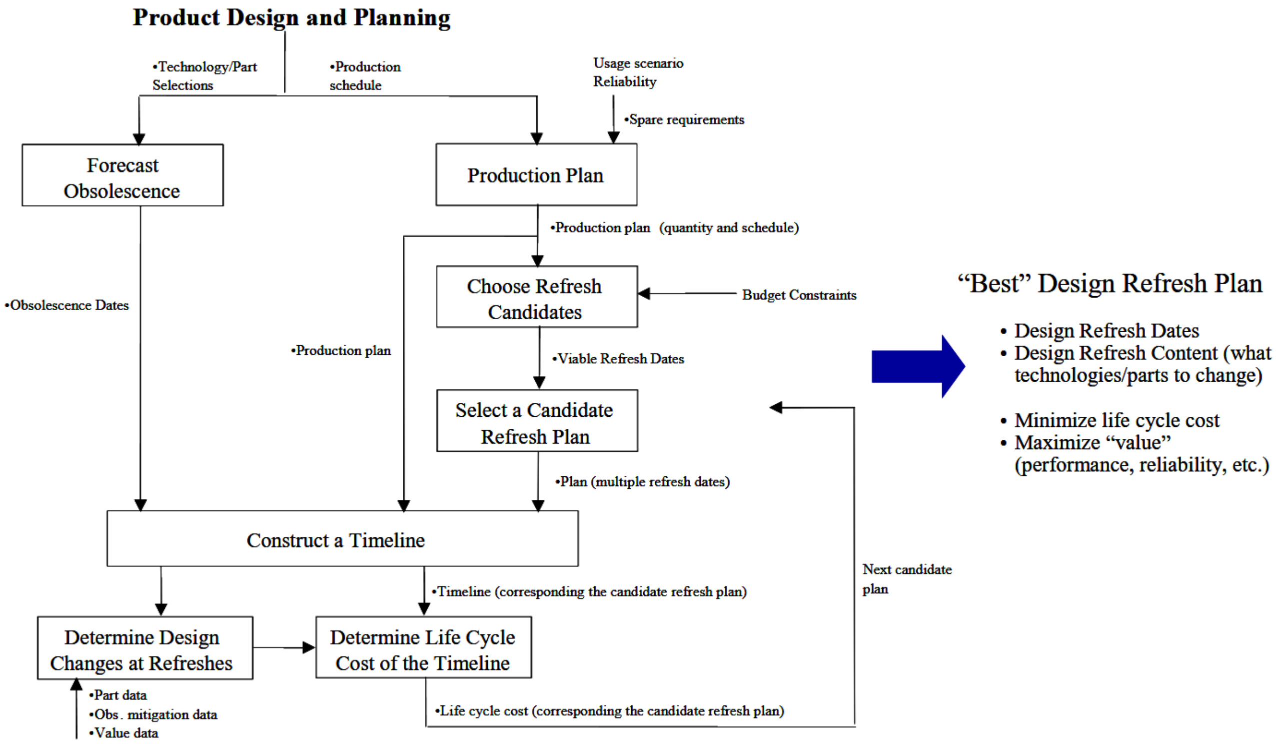


Figure 3.1: MOCA methodology for selecting optimal design refresh plans (Singh and Sandborn, 2006).

Within the model, lifecycle costs are estimated based on provided input data and the best design refresh periods are determined from the set of analysed candidates. Equation (3.2) shows how the lifecycle costs are determined for the MOCA methodology (Singh and Sandborn, 2006).

$$\text{Lifecycle Cost} = \sum_{i=1}^{n} \frac{Q_i C_i}{1 + R/100^{d_i}} + \sum_{j=1}^{r} \frac{NC_j}{1 + R/100^{d_j}} \tag{3.2}$$

The equation consists of the following parameters:

Q_i = Quantity of systems to be manufactured at manufacturing event i
C_i = Recurring costs of manufacturing a system instance at manufacturing event i
NC_j = Non-recurring cost of design refresh j
n = Number of manufacturing events
r = Number of design refreshes
R = Interest rate including percentage discount
d_i or d_j = Difference in years between event i or j and the net present value calculation date

In Equation (3.2), the values of parameter C_i in the first term and NC_j in the second term are based upon sub-equations (Singh and Sandborn, 2006). C_i depends on the procurement costs of all parts in the system, which can be modified based on the manufacturing date. The non-recurring design refresh costs NC_j consists of fixed (e.g. re-qualification cost) and variable costs, which depend on the boards and components included in redesigns.

The model has to make a trade-off between the two factors of Equation (3.2). Whenever items turn obsolete, the procurement costs of these parts increase based on a modifier and hence C_i in the first term increases. All r redesigns involve non-recurring engineering costs. The procurement costs of items within the redesigns decreases after the redesign is finished, until the part turns obsolete again.

By calculating the life-cycle costs of multiple refresh plans, the optimum plan can be picked from the set of proposed plans in the MOCA methodology. Multiple parameters are uncertain upfront in the model. For example, redesign costs, component costs and EOL dates. Therefore, it is difficult to provide an accurate estimate upfront. In order to provide reliable insights for the life-cycle costs, Monte Carlo modelling is used to attain statistically significant results. In order to use MOCA methodology, a time step for the simulation is required. According to Singh and Sandborn (2006), using a time step of one year results in a reasonably accurate representation of the time scale on which OEMs of long field life systems operate.

Within the paper, several limitations of the model are discussed:

- Software obsolescence is not treated within the methodology. It focuses specifically on hardware obsolescence.
- Parts inventory is not taken into account. In practice, the effective obsolescence date can differ significantly from the last order date described by the manufacturer.
- The capabilities to forecast future obsolescence dates are limited.
- The model does not take into account functional obsolescence.

The main limitation for applying this methodology to the context of Thales is that part inventory is not taken into account and therefore the lifecycle costs do not include holding costs of inventory. The model makes a trade-off between initiating a redesign and allowing an item's cost price to increase, which happens when the item turns obsolete. In practice, Thales cannot always procure obsolete items at authorised aftermarket parties against a price increase and performs LTBs. An advantage of the MOCA methodology is that it can be used during the original product design process as well as during the system sustainment phase.

3.1.3 The strategic proactive obsolescence management model

Meng et al. (2014) have formulated the strategic proactive obsolescence management model. This model optimises component LTB quantities in combination with redesigns at spare part level. The model makes the following decisions: The LTB quantities of components, the components which should be included in the redesigns and the redesign dates of spare parts. The formulated model is deterministic and does not consider data uncertainties. Based on graph theory - which model pairwise relations between objects - a mixed integer linear program is formulated and optimal decisions are selected which minimise obsolescence costs (Meng et al., 2014). A shortcoming of the research is that failure data is assumed to be deterministic, which is unfortunately not the case in practice at Thales as we have concluded in Section 2.6. Another limitation of the research is that redesign dates are optimised by including several components within redesigns, therefor reducing the redesign costs in comparison to redesigning one component at a time. Unfortunately, it is hard to determine the redesign impact for a combination of different components upfront, as stated by design experts of Thales. Therefore, the fundamental assumption in the model that redesign costs are a summation of the redesign costs per component plus the costs for prototype preparation and system qualification does not hold in practice.

3.2 Obsolescence costing

Romero Rojo et al. (2009a) identified the need for a cost model to estimate the total costs for mitigating and solving obsolescence issues. This model should be capable of making accurate cost predictions even when information (e.g. obsolescence predictions of a monitoring tool) is not in place yet. This section describes cost metrics available for obsolescence resolutions applied for components and outlines how a reliable cost estimate is constructed.

3.2.1 Cost metrics

According to Romero Rojo et al. (2009b), a major challenge for the estimation of costs related to obsolescence is the development of cost metrics. Moreover, Rojo (2011) concluded that no existing cost estimation models take into account the cost related to obsolescence. Both the Department of Defence (DoD) in the USA and the Ministry of Defence (MoD) in the UK commissioned external firms (Defense MicroElectronics Activity; QinetiQ and ARINC) to develop cost factors for obsolescence resolutions. The developed cost metrics by these departments are depicted in Figure 3.2. The figure shows significant cost differences for aftermarket options and emulation.

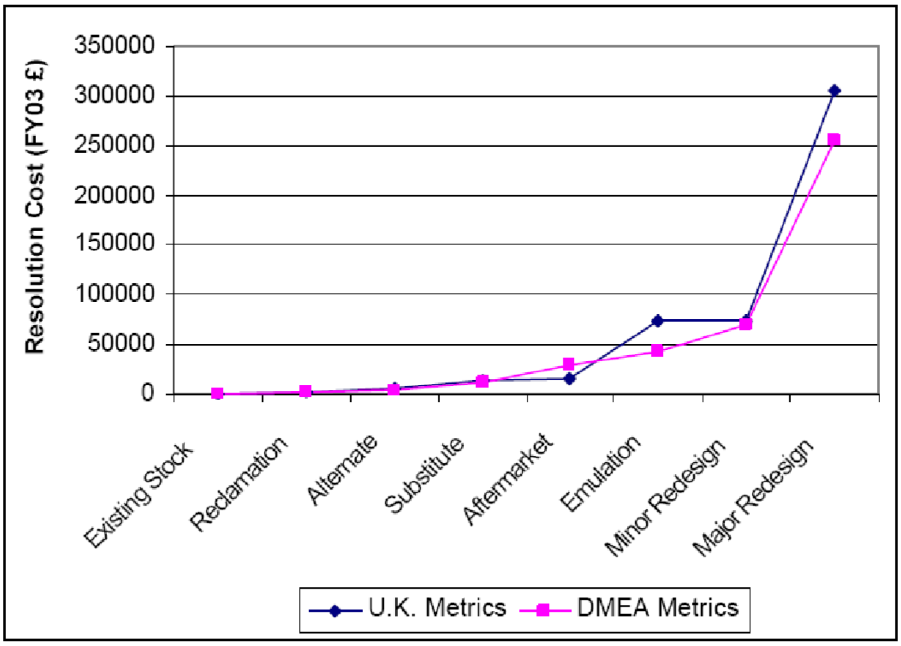


Figure 3.2: UK versus DMEA resolution cost metrics (Romero Rojo et al., 2011).

Romero Rojo et al. (2011) created a framework that can be used at the bidding stage of support contracts to estimate the obsolescence non-recurring engineering cost. This framework tried to overcome the outlined limitations of the cost metrics developed by the MoD an DoD. This framework acknowledges that previously developed cost factors lack practicality and has been set up by using input from industry experts. Based on industry consensus, cost metrics were established for all obsolescence resolution strategies also used at Thales (see Section 2.3). The cost metrics were created for components resolution specifically. Four cost factors are determined which alter the non-recurring engineering costs of resolving obsolescence issues (e.g. requalification cost).

Several limitations exist when using the framework for the situation at Thales. First, Romero Rojo et al. (2011) solve obsolescence problems at component level and not at product or assembly level. Second, the framework makes assumptions which are not applicable for the research at

Thales. For example, any component is expected to not become obsolete more than once during the contracted period and the consumption rate of spare parts is assumed to be deterministic. Third, the framework does not use any optimisation about what obsolescence resolution to use, but determines this based on past data and expert opinion.

3.2.2 Cost estimation process

Rojo (2011) states cost estimating aims to predict future costs of resources, methods and management, based on historical data and experience. However, the process of making accurate estimates can be difficult. Challenges to develop reliable cost estimates are listed (U.S. Government Accountability Office, 2020):

- Lack of historical data (especially for new processes or cutting edge technology)
- Lack of experience by the cost analyst
- Failing to recognise uncertainty and risks
- Restricted time for preparing estimates

In order to accurately estimate costs, either qualitative or quantitative techniques can be used. Qualitative techniques are based on either expert judgement or analogy-based reasoning (e.g. similar products have similar costs as those in the past). In practice, expert judgement is often used at the bidding stage for obsolescence costing, since organisations in defence usually do not have the required data to use other techniques at the bidding stage (Rojo, 2011). Section 2.5.4 showed this was also the case at Thales for the established PBL contract. U.S. Government Accountability Office (2020) state expert judgement is generally considered too subjective but can be useful in the absence of data.

An example of a quantitative technique is bottom-up costing. This method makes detailed estimates for every activity in the work breakdown structure and summarises them to provide a total cost estimate. This method requires a large amount of specific data and is time costly. In industry, this technique is often preferred since it ensures higher levels of accuracy over other techniques (Rojo, 2011). Moreover, the technique is especially applicable in the bidding phase.

U.S. Government Accountability Office (2020) states that a reliable cost estimate meets the following four characteristics:

- Comprehensive: This makes sure all cost elements are neither omitted nor double-counted.
- Well-documented: This allows cost estimates to be easily repeated or updated.
- Accurate: By estimating each cost element using the best methodology from the data collected and validating inputs, accurate cost estimates are developed.
- Credible: Any limitations of the analysis are discussed and documented. Parameters in major assumptions are varied to determine how sensitive it is to changes and a risk and uncertainty analysis should be included to determine the level of confidence associated with the estimate.

Similar characteristics are mentioned by Goh et al. (2010)

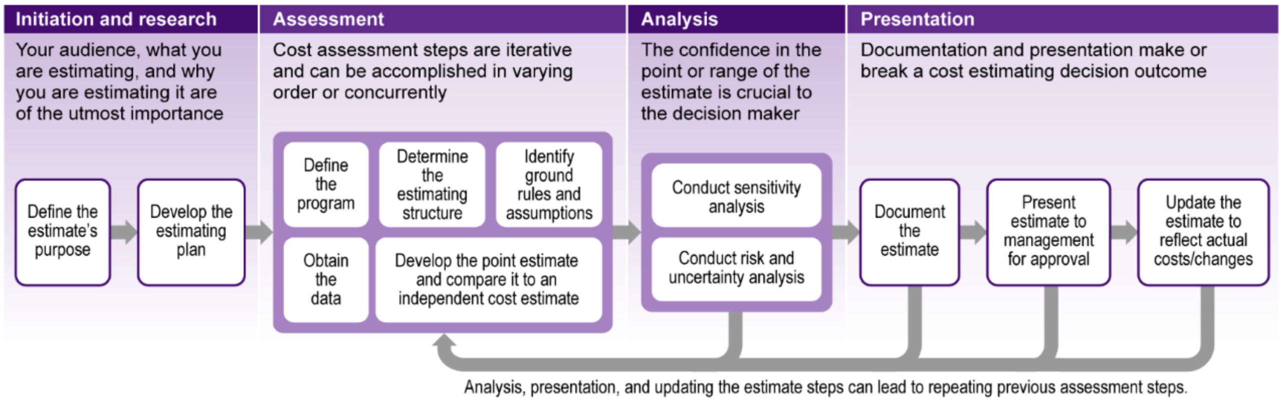


Figure 3.3: The 12 step cost estimating process (U.S. Government Accountability Office, 2020).

U.S. Government Accountability Office (2020) has defined a 12 step process to estimate costs. Figure 3.3 shows an overview of the process. We shortly discuss the steps in the analysis phase: Sensitivity and uncertainty analyses. These are crucial in situations where data is uncertain and limited, which is one of the conclusions drawn in Section 2.6.

3.2.3 Modeling with data uncertainty

Within a sensitivity analysis, estimates are recalculated by changing quantitative values for selected inputs. Factors that affect the cost estimate the most should be carefully investigated to ensure best possible values are used. When the cost estimate is sensitive to several factors, the estimate's input values and assumptions should be reviewed (U.S. Government Accountability Office, 2020).

One parameter which certainly needs a sensitivity analysis for the case of Thales are the inventory holding costs. Holding costs are estimated as a percentage of the cost of a product (Chopra and Meindl, 2016). Since this parameter is unknown internally, literature has been reviewed to determine the holding costs for obsolescence inventory. The following factors make up the holding costs of inventory (Chopra and Meindl, 2016; Durlinger, 2013):

- Cost of space / occupancy costs
- Cost of capital: The weighted-average cost of capital (WACC) can be used for this
- Miscellaneous costs: Costs related to theft, security and insurances
- Obsolescence costs: Determines the rate at which the value of the stored product drops
- Handling cost: The employee and administration costs of receiving and handling the products

For this research specifically, obsolescence costs and handling costs are not applicable. Obsolescence costs are taken into account separately in the research and handling costs are mainly applicable for fast moving items. The three other factors which make up the holding costs have been identified for the situation at Thales in cooperation with the responsible industrial controller and a cost manager.

Uncertainty can be classified into two types which is widely accepted in engineering verification and validation: epistemic and aleatory uncertainty (Goh et al., 2010). Epistemic uncertainty is caused by the lack of knowledge about the true value of a parameter or the behavior of a system and can be reduced by more accurate measurements or expert judgment (e.g. redesign costs, period until an item turns obsolete after redesign). Aleatory uncertainty is inherent variability that cannot be reduced by further measurement, although better sampling can improve knowledge about the variability (e.g. MTBF data).

Within an uncertainty analysis, cost elements and other parameters which are uncertain are assigned probability distributions or possible values. U.S. Government Accountability Office (2020) states that a wide variety of probability distributions are available for modeling cost risk and uncertainty. The most common distribution types which are deemed applicable for the situation at Thales are the normal distribution and the triangular distribution. Goh et al. (2010) mention that triangular distributions are applicable when data is based on expert opinion.

A Monte Carlo simulation can then be used to find a distribution for the resulting total costs based on all uncertain input data. Singh and Sandborn (2006) identified that two different types of uncertainties have to be managed for obsolescence costing: Cost analysis inputs and obsolescence dates. The last type is hardest to manage for the MOCA methodology, since LRU redesigns depend on obsolescence dates and LTBs of dozens of components.

3.3 Conclusion

Within this chapter, methods for analysing and modeling obsolescence costs have been reviewed. Moreover, literature on dealing with data uncertainty at the bidding stage of a contract has been inspected. We conclude the following based on the reviewed literature:

- Most optimisation models for the obsolescence resolution process focus on component level. The MOCA methodology focuses on product level and optimises obsolescence resolution decisions to minimise lifecycle costs. The main limitations of the methodology for our research is that part inventory is not taken into account. We decide to use the timeline of how events are managed in the MOCA methodology in the remainder of this research. This timeline makes sure that during the whole contracted period, obsolescence issues are resolved. Equation (3.2) which is used to determine the total lifecycle costs and determine the optimal design refresh plan will be altered to calculate the total obsolescence management costs.

- The models of Romero Rojo et al. (2011) and Meng et al. (2014) require extensive information at component level and are therefore considered too detailed to fully implement for this research, which focuses on system level costing. Moreover, the framework of Romero Rojo et al. (2011) does not provide any optimisation on obsolescence resolution, which is desired by Thales during the bidding stage.

- We note that no model in literature takes into account that LRUs can be used in multiple products (which do not have to be part of a PBL contract), which is the case at Thales for most LRUs with expensive redesigns. Hence, a solution should be introduced which distributes the costs of redesigns in the remainder of the research.

- Due to the uncertain nature of data used for obsolescence costing (Romero Rojo et al., 2011; Singh and Sandborn, 2006), the resulting cost estimate will take the form of a probability distribution function, which follows from Monte Carlo simulation. Singh and Sandborn (2006) state that two different types of uncertainties have to be managed for obsolescence costings: cost analysis input and obsolescence dates. A triangular distribution - which is based on expert opinion - can be used for these uncertainties in case no data is available.

4 Model formulation

This chapter addresses the following research question:

> *"How can a model for obsolescence management costs at product level be constructed for Thales?"*

Chapter 2 concluded that the current obsolescence resolution process does not make an optimal trade-off for expensive obsolescence resolutions (LTBs, redesigns and AMBs). This is caused by the absence of product roadmaps, as well as the policy to perform an LTB for ten years in case no roadmap is available (for electronic items specifically). Chapter 3 concluded that in the remainder of the research, we choose to use the timeline used by the MOCA methodology. This makes sure obsolescence issues are resolved when they arise by using obsolescence resolution strategies. This chapter is structured as follows:

- Section 4.1 provides an outline of the model and discusses its objectives
- Section 4.2 describes the implemented decision policies, which determine how obsolescence resolution decisions are made within the model
- Section 4.3 lists the assumptions and simplifications of the model
- Section 4.4 describes the parameters, variables and equations used within the model
- Section 4.5 gives conclusions about the constructed model for managing obsolescence costs at product level for Thales

4.1 Model outline

The goal of this research is to provide insights into the obsolescence management costs for a system's lifecycle during a predetermined period. This is done specifically for systems sold within a PBL contract, where Thales is responsible for the operationability of the systems. By using the model formulated in this chapter, Thales gains insights in the obsolescence resolution costs of all LRUs within a radar system. The formulated model implements obsolescence resolution decision for LRUs during the contracted period. Based on the resolutions implemented for various LRUs, obsolescence management costs can be determined for an example scenario that can occur in practice.

The tool in which the model is implemented is used to determine obsolescence management costs at product level. These costs can be split in two different parts: First, obsolescence monitoring costs are incurred for the products within the contract. These costs are independent of the decisions made for obsolescence resolutions and are general labour costs for obsolescence scans, risk assessment and configuration management. Monitoring costs also include costs when an equivalent or alternative component is introduced (e.g. an integrated circuit within a PCB can still be purchased at another supplier). These two obsolescence resolutions at component level are consequently taken into account in the obsolescence monitoring costs, since they are always implemented in practice.

Second, obsolescence resolution costs are incurred in the model. For every LRU within the product, an obsolescence resolution has to be implemented when the item turns obsolete. This can be an LTB, redesign or AMB. The obsolescence resolutions to implement are the decision variables in the model.

