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The impact of Additive Manufacturing on the life cycle cost of one-off parts at Thales Hengelo

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Management summary

Thales is a company active in a business which produces expensive, technological, highly complex systems for its customers. Because of these characteristics, Thales guarantees their customer a specific life span in which Thales will be able to deliver spare parts. This life span can be longer than 30 years. As result of this long lifespan, production techniques as well as production tools must be maintained for a long period, or parts/processes must be redesigned to be able to deliver spare parts. The use of additive manufacturing could be a solution to overcome several difficulties with respect to the production of parts during the after-sales phase of parts/systems.

Background

Thales is aware of the potential and possibilities regarding additive manufacturing (AM). However, Thales is not familiar with the impact of AM with respect to the life cycle. Therefore, a model is constructed which can assess the impact to introduce AM at the optimal moment during the life cycle. Since there are a lot of uncertainties with respect to the quality of additive manufactured products, the model is constructed for parts that only fail because of external incidents such as extreme weather conditions, damage during inspection, or damage during maintenance instances, battle damage, etc. These parts don't fail because of wear and tear or use. The parts are called 'one-off parts'.

The goal of this research is 'construct a model to assess the impact of the transition from conventional manufacturing (CM) to AM on the life cycle costs of one-off parts within radar systems at Thales Hengelo'. With the use of the model, the research can answer the following research question:

´How can Thales