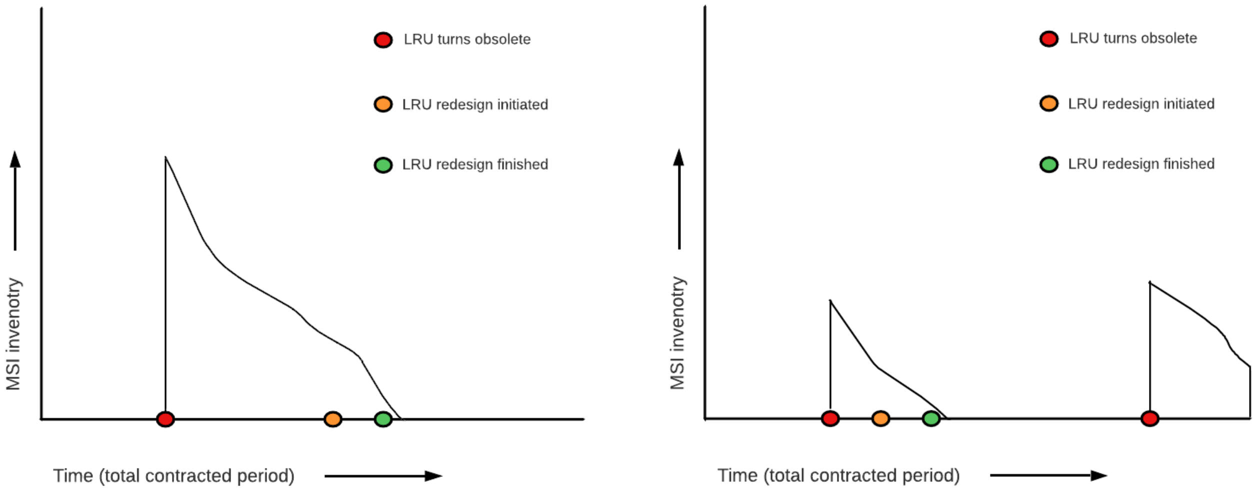
The obsolescence resolution decisions made for various LRUs are independent. Therefore, the formulated model is LRU specific. Within the tool, the formulated model is solved for all LRUs within a product and the obsolescence monitoring costs for the product are manually added afterwards. Equation (4.1) shows how the formulated model - which determines obsolescence resolution costs for an LRU - is used to determine the obsolescence management costs at product level.

$$\text{Obsolescence management costs} = T \cdot c_m + \sum_{i=1}^{I} c_{res,i} \tag{4.1}$$

Where:

T = The number of time intervals in the PBL contract
I = The number of LRUs within the product
c_m = The monitoring costs per time interval for the product
$c_{res,i}$ = The resolution costs for LRU i for all time intervals in T

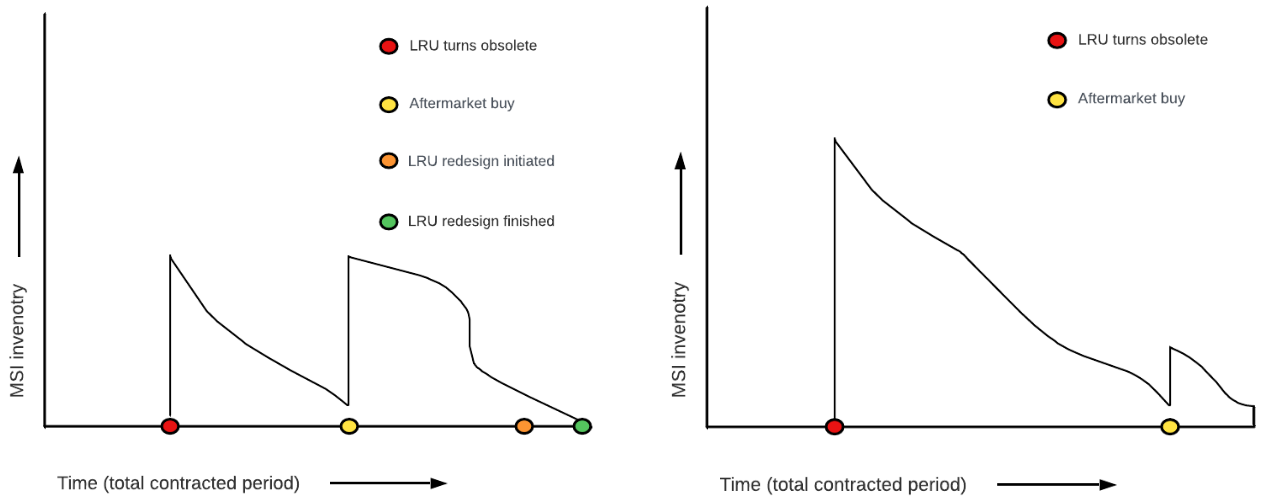
Figure 4.1 shows how different obsolescence resolution decision can be made. When an LRU turns obsolete, an LTB is usually performed. Within Figure 4.1a, a larger LTB quantity is performed compared to Figure 4.1b. Therefore, the total holding costs for this solution are higher. In Figure 4.1b, an additional LTB has to be performed however, since the LRU has turned obsolete a second time. The inventory levels depicted within Figure 4.1 are specifically for obsolescence. In practice, inventory is present before the LRU turns obsolete as well. However, the holding costs for that inventory is not part of the obsolescence management costs.



(a) LTB and redesign strategy (b) LTB and redesign strategy

Figure 4.1: Examples of decisions regarding the LTB and redesign strategy

Figure 4.2 shows that additional decisions can be made in case the authorised aftermarket is included as an obsolescence resolution option. Figure 4.2a shows that an AMB is performed next to an LTB. This brings additional purchase costs, but holding costs can be lowered in comparison to performing one large LTB when the LRU turns obsolete. Figure 4.2b shows that aftermarket buys can even mitigate redesigns altogether during the total contracted period. When AMBs are introduced as an obsolescence resolution strategy on top of LTBs and redesigns, cost savings can be made. For example, performing an AMB near the end of the contracted period can prevent the initiation of an expensive redesign.



(a) LTB, redesign and AMB strategy (b) LTB and AMB strategy

Figure 4.2: Examples of decisions regarding the LTB, redesign and AMB strategy

Outcomes of the model are partly based on the stochastic and uncertain nature of the described system and partly based on the choices by the decision maker. Therefore, the model can be classified as a Markov decision process (MDP) (Puterman, 1994). For MDPs with smaller state spaces, stochastic dynamic programming can be used to model the probability of being in a specific state based on the decisions and state variables in the previous stage via transition probabilities. By using stochastic dynamic programming, optimal decisions can be made which minimise the expected costs. However, since the state space of the formulated model is large, this is undesired for this research, as the run-time of such a program explodes.

Within the model, Monte Carlo simulation is used to take samples from the probability distributions of uncertain parameters and variables. Due to the complexity of the model, decision made within the model are based on decision policies, which are explained in Section 4.2.

4.2 Decision policies

The previous section describes that the formulated model has a large state space. Moreover, Section 4.4 shows the model is non-linear. Solving the formulated model using stochastic dynamic programming is therefore not desired, as the computational efforts are too high. Within this research, various decision policies are implemented to make obsolescence resolution decisions for an obsolete LRU, which are described in this section. The policies determine when a redesign is initiated and when an LTB / AMB is performed.

Within this research, five different policies can be selected to make obsolescence resolution decisions:

1. The current policy: For electronic items turning obsolete, a last time buy is performed until the end of the contracted period. In this way, redesigns for electronic items are mitigated. For mechanical items, a redesign is initiated and a last time buy is performed for the redesign lead time.
2. Performing LTBs: For all items turning obsolete, a last time buy is performed. This makes sure redesigns do not have to be performed.

3. Initiating a redesign: For all items turning obsolete, a redesign is initiated in combination with a last time buy for the redesign lead time. When using this resolution, holding costs are low.

4. Suggested policy 1: In case multiple obsolescence resolutions could be implemented, a heuristic is used to determine what obsolescence resolutions to implement. This heuristic analyses the costs of several resolutions based on expected parameter values. The resolution resulting in the lowest yearly costs is then implemented.

5. Suggested policy 2: Similarly to suggested policy 1, this policy determines what resolution to implement based on a heuristic in case a trade-off can be made. This policy analyses a different subset of possible resolutions compared to suggested policy 1 and analyses the costs for the remaining contracted period.

For each of these policies, a logic flowchart is provided which shows how the policy works. Moreover, we provide example output of the simulation model for the two simple policies and give more detailed explanation on the two suggested policies in Appendices C and D.

4.2.1 Current policy

For the current obsolescence resolution process for LRUs in the PBL contract at Thales, a simplified logic flowchart is created which is displayed in Figure 4.3. This shows how decisions are generally made for LRUs being obsolete at the start of a period. For electronic LRUs, an LTB for the remaining life time is usually performed in practice. When LTB stock is unable to meet the expected demand during the redesign lead time + 1 period, an AMB or redesign is performed.

For mechanical LRUs, a redesign is usually initiated instantly when an item turns obsolete. This differs from the decision for electronic LRUs, since mechanical items are usually cheap to redesign. Moreover, an LTB is performed to cover demand with 99% certainty during the redesign lead time. Demand during lead time can be uncertain for both mechanical and electronic items and is further explained in Section 4.4.8.

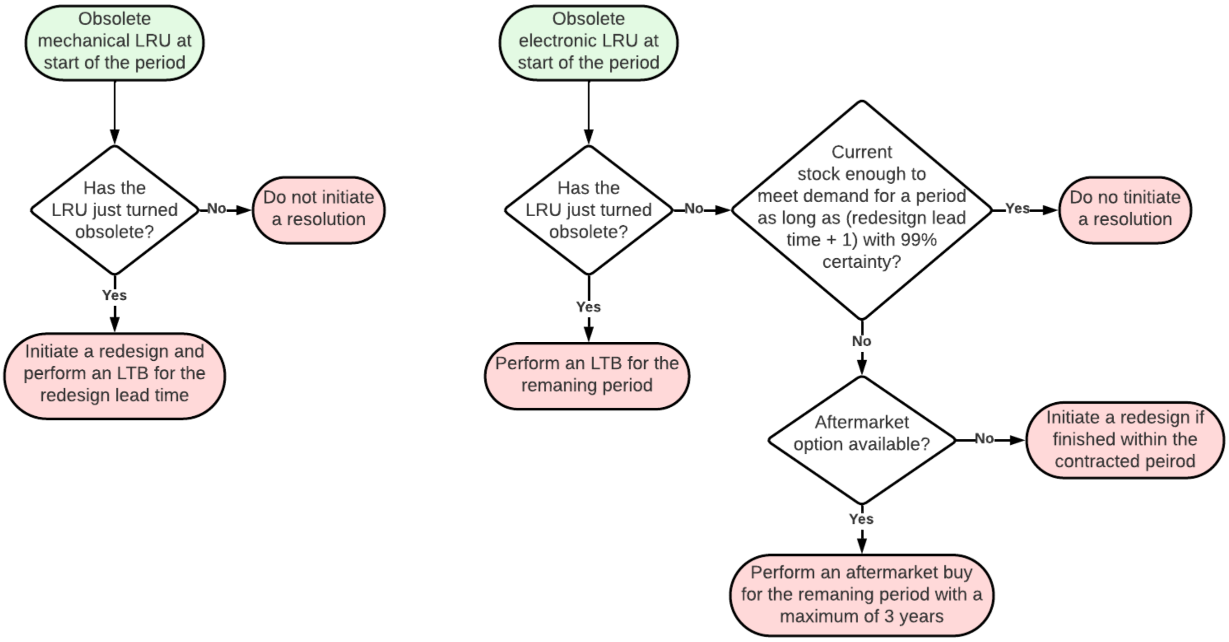


Figure 4.3: Logic flowchart for the current obsolescence resolution process

4.2.2 Simple policies

Next to the current policy, we chose to implement two simple policies within the model to make decision for the obsolescence resolution process: Performing an LTB for the remaining contracted period and always initiating a redesign. These two policies are illogical to use for some LRUs within radar systems of Thales. For example, if an LRU redesign is expensive and an LTB is cheap, it is undesired to initiate a redesign. However, we chose to implement these policies in the model for the following reasons: First, it shows that carefully selecting which obsolescence resolution to implement for obsolete LRUs results in significant cost reductions when determining obsolescence management costs within a PBL contract. Second, the policies can be used to quickly compare their results with the results of other policies. This allows obsolescence managers of Thales to quickly analyse simple policies which improves the model's utility. Explanation of these policies are provided below.

Simple policy 1: Performing LTBs
For the first simple policy, an LTB is performed for the remaining period within the contract in case an item turns obsolete, as displayed by the logic flowchart in Figure 4.4. When an LTB is performed, no other resolution is implemented for the remaining periods, even if the LTB quantity turns out to not be enough. For this policy, an example of expected output within the simulation model is provided in Figure 4.5. This shows an LTB is performed for the remaining six years within the contract.

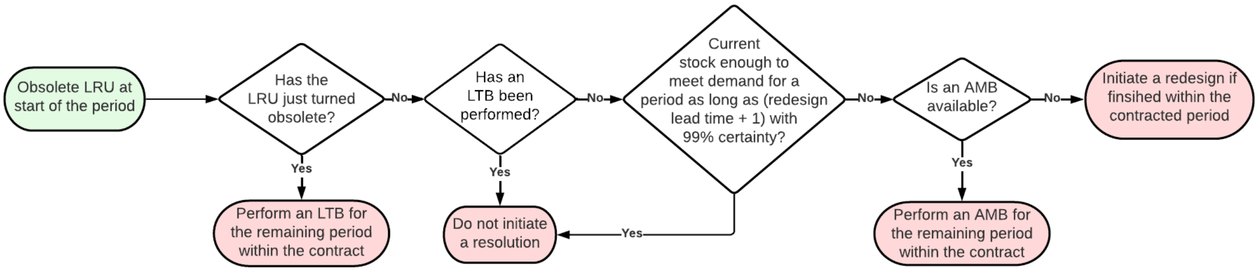


Figure 4.4: Logic flowchart for performing an LTB for the remaining period in the contract in case an item turns obsolete

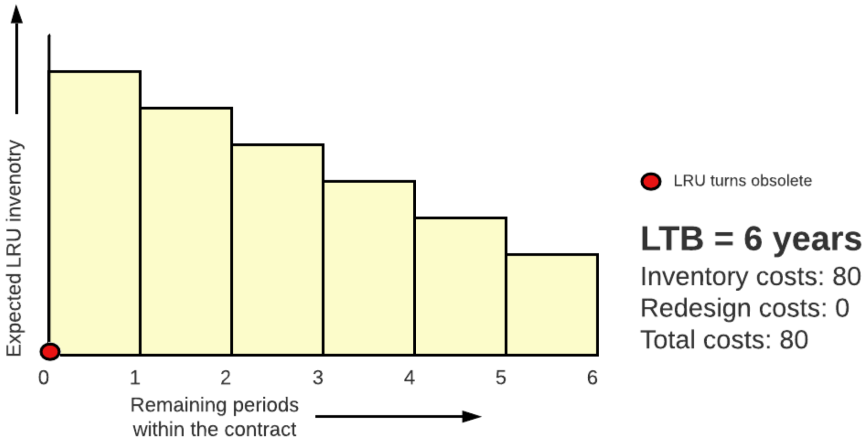


Figure 4.5: Example of simulation output when performing an LTB for the remaining contracted period

Simple policy 2: Initiating a redesign
For the second simple policy, Figure 4.6 shows that a redesign is instantly initiated in case an LRU turns obsolete. Moreover, an LTB is performed to cover demand during the redesign lead time. An example of simulation output of this policy is provided in Figure 4.7.

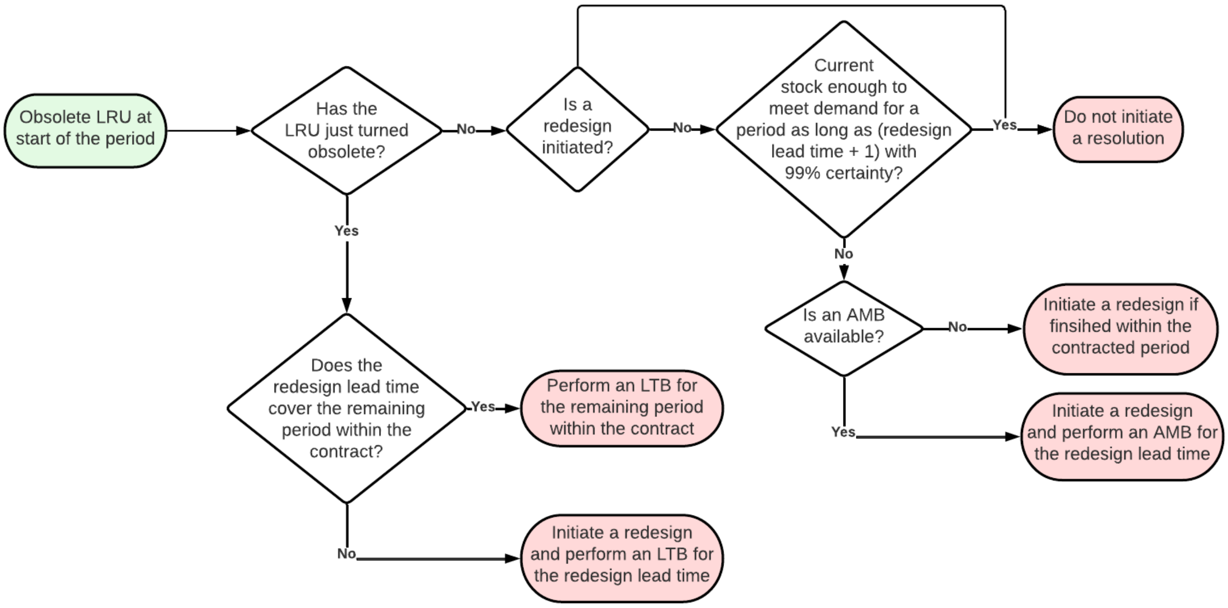


Figure 4.6: Logic flowchart for instantly performing a redesign in case an item turns obsolete

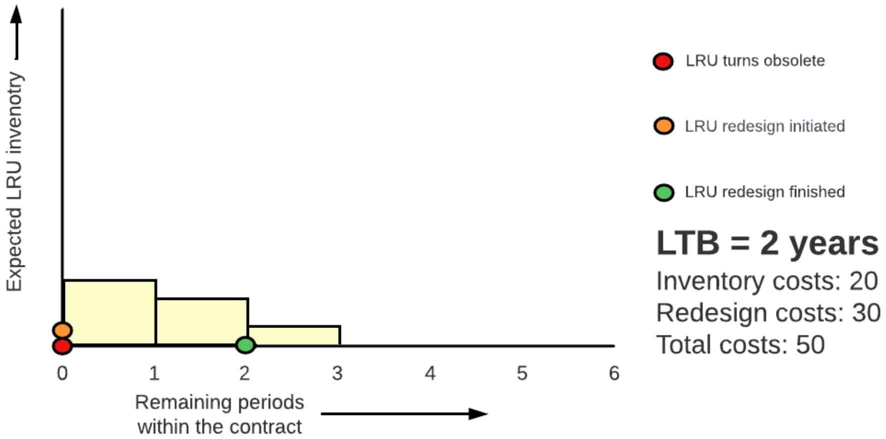


Figure 4.7: Example of simulation output when performing an LTB for the redesign lead time and initiating a redesign

4.2.3 Suggested policies

This subsection provides two additional policies, which we argue to be more logical for Thales to use when determining obsolescence management costs within PBL contracts. The policies make a trade-off between the costs of different obsolescence resolutions and make decisions based on these. With these policies, we expect to reduce obsolescence management costs in comparison to the first three policies. The logic flow diagram for both suggested policies is similar for the most part, with the exceptions of the heuristics in the red frames.

Suggested policy 1

Figure 4.8 gives a logic flowchart of the first suggested policy. Explanation of the part outside the red frame is provided first: Whenever an LRU just turned obsolete and a redesign can still be finished within the contracted period, a heuristic is used to determine which obsolescence resolutions to implement. When a redesign cannot be finished within time, an LTB is automatically performed. In case the LRU was obsolete the previous period as well, no LTB can be performed. Therefore, the algorithm enters the box *"Is a redesign initiated?"*. The algorithm only initiates a resolution in case no redesign is initiated and the current stock level is not enough to meet future demand with 99% certainty. If no AMB is available, a redesign is initiated. If an AMB is available, the heuristic is used to determine what obsolescence resolution is smart to implement.

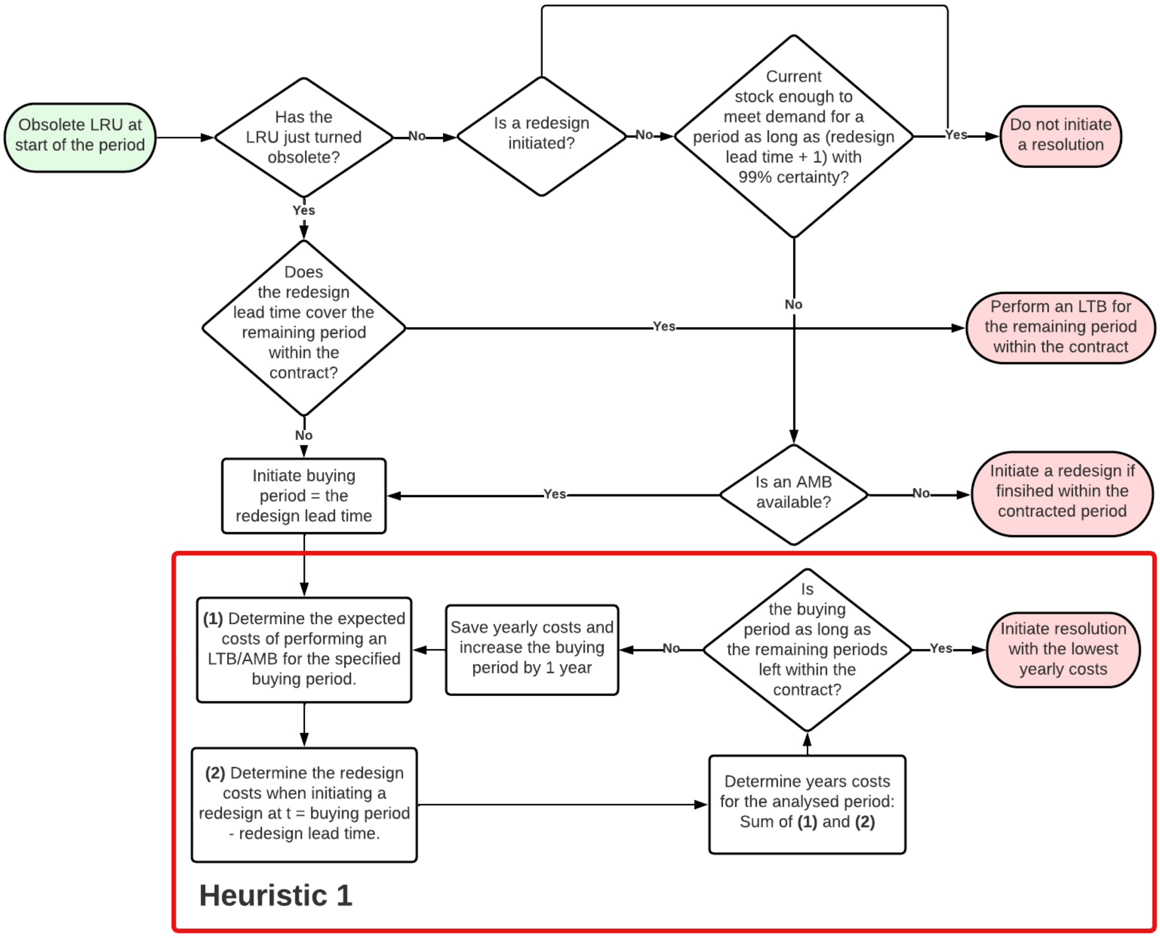


Figure 4.8: Logic flowchart of suggested policy 1

Within Heuristic 1, a trade-off is made between the costs of LTBs / AMBs and redesigns. The logic behind the heuristic is as follows: LTBs / AMBs likely become more expensive per period when they are performed for a longer time span, since the average inventory level likely increases when LTBs/ AMBs are performed for longer periods. This heuristic calculates the costs of performing an LTB / AMB for a specified buying period based on expected parameter values. This is shown by box **(1)**. Moreover, a redesign is initiated when expected to be necessary and these costs are determined, as shown in box **(2)**. The expected yearly costs of solving obsolescence by performing an LTB / AMB for the specified buying period, followed by a redesign are calculated in this manner. Within the heuristic, performing an LTB / AMB is analysed for several buying periods: For the redesign lead time up until the remaining periods within the contract. Based on this, the obsolescence resolutions with the lowest expected yearly costs are initiated. The logic this heuristic incorporates, is that by performing an LTB / AMB for one more period, a redesign can be postponed one period as well, which might be more cost-effective.

In short, this heuristic determines the obsolescence resolution costs of performing an LTB / AMB for a certain buying period in combination with a redesign, based on the expected values of stochastic parameters and variables (Section 4.4), which are: spare part demand coming from failures ($D(IB + PBL)_t$), redesign costs (c_r) and the available period after a redesign is finished (EO). The iteration with the lowest yearly costs is implemented. For this iteration, an LTB / AMB will be performed for the specified buying period.

Appendix C provides an example calculation with the required formulas to gain a better understanding of the heuristic.

Suggested policy 2

The second suggested policy is the same as the first suggested policy, with the exception of the heuristic which is used within the red frame, as depicted in Figure 4.9. Within this policy, the obsolescence resolution costs for the remaining period of the contract are determined for performing an LTB / AMB (**1**), possibly followed by a redesign (**2**) and LTB (**3**). This heuristic assumes that only one redesign can be initiated during the remaining period within the contract. Therefore, in case the LRU is expected to turn obsolete again after an initiated redesign, the heuristic assumes an LTB has to be performed when determining the total costs within the heuristic. Within the model however, multiple redesigns can be initiated when using this policy, since the heuristic only looks at the number of redesigns for the remaining contracted period. When a redesign was already performed in a previous period, the heuristic does not take this into account and consequently multiple redesigns can be performed.

Boxes **(1)** and **(2)** are the same as in Heuristic 1. An additional one is required however: Box **(3)**, since an additional LTB is required in case the LRU is expected to turn obsolete for a second time within the contracted period.

In short, this heuristic determines the expected obsolescence resolution costs for the remaining period within the contract, based on different initial buying periods. Similarly to the first heuristic, expected values of uncertain parameters and variables are used. An example is provided within Appendix D for further clarification of the heuristic.

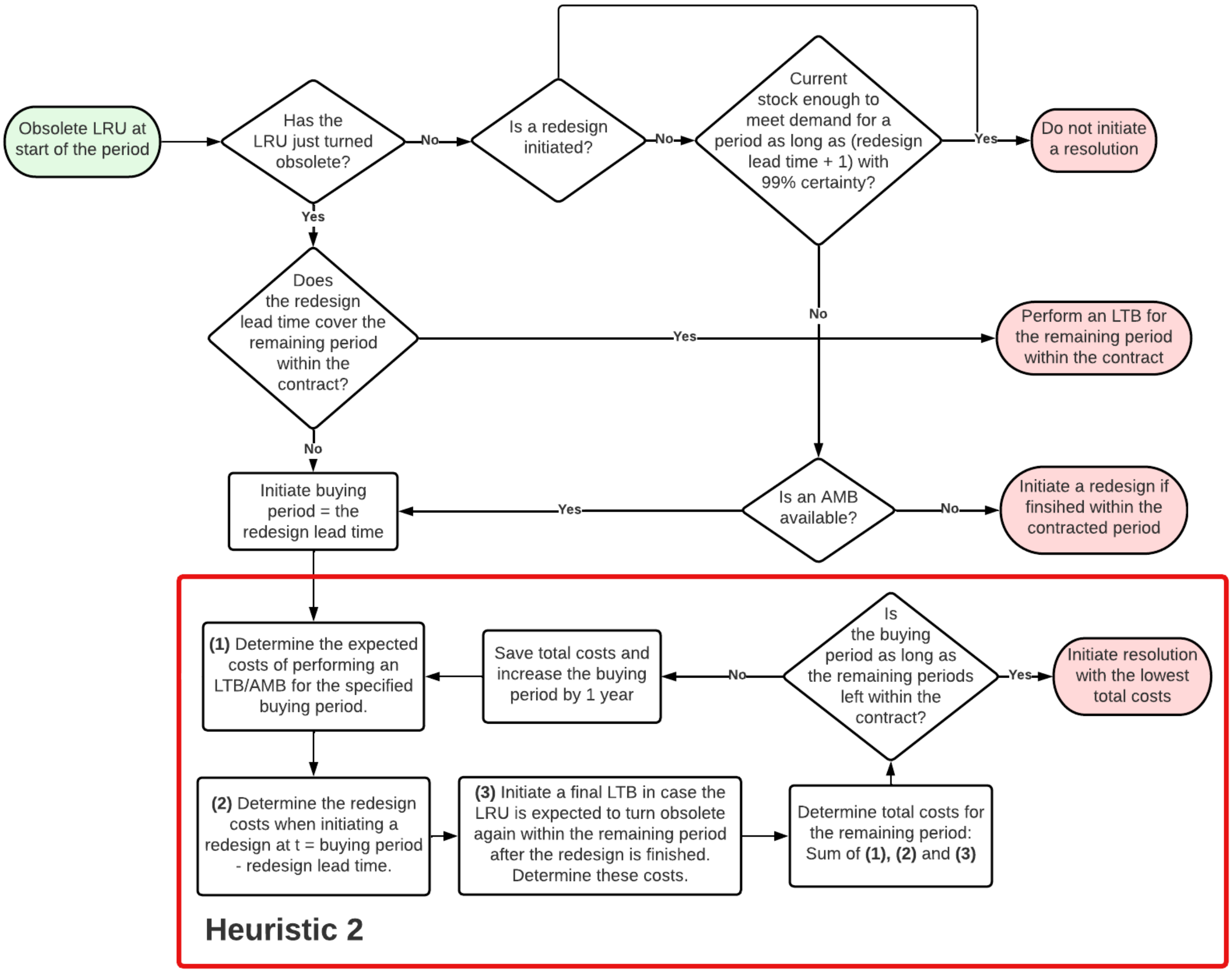


Figure 4.9: Logic flowchart of suggested policy 2

Limitations of Heuristic 1 and 2

The two heuristics which are used to determine which obsolescence resolutions to implement have several limitations:

1. Within both heuristics, uncertainty of parameters and variables is not taken into account when determining the expected resolution costs.

2. Within both heuristics, LTB / AMB quantities which can be procured are limited: The LTB and AMB quantities within box **(1)** and **(3)** of the heuristics are determined such that they are expected to be enough for the analysed buying period with 99% certainty. This certainty percentage is also currently used within Thales. For the formulated model, it might be optimal to use a different certainty percentage based on the input parameters of an LRU. For example, it is likely better to use a higher certainty percentage for LRUs with low holding costs and lower certainty percentages for LRUs with higher holding costs.

3. Both heuristics only analyse a limited combination of obsolescence resolutions to implement. Heuristic 1 only considers performing one LTB or AMB in combination with a redesign. Heuristic 2 also considers performing an additional LTB after a redesign. In

practice, more combinations of obsolescence resolutions are possible. For example, performing an LTB followed by an AMB a few periods later or initiating two redesigns in the remaining contracted period.

4. Heuristic 2 assumes a redesign can only be initiated once during the remaining period within the contract. For LRUs which turn obsolete relatively often and where performing a redesign is cheap, Heuristic 2 might perform an LTB or AMB for a longer period than optimal, since it assumes only 1 redesign can be initiated for the remaining contracted period. In practice it might be better to initiate a redesign multiple times.

4.3 Assumptions and simplifications

This subsection describes the assumptions and simplifications of the model compared to the real life situation:

1. **An EOL notice is always received before an item turns obsolete**. This assumption makes sure an LTB can be performed in case an item turns obsolete. In practice, components (and even some LRUs) might turn obsolete and no notification is received through an obsolescence scans or supplier. For components and items where this happens, an FFF replacement can generally be found or there are aftermarket possibilities.
2. **An LRU within the installed base is active for 20 years**. This assumption is used to update the installed base of an LRU. Whenever a radar system is sold, it remains active for 20 years at the customer site. Afterwards, the LRU is likely disposed.
3. **LRUs receiving preventive maintenance do not require corrective maintenance**. The likelihood of these items requiring corrective maintenance is significantly low to be negligible, according to experts within Thales. An example of such an item is a fan.
4. **The number of failed electronic LRUs (receiving corrective maintenance) within a period follow from a Poisson distribution**. This means that the memoryless property holds for the inter arrival times of failed LRUs, which is suitable for electronic items. The expected inter arrival time is based on the MTBF of an LRU.
5. **The unit and material costs of redesigned items are the same as the old version of an item**. In practice these costs might differ, but in general the costs are similar and therefore the differences are neglected in the model.
6. **A minimum order quantity (MOQ) is only used for buy items**. For make items, only component LTBs/AMBs have to be performed in practice and those MOQ values are considered non significant due to their low cost prices.
7. **The lead time for LTBs/AMBs is non significant**. In practice, it takes time for items to arrive after they are procured (e.g. 3 months). However, this is out of scope in this research, since lead time is dealt with by the logistics department before an item turns obsolete already.
8. **The redesign process can be initiated on request**. This assumption holds true for most LRUs, except for PCBs. Currently, there is limited capacity available at the design engineering department of Thales. As a consequence, redesigns might not be initiated immediately on request and other obsolescence resolutions might be required in practice.

9. **When an LRU breaks down and no obsolescence resolution is in place, penalty costs have to be paid**. In practice, for some LRUs the system might work in a degraded mode (e.g. 2 of the 3 batteries within a system must work to provide enough power) and therefore no obsolescence issues arise directly. The number of LRUs for which this is the case is low and failed LRUs are always replaced in practice.

10. **Components which are required to repair failed LRUs are always in stock and their costs are negligible**. For items that can be repaired successfully, a new component is required to substitute the broken one. In practice, it might be the case that a specific component is not in stock and obsolete when performing a repair, therefore making the repair impossible. Since holding costs are low for obsolete components procured for repairs, they are neglected in the model.

11. **Whenever an LRU turns obsolete, all underlying components within the item turn obsolete as well**. This assumption is true for LRU manufactured at subcontractors of Thales. For items being manufactured by Thales, this assumption is not true: For example, PCBs are manufactured by Thales themselves. Components within PCBs might turn obsolete, but when enough inventory stock is present the PCBs can still be manufactured. In practice, an LTB only has to be be performed for the obsolete components within the PCB. The model assumes once the PCB turns obsolete, an LTB has to be performed for all components. As a consequence, the model overestimates the inventory holding costs of items manufactured by Thales.

12. **Deterministic values are used for the redesign lead time and repair time frame**. In practice, the values for these parameters are uncertain. We chose to keep these parameter determenistic to decrease model complexity.

4.4 Parameters, variables and equations

In Section 2.4, parameters and characteristics which influence the obsolescence resolution decision are discussed. Based on this list, parameters have been included in the model. Some parameters and characteristics from Section 2.4 have been excluded from the model, since they are included in other parameters (e.g. redesign impact is included in redesign costs) or because they are not used in practice right now (RA).

4.4.1 Model index

$T =$ Set of time intervals within the PBL contract

4.4.2 Deterministic LRU parameters

EO = The expected number of periods the LRU is available after a redesign

MC = The material cost of the LRU

MP = The multiplicity of the LRU in the radar system

MOQ = The minimum order quantity of the LRU

SH = The maximum amount of years the LRU can be stored (shelf life)

EC = Indicates whether the LRU requires corrective maintenance for electronic components (0) or preventive maintenance for mechanical components (1)

RY = The repair yield of the LRU

RT = This indicates for how long enough knowledge is available at Thales or the supplier to perform repairs after the item turns obsolete (Repair time frame)

$MTBF$ = Indicates the MTBF of the LRU in hours (only used for electronic items)

PM = Indicates the preventive maintenance interval of the LRU in hours (only for mechanical LRUs)

I_0 = The stock level of the LRU at the start of time interval 0 reserved for the PBL contract being analysed

EF_t = The expected number of failures for the LRU per time interval for all radars in the PBL contract

$EF(T)_t$ = The expected number of failures for the LRU per time interval for all spares in the installed base (IB_t)
ES_t = The expected number of sales of the LRU during time interval t for newly sold products
IB_t = The installed base of the LRU at the start of period t (excluding the ones in the PBL contract)
OS_0 = The obsolescence status of the LRU in period 0 ($1 =$ *available*, $0 =$ *obsolete*)
OOS_0 = Indicates for how long the LRU is obsolete already at time interval 0 (only required if $OS_0 = 0$
RL = The redesign lead time of the LRU
AP = The amount of time intervals the LRU is available on the aftermarket after turning obsolete
AX_j = The absolute price increase on the aftermarket in case the LRU is obsolete for j periods
v_t = The distribution key used in period t to determine the fraction of redesign costs which have to be paid by the PBL contract. This value is determined via the equation explained in Appendix F.

4.4.3 Stochastic LRU parameters

O = The number of periods the LRU is available after a redesign. The value of this parameter is determined via a triangular distribution (Appendix E).
c_r = The total non-recurring engineering costs for a redesign of the LRU. The actual parameter value is determined via a triangular distribution again.

4.4.4 General model parameters

AH = The annual operating hours per radar system
n = The number of radar systems in the PBL contract
c_h = The holding costs expressed as a percentage of the material cost
c_p = Penalty costs per obsolete item which cannot be delivered from stock
c_d = The disposal costs when a spare part is not used for the PBL project

4.4.5 State variables

I_t = The stock level of the LRU at the start of time interval t reserved for the PBL project
BO_t = The number of backorders at the end of time interval t reserved for the PBL project
D_t = The demand of new LRUs from stock in time interval t for the PBL project
O_t = The number of periods the spare part is still available at the supplier from time t onwards
OS_t = The obsolescence status of the LRU at the start of time interval t (1 if available, 0 if obsolete)
F_t = The number of failed spare parts in time interval t for the PBL project
RP_t = Indicates whether repair capability is present for an LRU (1) or if a failed LRU is directly disposed (0) at time t
AM_t = The absolute price increase on the aftermarket in period t

4.4.6 Decision variables

$LTB_t =$ The LTB quantity of the LRU procured at the start of time interval t for the PBL project. An LTB can only be performed in case the LRU turned obsolete in period t.

$AMB_t =$ The quantity procured on the authorised aftermarket of the LRU at the start of time interval t for the PBL project. An AMB can only be performed in case the LRU turned obsolete before period t

$r_t =$ Indicates whether a redesign is initiated for the LRU at the start of period t (1) or not (0)

4.4.7 Model equations and constraints

Model objective

The model objective is to minimise LRU resolution costs. These are calculated via Equation (4.2):

$$\sum_{t=1}^{T} \big(\underbrace{I_t \cdot MC \cdot c_h}_{(1)} + \underbrace{AMB_t \cdot AM_t}_{(2)} + \underbrace{v_t \cdot r_t \cdot c_r}_{(3)} + \underbrace{BO_t \cdot c_p}_{(4)} \big) + \underbrace{I_{T+1} \cdot c_d}_{(5)} \tag{4.2}$$

The total costs can be split into five different cost factors:

1. Holding costs for inventory
2. Additional purchasing costs for items bought on the aftermarket
3. Redesign costs in case a redesign is initiated
4. Penalty costs in case an obsolete item has backorders
5. Disposal costs for inventory at the end of the contract

4.4.8 Updating parameters and state variables

The model consists of various parameters and state variables. Values of state variables depend on the simulation run and decision policy implemented. The equations used to update parameters and state variables are explained in this subsection.

Installed base

In order to use the distribution key (v_t) explained in Appendix F, the value of the installed base has to be known and is updated as shown in Equation (4.3). We assume that an LRU within the installed base is active for 20 years on average and is disposed afterwards. Hence, the installed base lowers by factor $\frac{1}{20}$ of IB_0 for the first 20 years and increases by the expected sales made in previous years. After 20 years, the installed base can simply be updated by subtracting LRUs which are sold exactly 20 years ago and increasing it with LRUs sold in period t.

$$IB_t = \begin{cases} \sum_{j=0}^{t} ES_j + \left\lceil IB_0 - \frac{min(t,20) \cdot IB_0}{20} \right\rceil, \text{ if } 1 \leq t \leq 20 \\ IB_{t-1} + ES_t - ES_{t-20}, \text{ if } t > 20 \end{cases} \tag{4.3}$$

Inventory and backorders

Equation (4.4) shows how item inventory is updated within the model. I_t indicates the inventory level at the start of period t. To determine the inventory level, demand from the previous period is deducted (D_{t-1}). This demand is based on a random process as calculated in Equation (4.11). We note that inventory can only be positive. When an item turned obsolete in period t, an LTB can be performed. Demand from period $t-1$ should not be satisfied by an LTB performed in period t, since this demand arose when the item was still available and not obsolete. Next, an AMB can only be performed in case the item was obsolete in the previous period as well. In case an AMB is performed, this quantity can satisfy demand from the previous period as well. In case an item is available in period t, no AMB or LTB is performed and obsolescence inventory can only decline.

Besides the inventory level at the start of period t, backorders are also included in the model. BO_t indicate the number of backorders at the end of period t, as demand from the current period is deducted. Whenever no inventory is available for LRU demand, it is placed as a backorder, as indicated by Equation (4.5). Penalty costs are included in the model for backorders.

$$I_t = \begin{cases} \Big(I_{t-1} - D_{t-1}\Big)^+ + LTB_t, \text{ if } OS_{t-1} = 1 \;\&\; OS_t = 0 \\ \Big(I_{t-1} - D_{t-1} + AMB_t\Big)^+, \text{ if } OS_{t-1} = 0 \;\&\; OS_t = 0 \\ \Big(I_{t-1} - D_{t-1}\Big)^+, \text{ if } OS_t = 1 \end{cases} \quad \forall\, t > 0 \tag{4.4}$$

$$BO_t = \Big(D_t - I_t\Big)^+ \cdot \Big(1 - OS_t\Big) \quad \forall\, t > 0 \tag{4.5}$$

Spare part failures

Equations (4.6) and (4.7) shows how the expected number of failed spare parts is determined for the installed base and PBL contract respectively for electronic items. Equation (4.8) shows how the actual number of failed spare parts F_t is based on a poisson distribution and is therefore uncertain.

$$EF(T)_t = \frac{AH \cdot IB_t}{MTBF} \quad \forall\, t, \text{ if } EC = 0 \tag{4.6}$$

$$EF = \frac{AH \cdot MP \cdot n}{MTBF} \quad \forall\, t, \text{ if } EC = 0 \tag{4.7}$$

$$P(F_t = k) = \frac{EF_t^k \cdot e^{-EF_t}}{k!} \forall\, t, \text{ if } EC = 0 \tag{4.8}$$

For mechanical items, the preventive maintenance interval is deterministic and based on PM as illustrated by Equation (4.9). The value x in between the $\lfloor x \rfloor$ brackets returns the greatest integer less than or equal to x and is known as the floor function. This value determines if preventive maintenance is performed within period t.

$$EF_t = F_t = MP \cdot n \cdot \left(\left\lfloor \frac{PM}{AH \cdot (t+1)} \right\rfloor - \left\lfloor \frac{PM}{AH \cdot (t)} \right\rfloor \right) \quad \forall\, t, \text{ if } EC = 1 \tag{4.9}$$

Repair process

The LRU still has its repair capability in case the repair time frame is longer than the time the item has been obsolete. This is displayed in Equation (4.10).

$$RP_t = \begin{cases} 1, \text{ if } RT - O_t > 0 \\ 0, \text{ if } RT - O_t \leq 0 \end{cases} \qquad \forall\, t \tag{4.10}$$

Spare part demand

Equation (4.11) shows the demand of new LRUs from stock during a period is simply the sum of the backorders from the previous period and the unrepairable LRU failures from the current period (UR_t). The number of LRUs which cannot be repaired is simply the number of failures in case there is no repair capability for the LRU, as displayed in Equation (4.11.1). In case the repair capability is present, the number of unrepairable LRUs is uncertain and based on the Binomial distribution as displayed in Equation (4.11.2).

$$D_t = UR_t + BO_{t-1} \quad \forall\, t \tag{4.11}$$

$$UR_t = F_t, \text{ if } RP = 0 \quad \forall\, t \tag{4.11.1}$$

$$P(UR_t = k) = \binom{F_t}{k} (1 - RY)^k \cdot RY^{F_t - k}, \text{ if } RP = 1 \quad \forall\, t \tag{4.11.2}$$

Obsolescence status

The number of periods the LRU is still available at the supplier (O_t) is updated as depicted in Equation (4.12). Whenever a redesign is just finished, the time the spare part is available is based on a chosen input distribution represented by the random variable X. For the case of Thales, we chose to use a triangular distribution for X as further explained in Appendix E.

In case the LRU is available at $t = 0$, the value of O_0 is determined as follows: First, the value for how long the LRU was available after its introduction is determined, which is based on the triangular distribution. Thereafter, we find the value of O_0 by picking a value between 1 and X from the discrete uniform distribution. We note that O_0 is uncertain in case the LRU is available at the start of the contract. In case the spare part is obsolete at the start of the contract, the value of OOS_0 is to determine how long the item is obsolete.

$$O_t = \begin{cases} \text{X, if } r_{t-RL} = 1 \\ O_{t-1} - 1, \text{ if } r_{t-RL} \neq 1 \end{cases} \qquad \forall\, t > 0 \tag{4.12}$$

The obsolescence status is based upon the value of O_t and is determined via Equation (4.13)

$$OS_t = \begin{cases} 1, \text{ if } O_t \geq 1 \\ 0, \text{ if } O_t \leq 0 \end{cases} \qquad \forall\, t \tag{4.13}$$

Aftermarket price increase

Equation (4.14) shows that the price increase on the aftermarket depends on the number of years the LRU is obsolete. Logically, the price increase on the aftermarket is only positive in case the LRU is obsolete for at least one period already.

$$\begin{cases} AM_t = 0, \text{ if } O_t \geq 0 \\ AM_t = AX_{-O_t}, \text{ if } O_t < 0 \end{cases} \qquad \forall\, t \tag{4.14}$$

4.4.9 Model constraints

LTBs can only be performed when the item turns obsolete in period t, as depicted in Equation (4.15). Moreover, Equation (4.16) makes sure an aftermarket buy can only be performed in case the LRU was obsolete last period already. Moreover, it can only be performed for the predetermined period it is available on the aftermarket.

$$LTB_t = 0, \text{ if } OS_{t-1} - OS_t \neq 1 \quad \forall\, t \tag{4.15}$$

$$AMB_t = 0, \text{ if } AP + O_t < 0 \text{ or } OS_{t-1} = 1 \quad \forall\, t \tag{4.16}$$

Equation (4.17) shows in case an LTB or AMB is performed, it should suffice the MOQ quantity.

$$LTB_t, AMB_t = 0 \text{ or } LTB_t, AMB_t \geq MOQ \quad \forall\, t \tag{4.17}$$

Some items can only be stored for a predetermined period, which is indicated by the SH value. Since one does not want to to buy too many items which have to be disposed at the end of their shelf life, these items have restrictions as to how much can be procured. Equation (4.18) shows this for electronic items and Equation (4.19) for mechanical items. The maximum amount that can be procured makes sure at least 90% of the time all spare part demand during the SH period can be fulfilled, which is based on the Poisson distribution for electronic items and a Binomial distribution for mechanical items.

For electronic items, the expected demand for new LRUs during the SH period is determined via Equation (4.18.2). The value $max(RT + O_t, 0))$ within this equation determines the number of years for which LRUs can still be repaired. Based on the expected demand, the lowest value for X is determined for which at least 90% of the expected demand can be met, as shown in Equation (4.18.1).

$$LTB_t - I_t, AMB_t - I_t \leq X \quad \forall\, t, \text{ if } EC = 0 \tag{4.18}$$

$$min \sum_{i=0}^{X} \frac{(\text{ed})^i \cdot e^{\text{ed}}}{i!} > 90\% \tag{4.18.1}$$

$$\text{expected demand (ed)} = \frac{AH \cdot MP \cdot n}{MTBF} \cdot (SH - min(SH, max(RT + O_t, 0) \cdot RY) \tag{4.18.2}$$

Equation (4.19) shows how the maximum LTB and AMB quantities are determined for mechanical items. Since the failures of mechanical items can be determined up front due to preventive maintenance, the uncertainty for the new LRU demand depends only on the number of successful repairs. The amount of items that can be procured depend on the number of certain spares, which cannot be repaired and certainly have to be procured. It also depends on the number of uncertain spares. Since these items might be repaired, not necessarily all of these failures require a spare. These quantities follow from Equations (4.19.2) and (4.19.3) respectively. For uncertain spares, the Binomial distribution depicted in Equation (4.19.1) determines how many new LRUs are required to meet the number of uncertain spares which cannot be repaired 90% of the time. This value, X, is to determine the maximum value of LTB_T and AMB_t in Equation (4.19).

Equation (4.19.4) determines the value of j. j indicates the last period where the repair capability is still present. Based on this value, a failure within a specific period is either assigned to uncertain spares or certain spares. In case no repairs can be performed at all, the number of uncertain spares is 0. Similarly, in case the repair capability is present in all periods, the number of certain spares is 0.

$$LTB_t - I_t, AMB_t - I_t \leq \text{cs } + X \quad \forall\, t \text{ if } EC = 1 \tag{4.19}$$

$$min \sum_{k=0}^{X} \binom{\text{us}}{k} (1 - RY)^k \cdot RY^{\text{us}-k} > 90\% \tag{4.19.1}$$

$$\text{uncertain spares (us)} \;=\begin{cases} \sum_{i=t}^{j} F_i \text{ if } RT + O_t > 0 \\ 0 \text{ if } RT + O_t \leq 0 \end{cases} \tag{4.19.2}$$

$$\text{certain spares (cs)} \;=\begin{cases} \sum_{i=j+1}^{min(T,t+SH-1)} F_i \text{ if } SH > RT + O_t \\ 0, \text{ if } SH \leq RT + O_t \end{cases} \tag{4.19.3}$$

$$j = \begin{cases} t - 1, \text{ if } RT + O_t \leq 0 \\ min(T, t + min(SH - 1, max(RT + O_t - 1, 0))) \end{cases} \tag{4.19.4}$$

Sign constraints
The sign constraints for the parameters and variables are listed below:

$$EO, MP, MOQ, SH, RT, RL, D_t, ES_t, IB_t,$$

$$I_t, BO_t, F_t, AP, LTB_t, AMB_t, O_t, n, OOS_0 \in 0,\ 1,\ \ldots \quad \forall\, t$$

$$MC, MTBF, AH, PM, EF_t, EF(T)_t, AM_t, c_r, c_h, c_p, c_d \geq 0 \quad \forall\, t$$

$$EC, RP_t, OS_t, r_t \in 0{,}1 \quad \forall\, t$$

$$0 \leq RY, v_t \leq 1$$

4.5 Conclusion

We conclude the following based on the formulated model:

- The formulated model can be characterised as an MDP. Due to the large state space of the model, five decision policies are formulated and can be used to determine the value of the decision variables. These are the following three obsolescence resolutions: LTBs, redesigns and AMBs.

- The model requires general input data as well as data for every specific LRU within a product. Underlying components in LRUs are not taken into account in the model as this requires too much detailed information. Component stock for LRU repairs are not included within the model.

- The objective of the model is to minimise obsolescence resolution costs of an LRU. The cost equation is displayed in Equation 4.2.

- The constructed model is LRU specific. Hence, the model should be used for all LRUs within a product to determine the obsolescence resolution costs.

5 Model case study

This chapter answers the following research question:

> *"How can the constructed model be applied for products sold within a PBL contract?"*

More specifically, experiments are carried out with the constructed model for one of the radar systems manufactured by Thales. First, data collection for model parameters is described in Section 5.1. Next, the simulation setup is discussed in Section 5.2. After this, the experimental design is discussed, which motivates why certain experiments are carried out with the model. Thereafter, model validation and verification is discussed in Section 5.4. Last, experiment results are discussed in the remaining sections.

5.1 Data collection

The formulated model consists of several parameters for which limited or no data is available in the available databases. The parameters for which this is the case are listed in Table 5.1. For example, for 14 LRUs in one of the radar systems, no material cost is available in the price lists. For parameters where values are based on expert opinion, an obsolescence manager or product lifecycle engineer provided a best guess estimate.

Table 5.1: Uncertainties / absence of data of model parameters

Parameter	Applicable to how many LRUs?	How is the parameter value estimated
LRU specific parameters		
O (periods until LRU turns obsolete)	All (366)	Through a triangular distribution based on expert opinion
MC (material costs)	14	Expert opinion
RY (repair yield)	38	Expert opinion
RT (repair time frame)	38	Expert opinion
$MTBF$ (mean time between failure)	45	Expert opinion
ES_t (expected sales)	All	Demand plan
c_r (redesign costs)	All	Through a triangular distribution. For all PCBs: based on internal data. Other LRUs: based on expert opinion.
RL (redesign lead time)	All	Expert opinion
AP (periods available on the aftermarket)	All	Expert opinion
AX_j (absolute price increase on the aftermarket)	All	Expert opinion
General model parameters		
c_p (penalty costs per backorder)	All	Expert opinion
c_h (holding costs)	All	Combination of literature and financial controller (see Section 3.2.3)
c_d (disposal costs)	All	Expert opinion

Next to the parameters listed in Table 5.1, parameter values which were retrievable from the available databases might be wrong (e.g. an item with a material cost of €0). Due to the large amount of data retrieved from all possible databases, it is not practical to check all parameter values manually. Therefore, all parameter values of items with a high unit costs only are checked manually. For the other items, only the parameter values were checked in case they seemed unlikely to be true (e.g. unit cost less than €1, MTBF larger than 10,000,000, etc.). Parameter values which seemed unlikely have been changed to a more likely value (e.g. use the material cost of a similar item) in consultation with an obsolescence manager.

Two practical changes have been made for experimentation with the model for the case of Thales: First, the model assumes components required to repair failed LRUs are always in stock and there costs are negligible (assumption 10). Together with relevant stakeholders, we chose to increase the material costs by 5% in case the item is repairable in a certain state, to account for the additional components that have to be put in stock.

Second, LRUs which are obsolete at the start of the contract receive a value of 0 for OOS_0, which indicates for how long the LRU is obsolete already at the start of the contract. This makes sure an LTB can still be performed for these LRUs. LRUs which are obsolete at the start of the contract often have stock at LRU level (or at component level for items manufactured by Thales). Therefore, it is a valid assumption to allow LTBs for obsolete items at the start of the contract. This has two implications for using the model:

- A manual check should performed to check whether sufficient inventory can be reserved at the start of the contract. In case this is not possible, additional costs have to be included for redesigns which have to be initiated for these LRUs in the remaining contracted period.
- When a redesign is initiated for these items at the start of a contract, it is illogical to use the formulated distribution key of the model, since spare part demand for initial production of the system is not taken into account within the distribution key. Therefore, we recommend to look at the redesign costs for these LRUs separately from the distribution key used in the model and include the initial demand for production when determining how the redesign costs are shared. This results in a higher fraction of the redesign which has to be paid by the PBL contract.

5.2 Simulation setup

Algorithm 1 gives a generic overview of the main steps of the program. After extracting and reviewing all data required for the model to work, the data is loaded into Python. Within the program, simulation runs are performed. Within one simulation run, obsolescence resolution costs are determined for the systems within the contract. The resulting costs differ per simulation run, due to the random draws for the probability distributions for uncertain parameters and variables. For every LRU (i) and every year in the contract (t), state variables are updated using the equations in Section 4.4.7 and decision variables are implemented based on the selected input policy from Section 4.2. After a simulation run is performed, an array with simulation statistics is returned. This arrays contains information about the costs, decision variables and state variables of every year. The output of all simulation runs are added to one big array called Monte Carlo statistics, with which analyses can be performed.

Algorithm 1: Simulation pseudo-code main

```
Procedure Load Excel data into python          ▷ Data checks included in Excel
    return Input data;
for $n \leftarrow 1$ to NumSimulationRuns do
    Procedure Perform simulation run (Input data);
    for $t \leftarrow 1$ to $T$ do
        for $i \leftarrow 1$ to $I$ do
            Procedure Decision variable values (Policy);
            Procedure Update state variables and save cost statistics;
            if $t = T$ then
                Update $c_d$
    return Simulation statistics;
Procedure Update Monte Carlo statistics (Simulation statistics);
    return Monte Carlo statistics;
```

5.3 Experimental design

This section provides information on the number of simulation runs that are carried out for the experiments being executed. Thereafter, the various experiments carried out are described.

5.3.1 Determining the number of replications

Due to the uncertain nature of the data, the simulation outputs differ per simulation run. In order to collect statistically significant output, the classical central limit theorem can be used. This theorem states that when the number of simulation runs is sufficiently large, the distribution of the sample means approximates a normal distribution (Law, 2014). The student's t-distribution displayed in Equation (5.1) can be used to see if the number of replications carried out is sufficient. This equation is applied on the total obsolescence management costs within the contract, as displayed in Equation (4.1). Within the simulation runs, an α and γ of 0.01 are used. For these values, carrying out a 1000 simulation runs is enough to satisfy the equation. The simulation run time is around 20-40 minutes for carrying out a 1000 simulation runs, depending on the model settings.

$$\frac{t_{n-1,1-\alpha/2}\frac{\tilde{S}}{\sqrt{n}}}{\tilde{X}} < \gamma \tag{5.1}$$

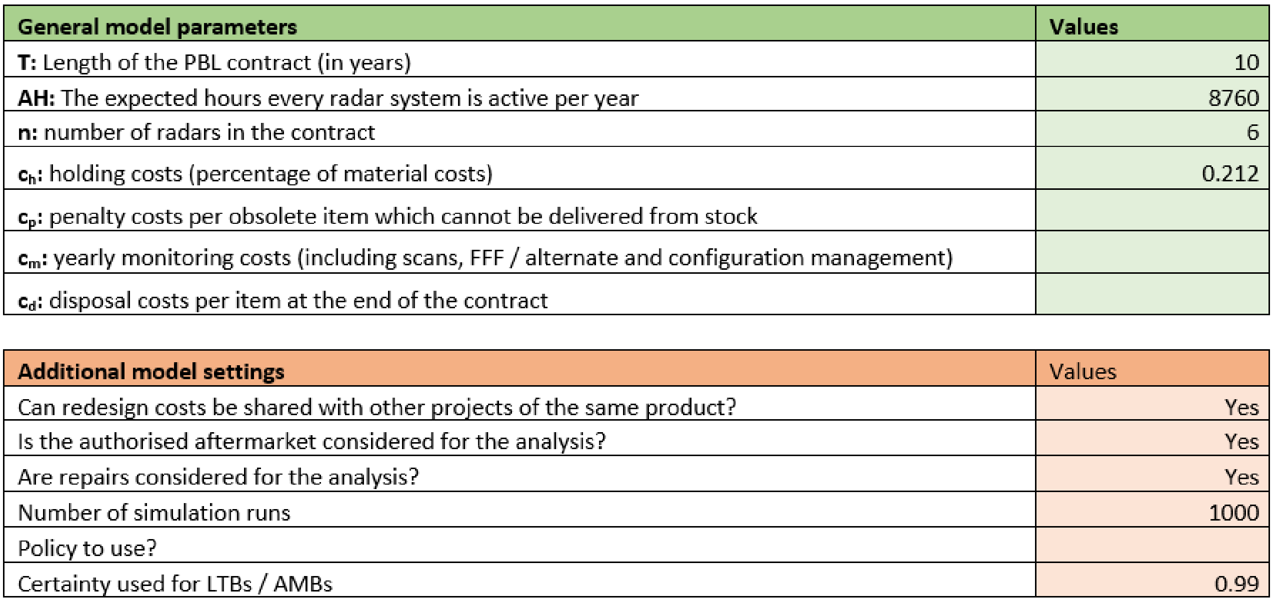
Where:

$\tilde{X}$ = the estimator of the mean
$\tilde{S}$ = the estimator of the standard deviation
n = the number of replications
γ = the maximum relative error
α = the significance level

5.3.2 Experiments 1 - 6

Experiments 1 up until 5 determine the obsolescence management costs for the PBL contract when using all of the five different policies from Section 4.2 for every LRU within the product. Within these experiments, the performance of the various policies can be compared when determining obsolescence management costs at product level. The input settings shown in Figure 5.2 are used[5]. Within these settings, the obsolescence monitoring costs are estimated with the help of an obsolescence manager, as well as LRU penalty and disposal costs. Within Experiment 6, the suggested policy resulting in the lowest resolution costs are used for every LRU separately. Thus, different decision policies can be used for the different LRUs. The suggested policies make use of heuristics to decide on the obsolescence resolutions and since these have limitations, one suggested policy might outperform the other based on the LRU characteristics. Using the policy which is best for a specific LRU might further reduce costs.

Table 5.2: Input settings used for Experiment 1 - 6



General model parameters	**Values**
T: Length of the PBL contract (in years)	10
AH: The expected hours every radar system is active per year	8760
n: number of radars in the contract	6
c_h: holding costs (percentage of material costs)	0.212
c_p: penalty costs per obsolete item which cannot be delivered from stock	
c_m: yearly monitoring costs (including scans, FFF / alternate and configuration management)	
c_d: disposal costs per item at the end of the contract	

Additional model settings	Values
Can redesign costs be shared with other projects of the same product?	Yes
Is the authorised aftermarket considered for the analysis?	Yes
Are repairs considered for the analysis?	Yes
Number of simulation runs	1000
Policy to use?	
Certainty used for LTBs / AMBs	0.99

---

[5] Some values are left empty on purpose, due to the confidential nature of the data.

Next to the general model parameters and settings, LRU specific parameters are also required to be entered within the model. Table 5.3 gives an example of these parameters for a PCB. Moreover, it shows the range of values parameters can attain for various LRUs[6].

Table 5.3: LRU parameter data: The range of possible values for various LRUs and an example

Parameter	**Example PCB**	**Range of possible values**
Expected O (periods until LRU turns obsolete)	7 years	3 - 15 years
Lower bound O (periods until LRU turns obsolete)	4 years	2 - 12 years
Upper bound O (periods until LRU turns obsolete)	12 years	5 - 20 years
MC (material cost)	confidential	€0.11 - €200,000
SH (shelf life)	inapplicable	5 years or inapplicable
RY (repair yield)	90%	0% or 90%
RT (repair time frame)	5 years	0 - 10 years
$MTBF$ (mean time between failure)	confidential	8,000 - 10,000,000 hours
PM (preventive maintenance interval)	inapplicable	2 - 25 years
AP (periods available on the aftermarket)	4 years	4 years or inapplicable
RL (redesign lead time)	2 years	1 - 2 years

5.3.3 Sensitivity analysis

The model uses multiple parameters which are based on expert opinion (e.g. redesign lead time) or which might change in the future (e.g. holding costs). For uncertain parameters where the cost output is expected to change significantly, a sensitivity analysis are carried out. Together with internal stakeholders, parameters for which changes are interesting to analyse have been selected. There are several parameters which are not selected for the sensitivity analysis, although they are unknown (e.g. disposal costs and penalty costs). These are not investigated since changes in there values are not interesting for Thales. The parameters which are investigated further through a sensitivity analysis can be found in Table 5.4.

Within the table, a change to the redesign lead time is presented, where there is a 30% possibility that a redesign takes an additional period. Within the model, the redesign lead time is discrete, but in practice it might occur that redesigns take longer than expected (and their lead time is stochastic). Therefore, an experiment for this is carried out within the sensitivity analysis, where a redesign might take longer than expected.

---

[6] MTBF data is not provided, due to the confidential nature of the data.

Table 5.4: Changes in parameter values and model settings for the sensitivity analysis

Parameter	**Changes in value**
O (periods until LRU turns obsolete)	± 2 years
$MTBF$ (mean time between failure)	- 20%
c_r (redesign costs)	± 20%
RT (repair time frame)	+ 5 years
RL (redesign lead time)	± 1
RL (redesign lead time)	30% chance redesign takes 1 more period
c_h (holding costs)	± 5%
IB_t (installed base) & ES_t (expected sales)	Altered manually by obsolescence manager
IB_t (installed base) & ES_t (expected sales)	Assume Thales broad values can be used for these parameters instead of product specific values
Model setting	**Change to setting**
Certainty percentage	99,9%, 95%, 90%, 80%
Redesign costs shared?	No
Aftermarket considered?	No
Repairs considered?	No

Moreover, the logic flowcharts of the different policies mentioned a specific certainty percentage: 99%. This is currently used within Thales when performing an LTB / AMB for a specific period. Within the model, the certainty percentage is used when performing an LTB / AMB for a specific period, as well as when checking whether demand can be met for a specified period. By changing this percentage, changes in the obsolescence resolution costs and number of backorders can be analysed.

Last, two experiments are carried out where the installed base and expected sales values are altered. Within the model, expected sales and installed base values are based on the demand plan of Thales. The context analysis showed that values of the demand plan are subject to change. Therefore, an experiment is performed, where the expected sales are adjusted manually, which reflects a possible change in the demand plan.

Within Experiments 1 - 6, the expected sales and installed base values of LRUs are based on product specific values. This means that although LRUs might also be used in other products Thales sells, these are not taken into account. When a redesigned LRU is backwards compatible within other products, Thales broad values can be used for the installed base and expected sales of LRUs, meaning that the installed base and expected sales of all products in which the LRU is present can be used. This experiment determines the obsolescence management costs under the assumption that LRU redesigns are backwards compatible into all systems Thales sells, which is not the case in practice.

5.4 Model validation and verification

When developing a simulation model, validation and verification is important to make sure the model is accurate and credible. Within this research, the model can unfortunately not be validated by comparing it to the current situation. For the PBL contract which is currently carried out at Thales, the contracted period is not finished and the registration of obsolescence costs is performed inaccurately. As a consequence, the model could not be validated by using current expenditures. It has been validated by obsolescence managers of Thales and checking whether outcomes of the model seem likely and reasonable to them. Besides this, model assumptions have been discussed and changes to the model were made in case assumptions were unlikely to be true in practice.

Moreover, model verification has happened constantly during implementation of the model in Python. During construction of the model, pieces of code were tested and debugged after every few lines of code that were written. On top of this, model outputs from all policies have been examined within the output dashboard in Excel and checked for correctness. When the model was finalised, no illogical decisions or results were found when examining the results.

5.5 Experiments

Table 5.5 shows the average obsolescence management costs from Experiments 1 up until 6. The second suggested policy performs best from the five implemented policies, closely followed by the first suggested policy. No significant difference can be seen in average obsolescence management costs of the two suggested policies. Moreover, Experiments 1 and 2 underperform compared to the other experiments. Further analysis, reveals this is mainly caused by electronic LRUs with low redesign costs and high material costs. An example of this performance is provided in Appendix H.1.

Table 5.5: Average obsolescence management costs of Experiments 1 - 6

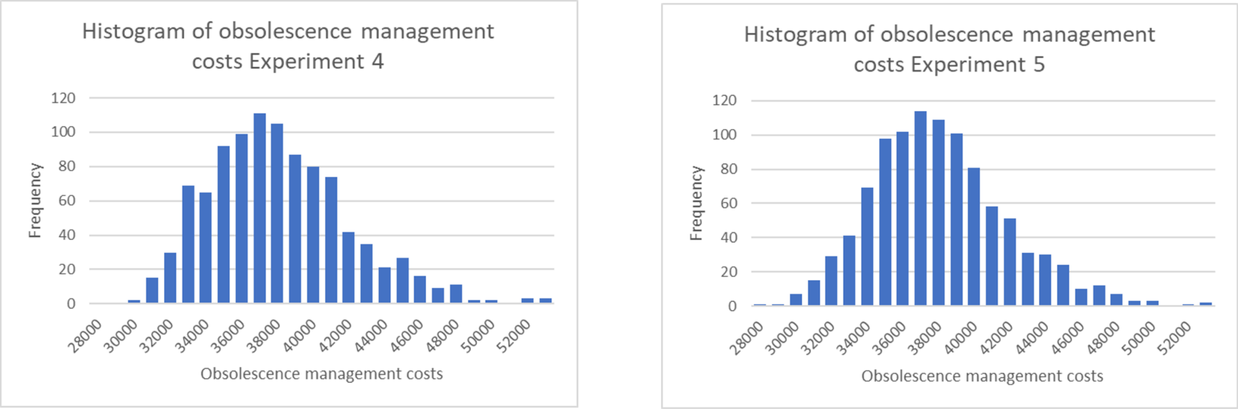
	Average obsolescence management costs	**Performance of costs compared to the current policy**
Experiment 1 (current policy)	€92,140	+0%
Experiment 2 (first simple policy)	€102,850	+11%
Experiment 3 (second simple policy)	€39,420	-57%
Experiment 4 (first suggested policy)	€37,570	-59%
Experiment 5 (second suggested policy)	€37,560	-59%
Experiment 6 (LRU specific policy)	€36,830	-60%

The second simple policy performs relatively well when comparing it to the two suggested policies, indicating that initiating a redesign once an LRU turns obsolete is a logical decision for most LRUs. Appendix H.2 shows that for some LRUs this policy is illogical. This policy does not perform well for LRUs with an expensive redesign and where holding costs do not increase significantly when increasing the buying period.

Experiment 6 further reduces the costs by €730 compared to Experiment 5. This shows that for some LRUs, the first suggested policy outperforms the second suggested policy. Further analysis of the difference in performance for the two suggested policies revealed that the second suggested policy performs better for most LRUs. Suggested policy 1 typically performs better for LRUs which meet the following two conditions: (1) redesigns costs are low compared to holding costs and (2) the number of available periods after a redesign is finished is low, allowing for multiple redesigns during the contracted period. An example of an LRU for which the first suggested policy performs better is provided in Appendix H.3. For the LRUs analysed within the experiments, no single LRU can be identified where suggested policy 2 significantly outperforms policy 1. Consequently, we recommend Thales to use suggested policy 1 when the two stated conditions are met and use suggested policy 2 otherwise.

Figure 5.1 shows that the obsolescence management costs can differ significantly per simulation run. This shows it is difficult give an accurate estimation of obsolescence management costs of a PBL contract, which is caused by the uncertainty within the model. The mean obsolescence management costs within Experiment 4 are €37,570. However, 10% of the simulation runs within this experiment had costs higher than €42,640. This is over 13.5% more than the average, which we argue to be a significant difference.

When considering that the model also includes deterministic parameters which are stochastic in practice (e.g. redesign lead time, expected sales), the standard deviation of obsolescence management costs is likely even higher in practice. The standard deviation of the cost estimate in Experiment 4 is €3,842, resulting in a coefficient of variation of 10%.



(a) Experiment 4

(b) Experiment 5

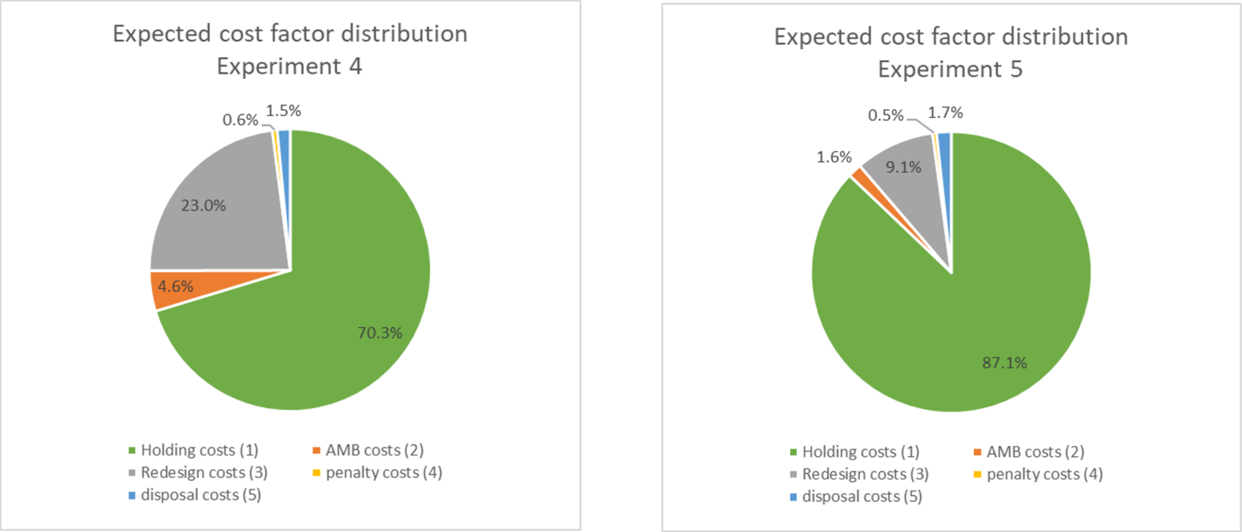
Figure 5.1: Histogram of the obsolescence management costs for 1000 simulation runs

Within the model, penalty costs are included per backorder and disposal costs are included for obsolescence inventory having to be discarded at the end of the contracted period. Table 5.6 shows the expected number of backorders and expected number of disposed items per simulation run for the 6 experiments. Within Experiment 2, the average backorderss are higher than within the other experiments, since no redesign or AMB can be performed when LRU demand is higher than expected. Moreover, the number of disposed items are higher in Experiments 1 and 2. These experiments perform LTBs for longer periods and thus procure larger safety inventories.

Table 5.6: Expected backorders and disposed items for Experiments 1 - 6

	Average backorders	**Average disposed items**
Experiment 1 (current policy)	0.66	800
Experiment 2 (first simple policy)	18.17	795
Experiment 3 (second simple policy)	1.31	245
Experiment 4 (first suggested policy)	1.49	394
Experiment 5 (second suggested policy)	1.20	436
Experiment 6 (LRU specific policy)	1.36	304

The expected costs per cost factor are also provided by the output of the python model. Figure 5.2 shows that for the two suggested policies, the first policy has higher redesign and AMB costs. This is a logical result from the assumption made by the second heuristic that only one redesign can be performed for the remainder of the contracted period.



(a) Experiment 4

(b) Experiment 5

Figure 5.2: Distribution of expected costs for the cost factors

An analysis is performed for assumption 8 of the model. This assumption states that redesigns can be initiated upon request. For PCBs, engineering capacity is restricted and this assumption does not hold in practice. Table 5.7 shows the obsolescence resolution costs for PCBs of Experiments 2, 4 and 5. Experiment 2 shows that when redesigns cannot be initiated and LTBs have to be performed, obsolescence resolution costs would increase by around €14,400 compared to Experiment 4 and 5. For this analysis, we note that in practice not all materials have to be put in stock when a PCB is obsolete, but only the obsolete components. This can reduce holding costs significantly in practice.

Table 5.7: Obsolescence resolution costs for PCBs

	Average resolution costs for PCBs
Experiment 2 (first simple policy)	€18,052
Experiment 4 (first suggested policy)	€3,614
Experiment 5 (second suggested policy)	€3,644

Desired obsolescence resolutions per LRU

Besides finding the obsolescence management costs of the various experiments, understanding what obsolescence resolution to implement for various LRUs is valuable for Thales. Experiments 4 and 5 provide the following insights on what obsolescence resolutions to implement:

For 42% of the LRUs, both experiments always perform an LTB for the remaining contracted period when an LRU turns obsolete. Typically, this decision is implemented for LRUs with low material costs and high redesign costs, but is also impacted by other LRU characteristics (e.g. MTBF, repair time frame, multiplicity). The excel dashboard shows for which LRUs an LTB is performed for the remaining period once the output data is manually pasted into excel. Moreover, it shows for which LRUs a redesign is always performed within the simulation runs. Figure G.2 in Appendix G.1 shows an example of such output.

One surprising result from the model is that for only 1% of the LRUs a redesign is always initiated within both experiments once the LRU turns obsolete. Experiment 3 - where redesigns are always initiated for items turning obsolete - performs almost as well as Experiments 4 and 5. However, the suggested policies show that in some instances it is better to not initiate a redesign directly once an LRU turns obsolete, since obsolescence management costs for these policies are lower.

Last, an ABC analysis is performed on the obsolescence resolution costs of all LRUs within the system. Figure 5.3 shows that 3% of the LRUs within the analysed radar system make up 50% of the obsolescence resolution costs and that 22% of the LRUs make up 95% of the costs. This shows that Thales should mainly focus on only a small portion of the LRUs within the radar system when managing obsolescence. Analysis reveals that LRUs with high obsolescence resolution costs typically have both high redesign and high material costs. Consequently, neither an LTB or redesign is a cheap resolution for these LRUs.

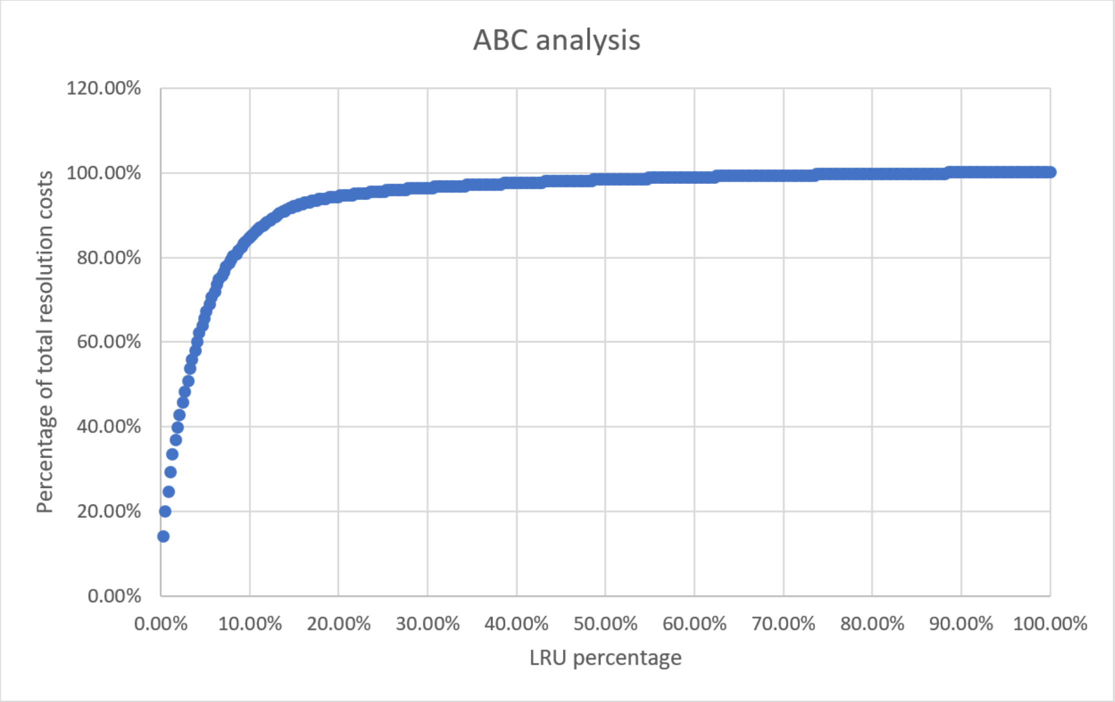


Figure 5.3: ABC analysis of obsolescence resolution costs

5.6 Sensitivity analysis

Table 5.8 shows the results of the sensitivity analyses carried out for uncertain parameters. Besides the change in parameter values displayed in the table, the same input settings are used as for the experiments. Moreover, suggested policy 1 is used to determine which obsolescence resolutions to implement. Some interesting insights from the sensitivity analysis are discussed in the remainder of this section.

Table 5.8: Summary of the results of the sensitivity analysis

Parameter	Change in value	Average obsolescence management costs	Difference Experiment 4
O (Available period after a redesign)	− 2 years	€ 44,157	+ 18%
O (Available period after a redesign)	+ 2 years	€ 33,054	- 12%
$MTBF$ (mean time between failure)	- 20%	€ 39,202	+ 4.4%
c_r (redesign costs)	− 20%	€ 36,161	- 3.7%
c_r (redesign costs)	+ 20%	€ 38,371	+ 2.2%
RT (repair time frame)	+ 5 years (only for items which can be repaired)	€ 34,013	- 9.4%
RL (redesign lead time)	− 1	€ 29,334	- 25%
RL (redesign lead time)	+ 1	€ 46,556	+ 24%
RL (redesign lead time)	30% chance the redesign takes 1 more period	€ 43,408	+ 16%
c_h (holding costs)	− 5%	€ 32,896	- 12%
c_h (holding costs)	+ 5%	€ 41,598	+ 10.8%
IB_t (installed base) & ES_t (expected sales)	Altered manually by obsolescence manager	€ 39,529	+ 5.2%
IB_t (installed base) & ES_t (expected sales)	Thales broad values used	€ 31,871	-15%
Change to setting		Average obsolescence management cost	Difference Experiment 4
Certainty percentage of 99,9% used		€ 46,099	+ 23%
Certainty percentage of 95% used		€ 31,588	- 16%
Certainty percentage of 90% used		€ 29,937	- 20%
Certainty percentage of 80% used		€ 30,055	- 20%
Redesign costs cannot be shared		€ 83,779	+ 123%
Authorised aftermarket not be used		€ 37,732	+0.5%
Repairs are not used		€ 63,749	+ 70%

Available period after a redesign (O)
The period until the LRU becomes obsolete after a redesign has a significant effect on the average obsolescence management costs. Since this parameter is based on expert opinion for all LRUs, it is important to carefully select values for this parameter (although this parameter is already determined via a triangular distribution). An increase in the value of this parameter makes initiating a redesign more likely for some LRUs, since obsolescence issues are resolved for a longer period.

Redesign lead time (RL)
The redesign lead time of LRUs have a significant effect on the obsolescence management costs. In case a redesign is initiated, an LTB is usually performed to cover demand during the redesign lead time. Adjusting the redesign lead time results in a situation where an LTB has to be performed for a longer or short period when a redesign is initiated, which affects holding costs. An example of this is provided in Appendix H.4. Moreover, the experiment in which a redesign might take 1 more period than expected with a 30% chance also had a significant increase in costs. This was mainly caused by an increase in penalty costs of ± €6,000.

Holding costs (c_h)
Holding costs have a significant impact on the obsolescence management costs in comparison to Experiment 4. As already highlighted, there is no consensus internally at Thales about the correct percentage of this variable. We suggest to use a value of 21.2% for c_h, which is based on literature and information provided by Thales' financial controller (see Section 3.2.3). Achieving consensus about this parameter is important, since it affects the preferred obsolescence resolutions to implement. Typically when the holding costs decrease, the model suggests to perform LTBs for longer periods since holding inventory is cheaper.

Repair time frame (RT)
When the repair time frame increases by 5 years for repairable LRUs, obsolescence management costs drop by 9.4%. This is a significant decrease, especially when considering that only 15% of the LRUs within the analysis are repairable. LTB quantities are significantly lower when stock is procured for a time frame over 5 years. Expensive redesigns can be mitigated in this way, as shown by the example in Appendix H.5.

Installed base (IB_t) and expected sales (ES_t)
Two experiments have been carried out where the installed base and expected sales quantities were adjusted. Within the first of these experiments, an expected order from one of the customers was removed from the demand plan. As a consequence, the distribution key would assign a higher percentage of the redesign costs to the PBL contract and expected obsolescence resolution costs increase as a result. In the second example, Thales broad values are used (meaning that the expected sales and the installed base of LRUs in other products Thales manufactures are also included). The total redesign costs reduce by 75% within this example, since the distribution key assigns a lower percentage of redesign costs to the PBL contract. Within this experiment, initiating redesigns was a more suitable resolution for LRUs with a high installed base and expected sales forecast.

Certainty percentage
Various experiments are carried out where the certainty percentage is adjusted. Lowering the certainty percentage decreases the LTB and AMB amounts for buying periods. When the certainty percentage is lowered by 4% or 9%, the obsolescence management costs are reduced by 16% and 20% respectively. This is mainly caused by a decrease in holding costs, due to lower LTB quantities. An example of this is provided in Appendix H.6.

Authorised aftermarket
When the authorised aftermarket is not considered as an obsolescence resolution option, the obsolescence management costs only increase by 0.5%. This shows that for the input data of the case study an AMB is seldomly performed.

5.7 Conclusion

The objective of this chapter is to apply the constructed model for a product which might be sold in a PBL contract. We draw the following conclusions from the executed experiments:

- Using suggested policy 1 or suggested policy 2 to make resolution decision yields significant cost reductions in comparison to the current policy. These reductions are largely caused by a change in resolution decision for expensive electronic LRUs. Instead of performing an LTB for the remaining contracted period (current policy), a redesign is initiated for these LRUs (suggested policies) and the costs are shared via the distribution key.

- Generally speaking, we recommend Thales to use suggested policy 1 for LRUs meeting the following two conditions: (1) redesign costs are low compared to holding costs and (2) multiple redesigns are possible during the contracted period. For all other LRUs, we recommend Thales to use suggested policy 2.

- The standard deviation of obsolescence management costs is high within the model (±10% of the expected costs). Therefore, no accurate estimate can be provided for the obsolescence management costs that are made, as in practice only one “simulation run” happens.

- The output of the simulation runs can be loaded into an excel dashboard (see Section 6.1.2). By using this dashboard, Thales can effectively see what obsolescence resolution are implemented for the various LRUs within the analysis in case they are obsolete.

- The sensitivity analysis showed that for uncertain parameters used in the model, possible changes can result in significant differences in the estimated costs. Moreover, it showed compelling cost reductions can be achieved. First, when the certainty percentage used within the model is lowered. Second, when LRUs with high obsolescence resolution costs are backwards compatible in all systems manufactured by Thales.

- LRUs where the demand and material costs are relatively low, performing an LTB for the remaining contracted period is typically the desired obsolescence resolution (42% of all LRUs within Experiment 4). For LRUs where repairs are not possible and where the demand and material costs are relatively high, a redesign should typically be initiated after the LRU turns obsolete.

6 Implementation plan

Within this chapter the following research question is answered:

> *"How can the constructed model be implemented successfully at Thales?"*

First, the current implementation of the model is described. Besides the model itself, additional model options and outputs can be retrieved from the model. These are explained in this section as well. Thereafter, two suggestions are made for further implementation of the model to improve usability of the model in the future for Thales.

6.1 Current implementation

The model is currently implemented by making use of two different programs: *MS Excel* and *Python*. Figure 6.1 shows how these programs are currently implemented. First, data from different databases is used to load date into an Excel file. Part of these databases can automatically be linked to Excel. Others cannot and data from these databases has to be copied into an Excel file manually. Next, simulation runs can be performed with the provided data and input settings. This happens within Python. Last, model output is analysed with Excel (e.g. what obsolescence resolutions to perform for different LRUs). This data has to be loaded into Excel manually from Python and a manual is created which outlines how the data should be extracted once the simulation runs are performed.

Figure 6.1: Current implementation of the model

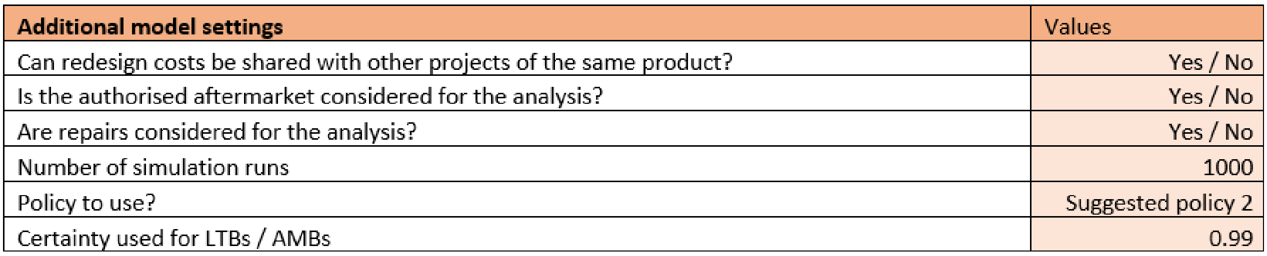
6.1.1 Additional model options

Next to parameters which are required to run the model, additional options can be selected and adjusted by the model user. Figure 6.2 shows how these additional settings can be adjusted in Excel. A short description for some of the options is provided:

1. **Can redesign costs be shared with other projects of the same product?**: In case this value is changed to no, the distribution keys of the model all have a value of 1, since no expected sales or installed base is taken into account.
2. **Is the authorised aftermarket considered for the analysis?**: In case the authorised aftermarket is not considered for the analysis, no AMBs can be performed.
3. **Are repairs considered for the analysis?**: In case repairs are not considered for the analysis, the model assumes items can not be repaired and a new spare part is required for every failed LRU.

4. **Certainty used for LTBs / AMBs**: The certainty percentage to use when performing LTBs and AMBs can be altered. This percentage is also used for checking whether demand can be met for a specified period. The higher the percentage, the lower the expected backorders during the contracted period.

By implementing these options, the model offers additional options and analyses for the obsolescence management department of Thales.



Additional model settings	Values
Can redesign costs be shared with other projects of the same product?	Yes / No
Is the authorised aftermarket considered for the analysis?	Yes / No
Are repairs considered for the analysis?	Yes / No
Number of simulation runs	1000
Policy to use?	Suggested policy 2
Certainty used for LTBs / AMBs	0.99

Figure 6.2: Additional model settings of the implemented model

6.1.2 Additional model outputs

On top of the total obsolescence management costs within the PBL contract, additional outputs of the model are valuable for Thales and are therefore generated as well for the output analysis:

- Expected costs per cost factor per LRU. The cost factors are formulated within Section 4.4.7, with the addition of replacement and repair costs.
- Expected number of redesigns per LRU
- Expected number of LTBs / AMBs per LRU
- Expected number of backorders per simulation run
- Example graphs of an LRU simulation run

Appendix G.1 shows a histogram of obsolescence management costs per simulation run, as well as some of the listed additional model outputs, which gives an impression of the various analyses that can be done with the model. Moreover, Appendix G.2 gives some example output of a simulation run of an LRU. Within this example, an LTB of 1 piece is performed when the item turned obsolete.

6.2 Improvements for implementation

In order to improve usability and increase the value of the model for Thales, we argue the following two steps are most important to undertake:

Improve input data quality
First, we recommend Thales to improve their data credibility and accuracy for various parameters. For some parameters, it is hard to acquire accurate data (e.g. MTBF), since field data is not shared by customers. For other parameters (e.g. redesign lead time and repair yield), databases can be set up where automatic administration takes place in case information is acquired for on of the parameters. This would allow Thales to base their model inputs on more credible sources than expert opinion.

Create a dashboard of the python model output
Second, the output of the current python model can be automated further with a dashboard to improve model analysis. Although Python has packages with which dashboards can be easily made, these are not available for use in the environment of Thales due to security measures. Manually selecting data from the Python model and pasting it into Excel is time consuming. When the model output can be linked to another software program (e.g. *PowerBI*) which is supported internally, a dashboard can be created where model output can be analysed more effectively. With such a dashboard, LRUs and simulation runs can be selected quickly to discuss the model results internally.

6.3 Conclusion

This chapter described how the model is currently implemented for Thales and provides suggestions for further implementation of the model. We draw the following conclusions for the implemented model:

- Example simulation runs of LRUs can be reviewed by obsolescence managers when using the model. This allows to see what happens to obsolescence resolutions costs when uncertain input parameters are changed.
- For various LRU parameters, data was unavailable and based on expert opinion. For some of these parameters, databases can be set up to improve data accuracy and credibility.
- The current model requires the user to manually select data from python and paste it into Excel. This is inefficient when carrying out analyses with the model and comparing different settings. Automatically linking the output data to a dashboard in a software program of choice would improve the models practicality significantly.

7 Conclusion and Recommendations

Since all research questions are answered in the previous chapters, conclusions and recommendations are provided for the executed research. Besides this, the theoretical contribution of the research, its limitations and interesting future research areas are discussed.

7.1 Conclusion

At the start of this research, the following research goal was established to support the obsolescence department in establishing obsolescence management costs within PBL contracts:

"Provide a method for the obsolescence department of Thales which provides insights into the obsolescence management costs for part of a system's lifecycle."

From the context analysis, we concluded that no clear trade-off is made between the following three obsolescence resolutions: LTB, redesign and AMB. Therefore, the optimisation model constructed within this research focuses on these resolutions specifically. The logic implemented in the MOCA methodology of Singh and Sandborn (2006), which makes sure an obsolescence resolution always has to be implemented, is used within the formulated model. Thus, an LTB, redesign and/or AMB is performed for obsolete items.

In Chapter 4, a mathematical model is formulated which makes decisions on what obsolescence resolutions to implement for an obsolete LRU. These decisions follow from one of the five implemented decision policies. With the implemented model, experiments have been carried out for a possible future PBL contract. We draw the following 4 major conclusions from the experiments:

- When one of the two suggested policies is used, obsolescence resolution decision are improved and obsolescence management costs for PBL contracts are reduced by 68% compared to using the current policy which is used to determine costs within PBL contracts.
- The standard deviation of the obsolescence management costs per simulation run is high (e.g. €3,842 in Experiment 4). Moreover, the sensitivity analysis showed that changing values of uncertain parameters can significantly increase / decrease obsolescence management costs. Therefore, we conclude that providing an accurate estimate of obsolescence management costs is not possible and we provide a recommendation for this issue in Section 7.2.
- The output of simulation runs can be loaded into an excel dashboard manually. By using this dashboard, Thales can quickly see what obsolescence resolutions are implemented for the various LRUs in case they turn obsolete.
- Last, Experiment 4 showed that 22% of the LRUs make up 95% of the obsolescence resolution costs and that 3% of the LRUs make up 50% of the obsolescence resolution costs. This shows that Thales should focus on a small portion of the LRUs to see how obsolescence resolution costs can be reduced further (e.g. using a lower certainty percentage or increasing the repair time frame).

The implementation plan described in Chapter 6 concluded that the current implementation of the model requires repetitive manual actions to gain useful insights from the model output. Therefore, options should be investigated to create an automatic dashboard output after running the simulation model, which improves model functionality.

We conclude that the research goal is achieved, since the constructed model can be used to estimate obsolescence management costs for a specified period, which is required when establishing PBL contracts with customers. On top of this, the model provides insights into what obsolescence resolutions are smart to implement for various LRUs and these insights can be extracted from the model manually.

7.2 Recommendations

We provide the following list of recommendations to fully benefit from the main findings within this research:

- We recommend Thales to use the implemented simulation model when determining obsolescence management costs for PBL contracts at the bidding stage. The best performing suggested policy per LRU should be used within the model, as this results in the lowest obsolescence management costs.
- The high variance in obsolescence management costs per simulation run shows it is hard to give an accurate cost estimate up front. As a consequence, we recommend Thales include a risk factor for obsolescence management costs within PBL contracts. For example, Thales could use the 80^{th} percentile of the resulting obsolescence management costs from the carried out simulation runs.
- We recommend Thales to use the model when LRUs procured at subcontractors receive an EOL. For these LRUs, the model reflects the real life situation well (as LTBs are performed at LRU level). The model output gives an indication whether a redesign should be initiated immediately or if an LTB should be performed to resolve obsolescence. For LRUs manufactured by Thales, we do not recommend to use the model for resolution decisions in practice, as LTBs are performed at component level.
- The sensitivity analysis showed that when the repair time frame is increased by 5 years, significant cost reductions can be made for LRUs within the contract. For LRUs where the cost reduction is compelling, it is worth investigating what the requirements and costs are for increasing the repair time frame.
- Experimentation showed that obsolescence resolution costs can be reduced significantly when reducing the certainty percentage when performing LTBs / AMBs. We recommend Thales to use a lower certainty percentage for expensive LRUs and a higher certainty percentage for cheap LRUs when performing LTBs. This will lower obsolescence management costs, without a decrease in availability from stock. As a guideline we suggest Thales to use a certainty percentage of 99% for LRUs with material costs less than €500. Use a certainty percentage of 95% for LRUs with material costs less than €10,000 but more than €500 and use a certainty percentage of 90% for LRUs with material costs more than €10,000.
- Thales should investigate whether redesigns of different LRU types are backwards compatible into all systems of Thales. When Thales determines for which LRUs this is the case, obsolescence management costs can be reduced further within PBL contracts and obsolescence resolution decisions can be improved.

7.3 Discussion

Within this section, the theoretical contribution of the research is explained. Thereafter, the main research limitations and valuable future research areas are discussed.

7.3.1 Theoretical contribution

No obsolescence optimisation model (which can be applied at product level) in literature takes into account data uncertainty (Meng et al., 2014), as well as item inventory (Singh and Sandborn, 2006). This research contributes to theory by creating an optimisation model which takes into account both of these factors. Moreover, we argue our model includes two essential LRU characteristics that are overlooked in literature: First, repair characteristics. Our model shows that items which can be repaired, have different resolution decisions than similar items which cannot be repaired. For these items, an LTB strategy makes more sense due to lower holding costs.

Second, backwards compatibility is overlooked in obsolescence optimisation models in literature. In case an LRU is backwards compatible into other systems sold by an OEM, redesign costs can be shared among the different systems, making it more sensible to initiate redesign for items where the new revision is backwards compatible. Our model shows that obsolescence costs can be reduced significantly when redesign costs can be shared with other systems, making it vital to investigate in what systems a redesigned LRU can be used.

7.3.2 Research limitations

The conducted research has three major limitations besides the uncertainty of input data. The first two limitations are the result of the assumptions and simplifications listed in Section 4.3. Assumption 8 states that LRU redesigns can be initiated upon request. In practice this is not the case for Thales' PCBs. Experimentation showed that when PCBs cannot be redesigned at all due to capacity constraints, obsolescence resolution costs increased by 56% on average for the whole system.

Moreover, Assumption 11 states that when an LRU turns obsolete, all underlying components within the item turn obsolete as well. In practice, only part of the components within an LRU are obsolete when an item is manufactured by Thales. For these LRUs, only some components have to be put in stock to be able to continue manufacturing. Therefor, the model overestimates obsolescence resolution costs for LRUs manufactured by Thales. For these items, the model provides resolution decision which might not be logical in practice. Although this limits the applicability of the model to some LRUs, the model does provide a reliable upper bound for the actual obsolescence management costs of LRUs manufactured by Thales.

Last, the obsolescence resolutions which are implemented for obsolete LRUs follow from one of the five constructed decision policies. These decision policies do not necessarily implement the best obsolescence resolution which minimise obsolescence management costs, but are based on heuristics. Theoretically, the obsolescence management costs might be decreased further if improved decisions can be made by using a more complex heuristics or a model based on reinforcement learning. Currently, we do not know to what extend the implemented obsolescence resolutions are optimal.

7.3.3 Future research

Based on the research conclusions and limitations, we believe future research is valuable for Thales in two specific areas: Conducting research on what requirements LRUs have to make them backwards compatible in multiple systems might be valuable. This research shows that obsolescence management costs can be reduced significantly (-15% within the case study) when a redesigned LRU is backwards compatible in multiple systems without additional costs being made.

For LRUs manufactured by Thales, the current model does not include information about its underlying components. Creating a model which includes component information might be valuable for Thales. Although acquiring all data about components is time consuming, we argue such a model can provide useful insights under what circumstances make LRUs should be redesigned and for which time frame an LTB should be performed in case a component turns obsolete. The design engineering of Thales is dealing with capacity constraints and PCBs are among the most expensive LRUs with regards to obsolescence. This makes this research area even more valuable for Thales.

References

Chopra, S. and Meindl, P. (2016). Estimating Cycle Inventory-Related Costs in Practice. *Supply Chain Management: Strategy, planning, and Operation* (pp. 283-285). Pearson.

Durlinger, P. (2013). *Effectief Voorraadbeheer: Een Stappenplan.* Kluwer.

Goh, Y. M., Newnes, L. B., Mileham, A. R., McMahon, C. A., and Saravi, M. E. (2010). Uncertainty in through-life costing—review and perspectives. *IEEE Transactions on Engineering Management*, 57(4):689–701.

Herald, T., Verma, D., Lubert, C., and Cloutier, R. (2008). An obsolescence management framework for system baseline evolution-perspectives through the system life cycle. *Systems Engineering*, 12(1):1–20.

International Electrotechnical Comission (2019). *International Standard Obsolescence management* (IEC 62402:2019).

Kapletia, D. and Probert, D. (2010). Migrating from products to solutions: An exploration of system support in the uk defense industry. *Industrial Marketing Management*, 39(4):582–592.

Law, A. M. (2014). *Simulation modeling and analysis.* McGraw-Hill Education, 5 edition.

Meng, X., Thornberg, B., and Olsson, L. (2014). Strategic proactive obsolescence management model. *IEEE Transactions on Components, Packaging and Manufacturing Technology*, 4(6):1099–1108.

Porter, G. Z. (1998). *An economic method for evaluating electronic component obsolescence solutions* [White paper]. Boeing Company.

Puterman, M. L. (1994). *Markov decision processes*, volume 2, page 331–434. Wiley-Interscience.

Reimert, W. H. M. (2020). *Obsolescence management strategies at Thales Hengelo* [Master's thesis, University of Twente].

Rojo, F. J. R. (2011). *Development of a framework for obsolescence resolution cost estimation* [doctoral dissertation, Cranfield University].

Romero Rojo, F. J., Roy, R., and Shehab, E. (2009a). Obsolescence challenges for product-service systems in aerospace and defence industry. *The International Journal of Advanced Manufacturing Technology*, 49(9-12):1235–1250.

Romero Rojo, F. J., Roy, R., and Shehab, E. (2009b). Obsolescence management for long-life contracts: State of the art and future trends. *The International Journal of Advanced Manufacturing Technology*, 49(9-12):1235–1250.

Romero Rojo, F. J., Roy, R., Shehab, E., Cheruvu, K., and Mason, P. (2011). A cost estimating framework for electronic, electrical and electromechanical (EEE) components obsolescence within the use-oriented product–service systems contracts. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 226(1):154–166.

Singh, P. and Sandborn, P. (2006). Obsolescence driven design refresh planning for sustainment-dominated systems. *The Engineering Economist*, 51(2):115–139.

Spectrum Signal Processing (n.d.).

Thales Group (2023). *About Thales*. `https://www.thalesgroup.com/en/global/group`.

TNL NAVAL (2023). *Obsolescence Management Handbook TNL NAVAL*.

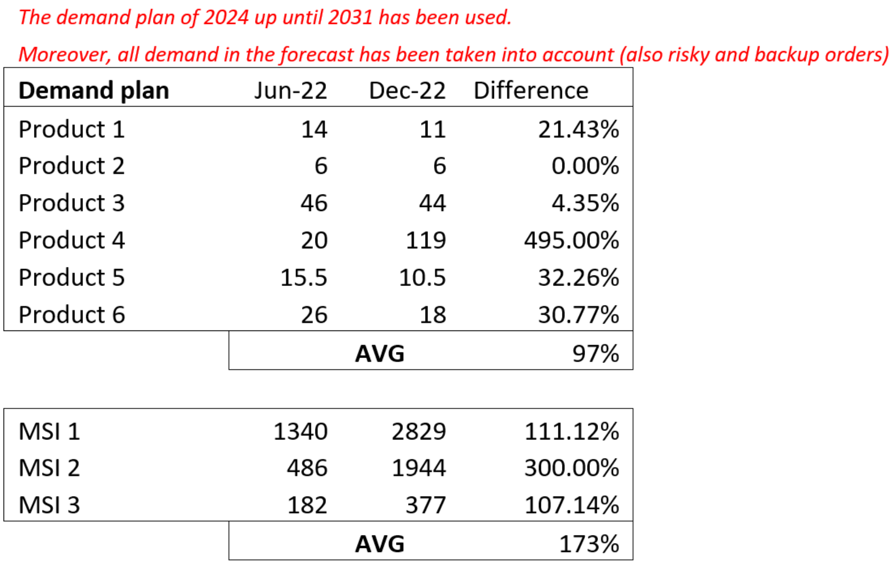
U.S. Government Accountability Office (2020). Cost assessment guide: Best practices for estimating and managing program costs.

A Comparison of demand plans

According to experts at Thales, the parameter which is often subject to change from year to year in the LTB formula is the *future sales*. This value is retrieved from the internal demand plan. To see whether the statement of the obsolescence managers was right we reviewed the internal demand plan, which is updated every 2 months. Within the demand plan, a distinction is made between different scenarios per customer. For example, an order might have been placed and the demand is certain. For other customers, the sales are still in the bid phase and therefore the forecast is risky.

The demand plan of June 2022 is compared to the one of December 2022. The demand plan of 6 different products and 3 different MSIs (which are currently being redesigned) have been reviewed. Table A.1 shows the results of the analysis. Although the time the demand plan was released only differs half a year, large differences in the forecast can be seen at both product and MSI level. Obsolescence managers within Thales state this is mainly caused by the war in Ukraine. It should be noted that the MSI analysed are currently in a redesign process, which is likely the result of the large increase in demand.

Table A.1: Comparison demand forecast June 2022 and December 2022



The demand plan of 2024 up until 2031 has been used.

Moreover, all demand in the forecast has been taken into account (also risky and backup orders)

Demand plan	Jun-22	Dec-22	Difference
Product 1	14	11	21.43%
Product 2	6	6	0.00%
Product 3	46	44	4.35%
Product 4	20	119	495.00%
Product 5	15.5	10.5	32.26%
Product 6	26	18	30.77%
		AVG	97%

MSI 1	1340	2829	111.12%
MSI 2	486	1944	300.00%
MSI 3	182	377	107.14%
		AVG	173%

Currently, the demand plan is undergoing changes to make the forecast more accurate and change the software in which it is provided. The new demand plan will show orders with commitment for the coming 3 years and the other demand will be probability based (how likely will an order be placed by the customer affects the forecast).

B Determining LTB quantities

When a decision is made to perform an LTB of an item to resolve obsolescence, Thales uses one of two equations to determine the ordering quantity. The first equation is used for relatively cheap and simple items. The second one requires more data and is therefore used for complex and expensive items only. The equations are important within this research since using them allows us to find the LTB quantities and costs for spare parts in PBL contracts specifically.

Table B.1: Parameters required for LTB (and RMB) calculations

	Parameter	Description
Required for both equations	IB	Installed base (#systems)
	FS	Future sales (#systems)
	MP	Multiplicity of item per system
Required for equation (2)	AH	Annual operating hours per system
	MTBF	Mean time between failure (hours)
	RY	Repair yield (% of succesful repairs, 90% used if unknown)
	PP	Planning period (10 years if unknown)
	RT	Repair time (5 years if unknown)

Table B.1 shows the parameters required for performing the LTB calculations of both equation (1) and (2). The first equation is relatively simple and does not require much data. The order quantity (Q) is determined as follows:

$$Q = (\text{FS} \cdot \text{MP}) + \ 0.15 \cdot (\text{IB} + \text{FS}) \cdot \text{MP} \tag{B.1}$$

Equation (1) consists of two parts: The first term calculates the required parts for the production of all future sales. The second term makes sure (15%) initial spare parts are incorporated. This can also be 10%. These initial spare parts are used for component failure during production or breakdown during the warranty period. Experts within Thales state that this percentage is effective in practice. We note it is remarkable that the remaining time until end-of-life of systems in the field does not play a role and is not used.

The second equation requires more data, since the required quantity is calculated using past customer data. The following additional data are required: the system operating hours, planning period, the mean time between failure (MTBF) and repair yield. Based on this, the spare part demand is determined more accurately instead of using 10 or 15% as a baseline. The order quantity is determined via Equation (B.2) and its corresponding sub-equations:

$$Q = (\text{FS} \cdot \text{MP}) + \text{required spare parts} \tag{B.2}$$

$$\text{required spare parts} = min \sum_{i=0}^{X} \frac{(\text{spare part demand})^i \cdot e^{\text{spare part demand}}}{i!} > 99\% \tag{B.2.1}$$

$$\text{spare part demand} = \frac{\text{AH} \cdot (\text{IB} + \text{FS}) \cdot \text{MP}}{\text{MTBF}} \cdot (\text{PP} - \min(\text{RT,PP}) \cdot \text{RY}) \tag{B.2.1.1}$$

Equation (B.2.1) shows that the required spare parts for the remaining planning period are calculated via a Poisson distribution. This distribution is used for electronic items specifically, since these items have a constant failure rate. It selects the minimum number of required spare parts to fulfil spare part demand 99% of the time. Equation (B.2.1.1) shows how the spare part demand used in Equation (B.2.1) is calculated. The total operating hours of all items is divided by the MTBF to attain the expected failures per year. In case Thales does not know how long an item can be repaired after production, they assume they are still able to repair MSIs for five years (with a specific repair yield). After five years, knowledge and tooling required for repair are is assumed to be unavailable. It is thus required to replace all failed parts after the repair time has passed. The order quantity of both Equation (1) and (2) are based on data which is uncertain. For example, the annual operating hours per system are based on data provided by the client and the future sales are based on the internal demand plan, which is merely a forecast. Therefore, the order quantity from both equations is always reviewed by obsolescence managers and a higher order quantity is often ordered (e.g. when a redesign is extremely expensive or item costs are relatively low).

C Example for Heuristic 1

An example calculation of Heuristic 1 is explained in Section 4.2.3 is provided in Figure C.1: We assume an LRU just turned obsolete and has a redesign lead time of 2 years. Moreover, the expected period the item is available after a redesign is 4 years. Within iteration 1 of the heuristic, an LTB for 2 years is performed (with 99% certainty) and a redesign is initiated instantly, which is thus finished after 2 years. Based on these two resolutions, the expected yearly costs are calculated. Within iteration 2 and 3, an LTB is performed for 3 and 4 years respectively, as the buying period increases by 1 year every iteration. Within these iterations, a redesign is initiated after 1 and 2 years respectively. The yearly costs of these iteration can be seen in the figure as well. Because the LTB is performed for longer periods, the inventory costs increase. However, since a redesign can be initiated 1 year later, the number of period which can be covered within these resolutions is expected to be higher. The yearly costs are the sum of the inventory and redesign costs and are divided by the number of periods inspected. Since the yearly costs in iteration 2 are lower than in iteration 3, the LTB proposed in iteration 2 is performed within the example: Perform an LTB for 3 years.

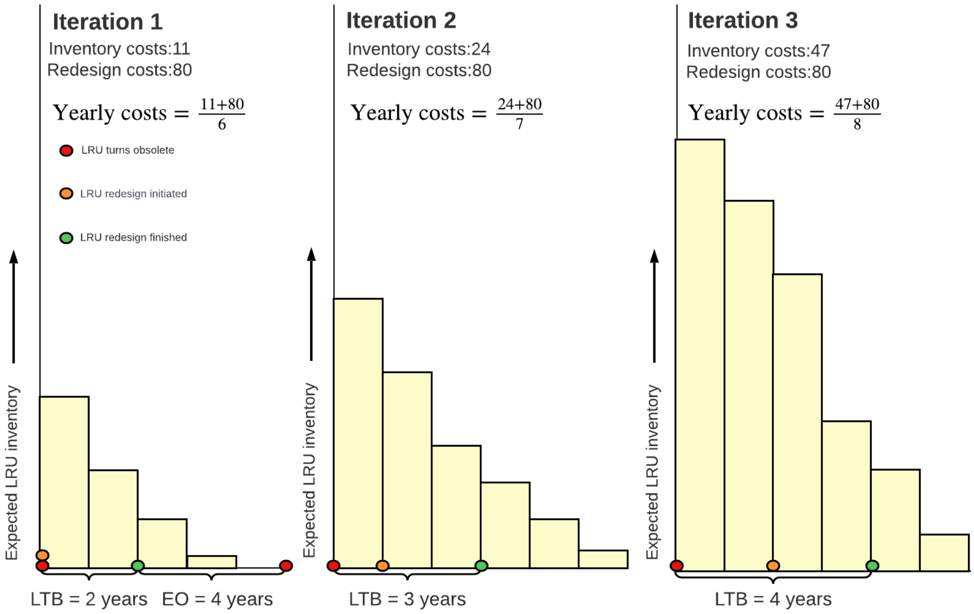


Figure C.1: Iterations analysed within the example of Heuristic 1

For the calculation of the yearly costs, two different procedures are used to determine the yearly costs: One for performing an LTB and one for performing an AMB. For an LTB, we assume an LTB has to be performed for the whole installed base of Thales (thus also for LRUs not present in the PBL contract). This makes sure the decision to be implemented is best for the whole installed base, and is not optimised for the PBL contract under investigation specifically (which does not take into account economies of scale). Equation (C.1.1) show how the obsolescence inventory is updated for every year within the analysis. Based on this, the the yearly costs for the specified LTB period is determined via Equation (C.1), where redesign costs are not incurred in case the buying period covers the remaining period (see Equation C.1.2). At the start of the iteration, an LTB is performed which suffices the required LRU amount with 99% certainty.

$$\text{Yearly Costs} = \frac{\sum_{t=0}^{\text{Buying period}-1}\big(I_t \cdot c_h \cdot MC\big) + c_r}{\text{Buying period} + EO} \tag{C.1}$$

$$I_t = \begin{cases} LTB(T)_t & \text{if } t = 0 \\ \max\big(0, I_{t-1} - ES_{t-1} - E[D(IB + PBL)]_{t-1}\big) & \text{if } t > 0 \end{cases} \tag{C.1.1}$$

$$c_r = \begin{cases} 0 & \text{if Buying period} = \text{Remaining contracted period} \\ E[c_r] & \text{if Buying period} < \text{Remaining contracted period} \end{cases} \tag{C.1.2}$$

For the calculation of AMB costs, we assume an AMB only has to be performed for the PBL contract. We chose to do this since current inventory levels have to be taken into account to calculate the correct expected inventory costs. Equation (C.2.1) shows this. In case an AMB is performed instead of an LTB within this policy, the additional procurement costs for buying an item on the aftermarket also have to be included in the yearly costs and the expected redesign costs of the LRU have to be distributed using the distribution key, as shown in Equation (C.2). Contrary to the LTB cost calculations, economies of scale are not taken into account within these calculations when performing an AMB, since an AMB is only performed for the PBL contract.

$$\text{Yearly Costs} = \frac{\sum_{t=0}^{\text{Buying period}-1}\big(I_t \cdot c_h \cdot MC\big) + c_r \cdot v_{t+\text{Buying period}-RL} + AM \cdot AMB(PBL)_0}{\text{Buying period} + EO} \tag{C.2}$$

$$I_t = \begin{cases} AMB(PBL)_t + I_t & \text{if } t = 0 \\ \max\big(0, I_{t-1} - E[D(PBL)]_{t-1}\big) & \text{if } t > 0 \end{cases} \tag{C.2.1}$$

$$c_r = \begin{cases} 0 & \text{if Buying period} = \text{Remaining contracted period} \\ E[c_r] & \text{if Buying period} < \text{Remaining contracted period} \end{cases} \tag{C.2.2}$$

We explain two implications when this heuristic is used for the obsolescence resolution process. First, a large increase in inventory costs can often be seen at an iteration when an item loses it's repair capability in the last year of the LTB. This results in an increase of the $E[D(PBL)]_t$ by factor $\frac{1}{1-RY}$ in comparison to $E[D(PBL)]_{t-1}$. This is an increase of 900% for items with a 90% repair yield. Second, a large increase in inventory costs can often be seen whenever expected sales occur within the last year of the LTB. For both implications, inventory costs often increase significantly compared to the previous iteration, making it likely for the yearly costs to increase compared to the previous iteration.

D Example for Heuristic 2

This Chapter shows an example calculation of the second suggested policy, explained in Section 4.2.3. We assume an LRU turns obsolete and has a redesign lead time of 2 years. Moreover, the expected available period after redesign (EO) is 3 years. Within this heuristic, all possible LTB periods are examined until the end of the contract. Within this example, that is 2 up until 6 years. Within the first iteration of the heuristic, an LTB is performed for 2 years and a redesign is initiated at t = 0. After the redesign is finished, it turns obsolete at t = 5 however, which forces an LTB for 1 more year.

Within the second iteration, an LTB is performed for 3 years instead of 2. Therefore, we expect a redesign has to be initiated at t = 1, which is therefor also finished 1 year later. Within this iteration, we expect the redesigned LRU stays available until the end of the contracted period. Therefore, no additional LTB has to be performed, contrary to the previous iteration.

Iterations 3 and 4, where LTBs of 4 and 5 years are performed respectively, are not shown within this example figure. Within the last iteration, an LTB is performed for 6 years, which is the remaining period within the contract. Therefore, no redesign has to be initiated when implementing this resolution.

Within this example, performing an LTB for 2 years turns out to have the lowest total costs. Hence, this solution will be implemented by the model.

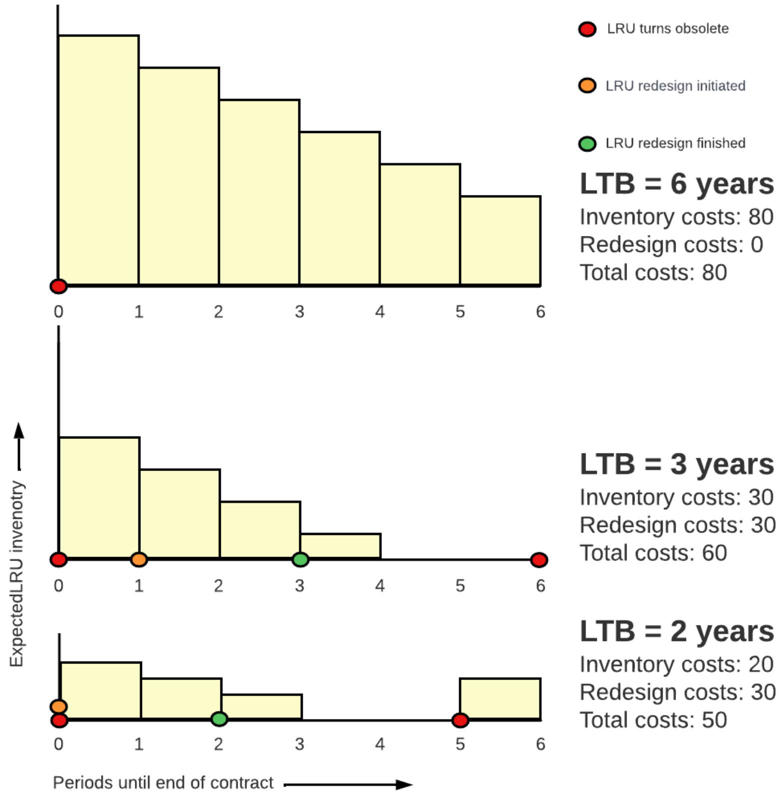


Figure D.1: Output for the example of Heuristic 2

In order to calculate the total costs within this heuristic, similar formulas are used as for the first heuristic. However, under certain cases a second LTB has to be performed, as shown by Equation (D.1.3). Based on the determined inventory levels in Equation (D.1.1) and (D.1.3) and the redesign costs to incur from Equation (D.1.2), the total costs can be determined.

$$\text{Total Costs} = \sum_{t=0}^{\text{Buying period}-1} \Big(\big(I(1)_t + I(2)_t\big) \cdot c_h \cdot MC \Big) + c_r \tag{D.1}$$

$$I(1)_t = \begin{cases} LTB(T)_t & \text{if } t = 0 \\ \max\big(0, I_{t-1} - ES_{t-1} - E[D(IB + PBL)]_{t-1}\big) & \text{if } t > 0 \end{cases} \tag{D.1.1}$$

$$c_r = \begin{cases} 0 & \text{if Buying period} = \text{Remaining contracted period} \\ E[c_r] & \text{if Buying period} < \text{Remaining contracted period} \end{cases} \tag{D.1.2}$$

$$I(2)_t = \begin{cases} 0 & \text{if } t < \text{Buying period} + EO \\ LTB(T)_t & \text{if } t = \text{Buying period} + EO \\ I_{t-1} - ES_{t-1} - E[D(IB + PBL)]_{t-1} & \text{if } t > \text{Buying period} + EO \end{cases} \tag{D.1.3}$$

In case an AMB can only be performed at t = 0, Equation (D.2) and its sub-equations are used to determine the total costs of the analysed LTB period. Similarly to the first suggested policy, we assume an AMB only has to be performed for the PBL contract Therefore, economies of scale are not taken into account within these calculations.

$$\begin{aligned} \text{Total Costs} = &\sum_{t=0}^{\text{Buying period}-1} \Big(\big(I(1)_t + I(2)_t\big) \cdot c_h \cdot MC \Big) \\ &+ c_r \cdot v_{t+\text{Buying period}-RL} + AM \cdot AMB(PBL)_0 \end{aligned} \tag{D.2}$$

$$I(1)_t = \begin{cases} AMB(PBL)_t + I_t & \text{if } t = 0 \\ \max\big(0, I_{t-1} - E[D(PBL)]_{t-1}\big) & \text{if } t > 0 \end{cases} \tag{D.2.1}$$

$$c_r = \begin{cases} 0 & \text{if Buying period} = \text{Remaining contracted period} \\ E[c_r] & \text{if Buying period} < \text{Remaining contracted period} \end{cases} \tag{D.2.2}$$

$$I(2)_t = \begin{cases} 0 & \text{if } t < \text{Buying period} + EO \\ LTB(PBL)_t & \text{if } t = \text{Buying period} + EO \\ I_{t-1} - E[D(PBL)]_{t-1} & \text{if } t > \text{Buying period} + EO \end{cases} \tag{D.2.3}$$

E Triangular distribution

The triangular distribution is a continuous distribution often used in case data is absent and is also known as a "lack of knowledge" distribution. Determining random values for the triangular distribution. Figure E.1 shows the probability density function of the triangular distribution. Based on this, the cumulative distribution function can be found by using Equation (E.1). The probability that x is smaller than b is $\frac{b-a}{c-a}$. We note that the triangular distribution is continuous and when we use it for randomly generating integers, we have to round up or down. An example of rounding down the values is displayed in Figure E.2.

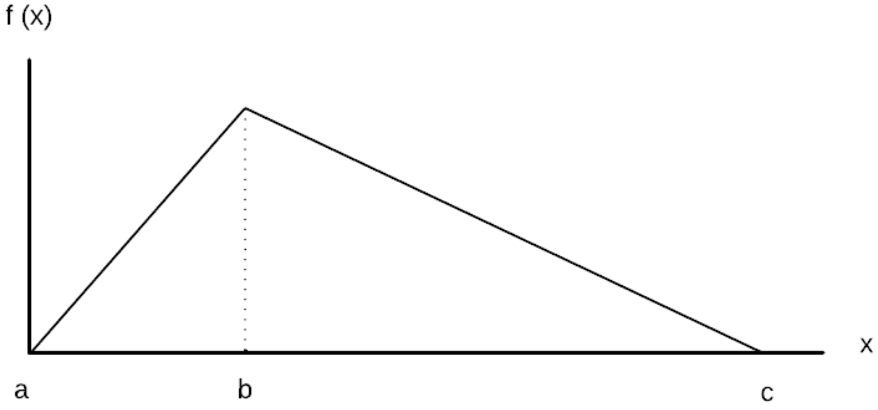


Figure E.1: PDF of a triangular distribution

$$\text{CDF} = \begin{cases} 0 \text{ if } x \leq a \\ \frac{(x-a)^2}{(c-a)(b-a)} \text{ if } a < x \leq b \\ \\ 1 - \frac{(c-x)^2}{(c-a)(c-b)} \text{ if } b < x \leq c \\ 1 \text{ if } c \leq x \end{cases} \tag{E.1}$$

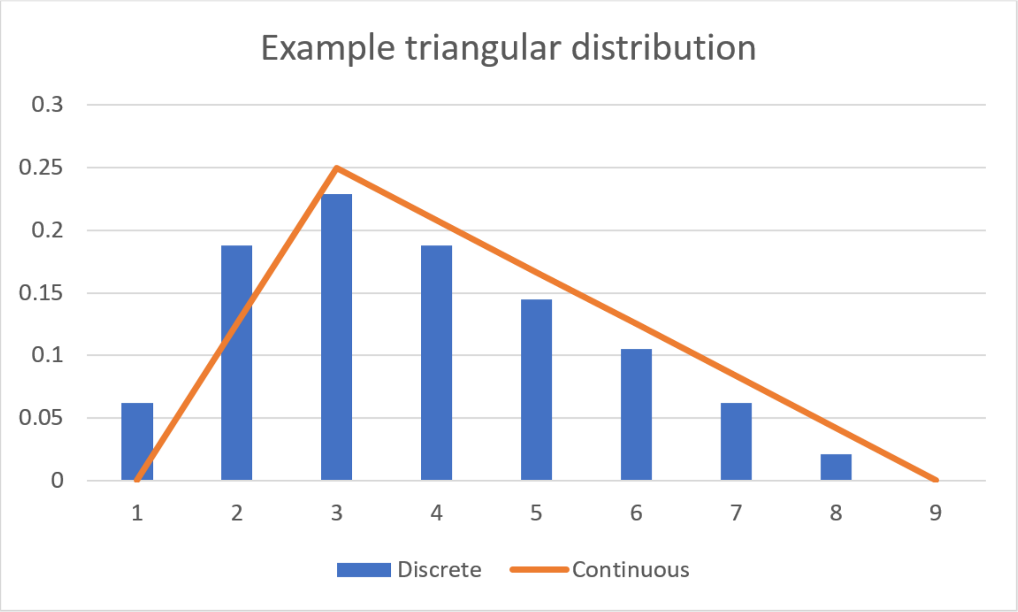


Figure E.2: Example of rounding down continuous values of a triangular distribution

F Distribution key

Within the model objective, v_t is the fraction of the redesign costs that have to be paid by the PBL contract in case a redesign is initiated in period t. Since redesigned spare parts are not only used by the systems with a PBL, but also by other systems in the field and future sales, the costs of redesigning a product have to be distributed.

Equation (F.1) shows which fraction of costs are paid by the PBL contract. The expected spare part failures are determined for the period the redesigned LRU is expected to be available. The PBL contract pays the expected fraction of the total LRU demand after the redesign is finished.

$$v_t = \frac{\sum_{j=t+RL}^{max(t+RL+EO-1,T)} EF_t}{\sum_{j=t+RL}^{t+RL+EO-1} \left(ES_j + EF(T)_j\right) + \sum_{j=t+RL}^{max(t+RL+EO_t-1,T)} EF_j} \qquad \forall\, t \tag{F.1}$$

We provide an example to clarify the equation. We assume in period $t = 6$ a redesign is initiated which takes 2 periods. The LRU is expected to be available for 6 periods after the redesign is finished and the PBL contract ends in period $t = 10$. For the PBL contract, we expect 1 failed part (EF_t) per period. For the installed base, we expect 2 failed parts ($EF(T)_j$) per period. Last, for the expected sales, we expect 4 sales (ES_j) per period. This results in $\frac{1}{13}$ of the redesign costs having to be paid by the PBL contract, as shown in Equation (F.2). Figure F.1 provides an overview of the calculation, which shows the intuitive nature with which the distribution key has been formulated. We note that in practice, the values of EF_t, $EF(T)_t$, ES_j can differ per period, but have been kept the same in this example for clarity.

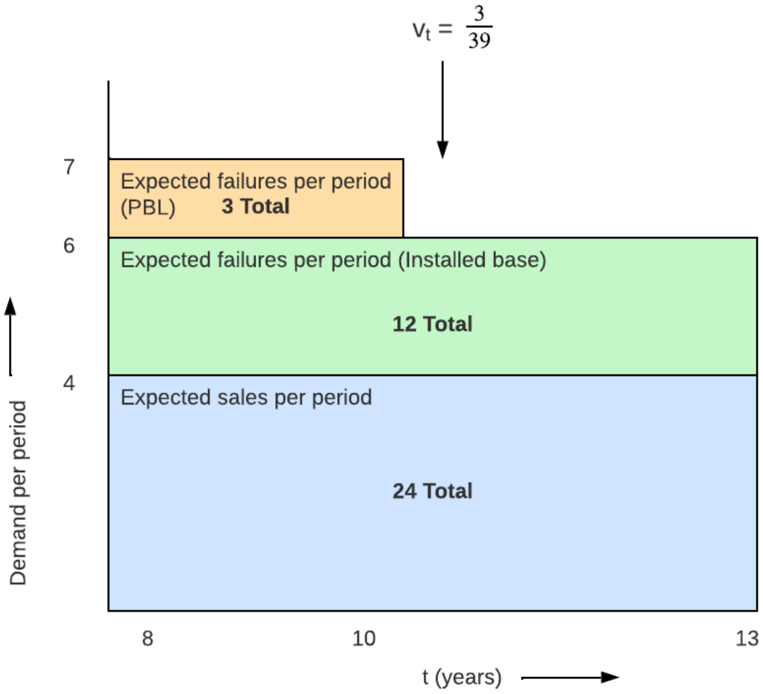
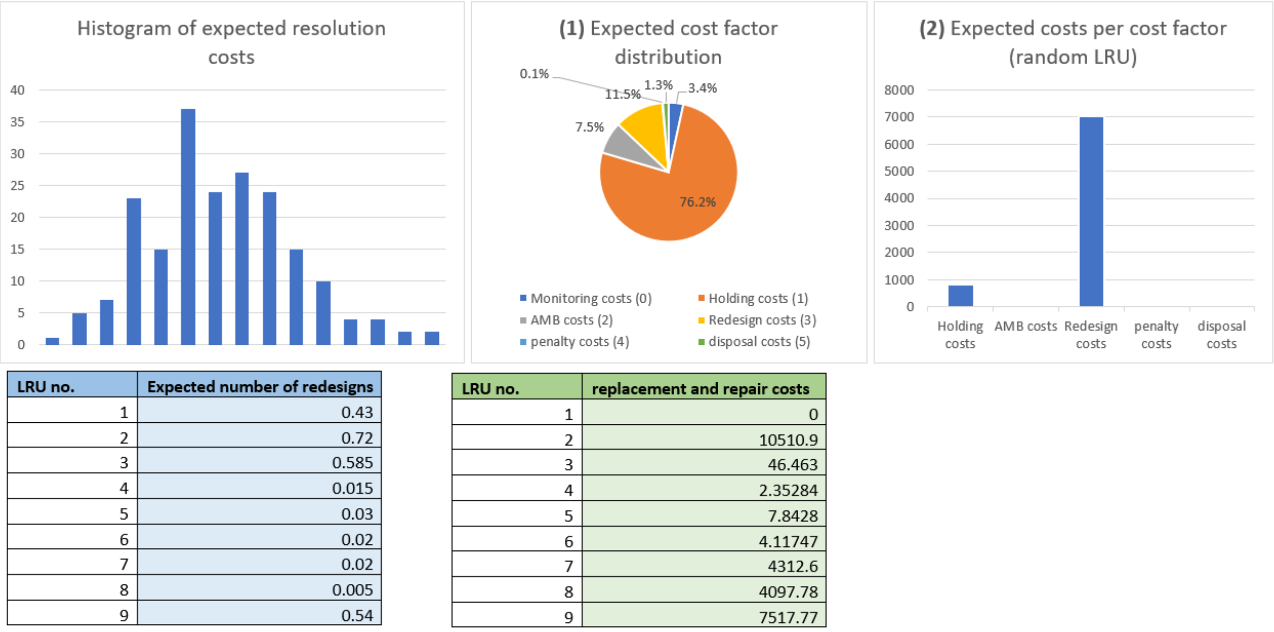


Figure F.1: Example how distribution key v_t works

$$v_6 = \frac{\sum_{j=8}^{max(13,10)} 1}{\sum_{j=8}^{13} \left(4+2\right) + \sum_{j=8}^{max(13,10)} 1} = \frac{3}{6 \cdot 6 + 3} = \frac{1}{13} \tag{F.2}$$

G Example of model outputs

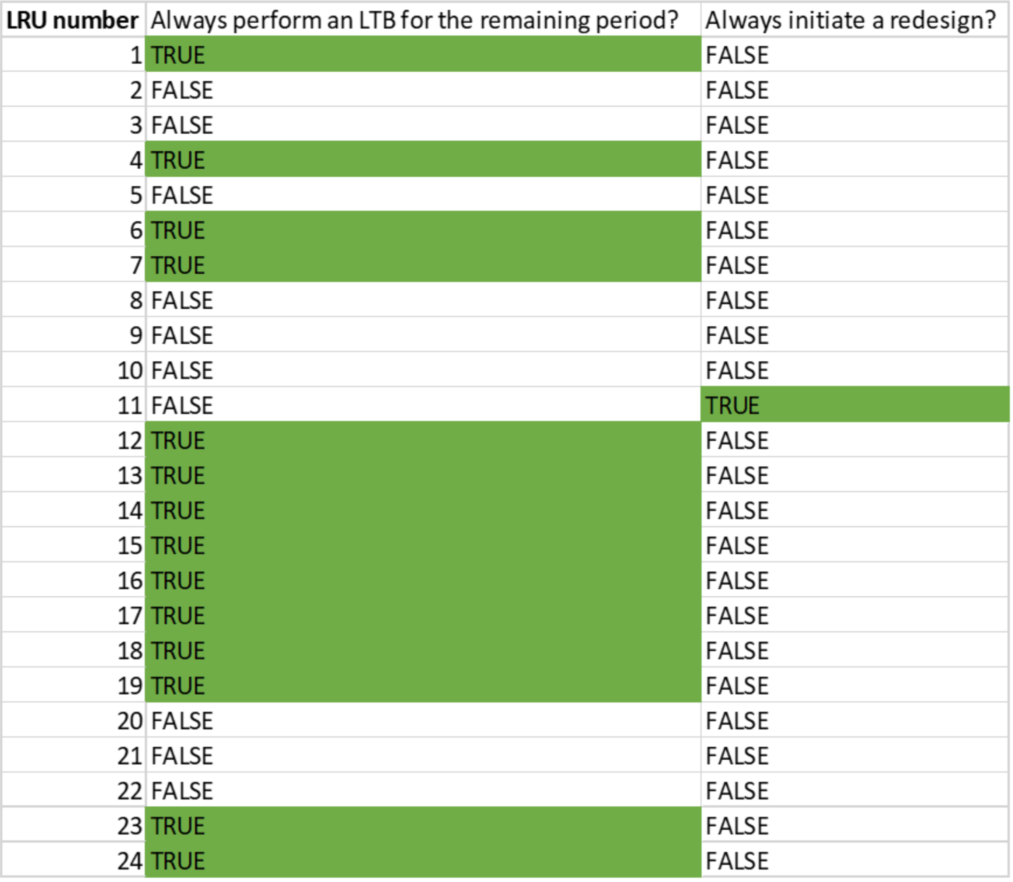
G.1 Example of model output



LRU no.	Expected number of redesigns
1	0.43
2	0.72
3	0.585
4	0.015
5	0.03
6	0.02
7	0.02
8	0.005
9	0.54

LRU no.	replacement and repair costs
1	0
2	10510.9
3	46.463
4	2.35284
5	7.8428
6	4.11747
7	4312.6
8	4097.78
9	7517.77

Figure G.1: Example output of the simulation model



LRU number	Always perform an LTB for the remaining period?	Always initiate a redesign?
1	TRUE	FALSE
2	FALSE	FALSE
3	FALSE	FALSE
4	TRUE	FALSE
5	FALSE	FALSE
6	TRUE	FALSE
7	TRUE	FALSE
8	FALSE	FALSE
9	FALSE	FALSE
10	FALSE	FALSE
11	FALSE	TRUE
12	TRUE	FALSE
13	TRUE	FALSE
14	TRUE	FALSE
15	TRUE	FALSE
16	TRUE	FALSE
17	TRUE	FALSE
18	TRUE	FALSE
19	TRUE	FALSE
20	FALSE	FALSE
21	FALSE	FALSE
22	FALSE	FALSE
23	TRUE	FALSE
24	TRUE	FALSE

Figure G.2: Example output on what obsolescence resolutions are implemented

G.2 Example of simulation run

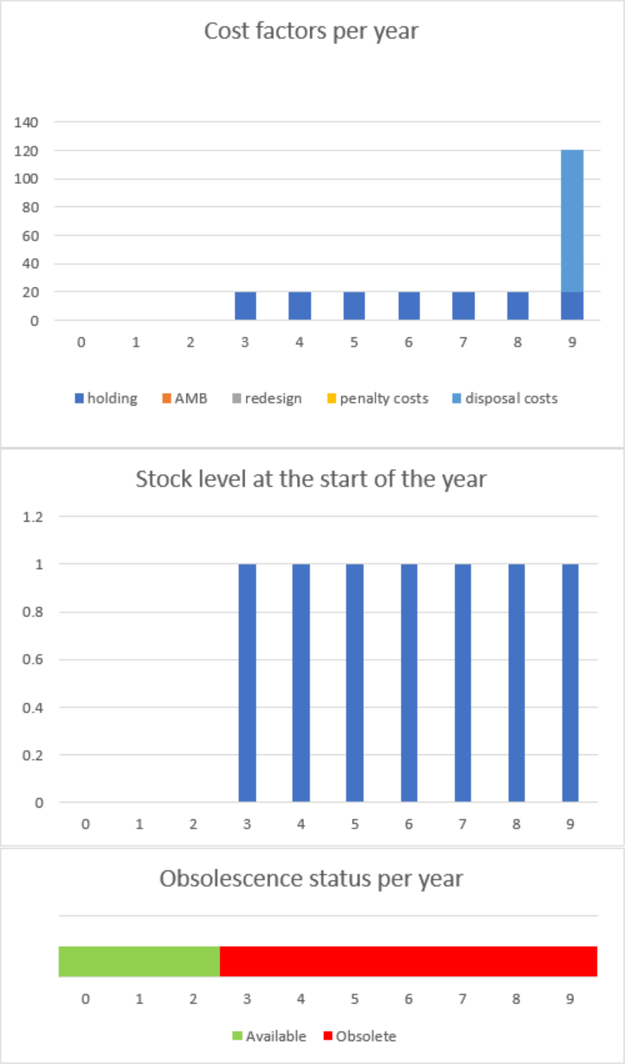


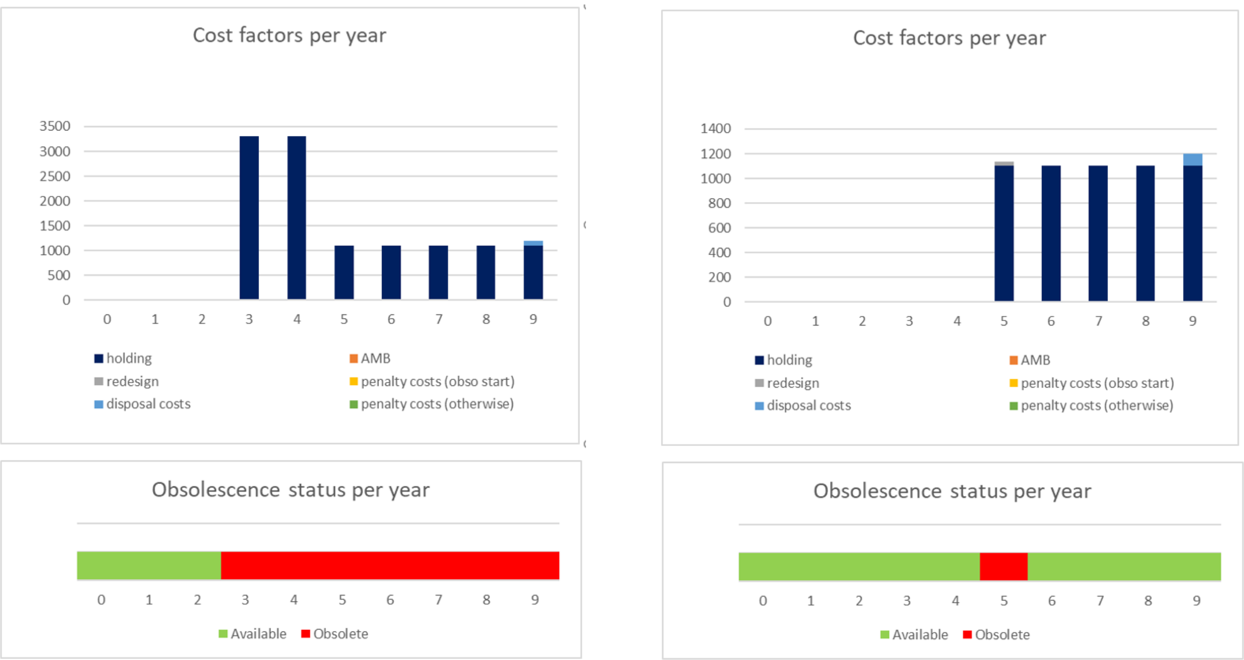
Figure G.3: Example of the costs, obsolescence status and stock level of an LRU within a simulation run

H Analysis of experiment output

H.1 Explanation for the performance of the current policy and the first simple policy

The obsolescence management costs within the experiments was higher when using the current policy or simple policy 1 compared to the other policies. Analysis revealed this is mainly caused by electronic LRUs with high material cost and low redesign costs. Figure H.1a provides the results from an example simulation run when one of these two policies is used. Because the LRU is electronic, an LTB is performed for the remaining period, with high inventory costs. Figure H.1b shows an example run when one of the other policies is used. When using these policies, a redesign is initiated once the LRU turns obsolete. An LTB is performed for the redesign lead time and not for the remaining contracted period, resulting in lower obsolescence resolution costs. In short:

- Figure H.1a shows that an LTB is performed for the remaining period when the current policy and simple policy 1 are used for this example LRU.
- Figure H.1b shows that a redesign is initiated once the LRU turns obsolete when simple policy 2, suggested policy 1 or suggested policy 2 are used for this example LRU. Moreover, an LTB is performed to cover demand during redesign lead time.



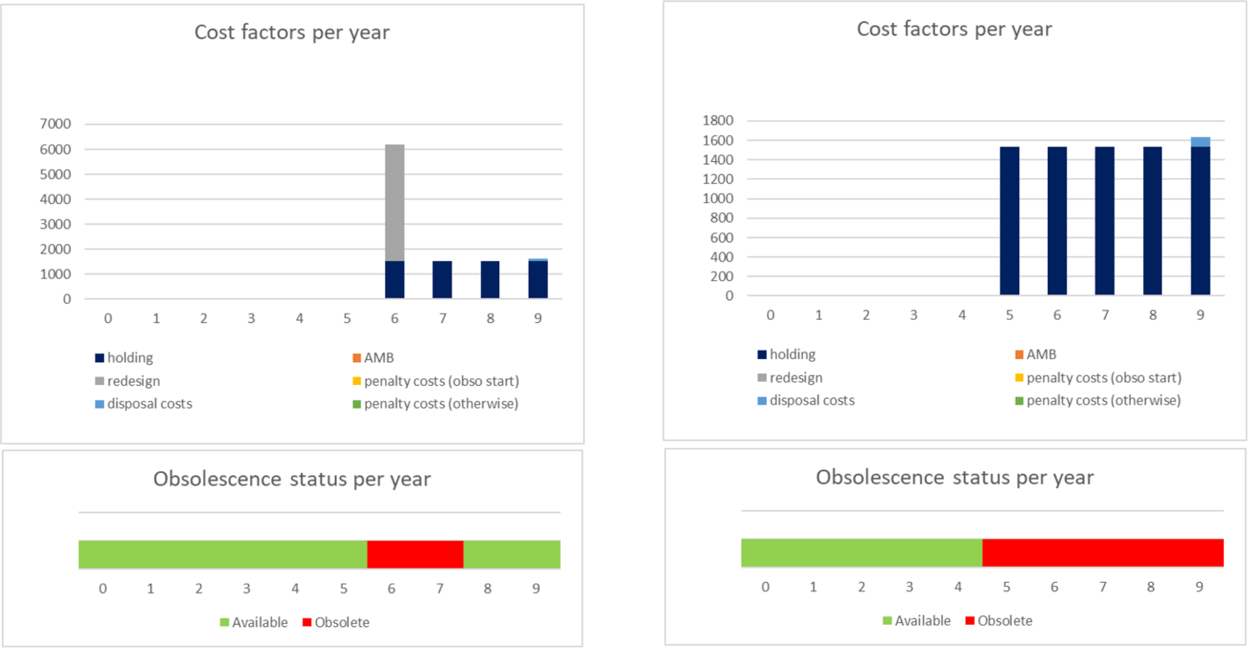
(a) current policy and simple policy 1

(b) simple policy 2, suggested policy 1 and suggested policy 2

Figure H.1: Example output of an electronic LRU with high material costs and low redesign costs

H.2 Explanation for the sub-optimal performance of the second simple policy

In general, the second simple policy performs quite well in comparison to the other four implemented policies within the carried out experiments. For some LRUs however, it is illogical to initiate a redesign once the LRU turns obsolete. Figure H.2 shows this for an example LRU. Since the LRU can be repaired and has a high MTBF value, ordering 1 spare when the item turns obsolete is enough to meet expected demand within the remaining contracted period, as shown in Figure H.2b. Since an LTB of 1 spare part will also be performed in case a redesign is initiated, it does not make sense to perform a redesign at all for this LRU.



(a) simple policy 2

(b) suggested policy 1 and suggested policy 2

Figure H.2: Example output of an electronic LRU with a high MTBF and low material cost

H.3 Explanation for difference in performance of the two suggested policies

Figure H.3 shows an example of an LRU where suggested policy 1 outperforms suggested policy 2. Since suggested policy 2 assumes only 1 redesign can be initiated during the remaining contracted period, it performs an LTB for a longer period to procrastinate the initiation of a redesign, as Figure H.3b shows. This example shows the following:

- When multiple redesigns for an LRU are possible within the contracted period, suggested policy 2 might make unrealistic decisions.
- These decisions have a significant effect on the resolution costs in case the holding costs of an LRU are high.

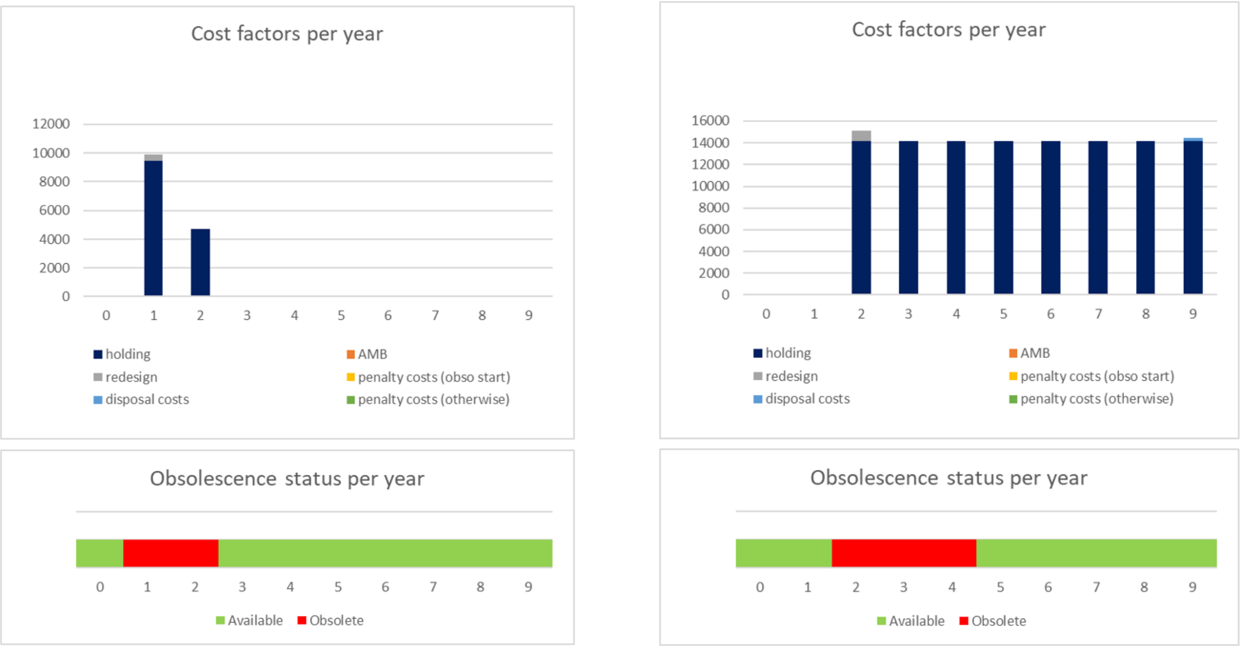
(a) suggested policy 1

(b) suggested policy 2

Figure H.3: Example output of an LRU which turns obsolete quickly after a redesign

H.4 Example of increased costs due to a change in redesign lead time

Figure H.4 shows that when the redesign lead time increases for an LRU, the LTB quantity likely increases as well, to make sure demand during lead time can be met with the required certainty percentage. As a result, the holding costs increase.



(a) Redesign lead time of 2 years

(b) Redesign lead time of 3 years

Figure H.4: Difference in LTB quantity for an LRU when the redesign lead time changes

H.5 Example of an increase in repair time frame

Figure H.5a shows an example simulation run in which an expensive redesign is initiated in year 5 for a repairable LRU. This is required since LRUs cannot be repaired anymore from period 7 onwards. When the LRU loses its repair capability, expected LRU demand increases by factor 10 compared to earlier periods (due to a repair yield of 90%). Figure H.5b shows a simulation run in which no redesign is initiated for the same LRU. Since repairs can be performed during the remaining contracted period within this example, performing an LTB of 5 pieces is enough to meet expected demand during the remaining period. This example shows compelling cost savings can be made when the repair time frame is extended for LRUs with high redesign and holding costs.

(a) Repair time frame of 5 years

(b) Repair time frame of 10 years

Figure H.5: Example output of a repairable LRU

H.6 Example of a reduction in certainty percentage

Figure H.6 shows that a higher LTB quantity (3) is used when a certainty percentage of 99% is used in comparison to a certainty percentage of 95%. In the latter case, an LTB quantity of 2 is used.

(a) certainty percentage of 99%

(b) certainty percentage of 95%

Figure H.6: Example LRU output when the certainty percentage is reduced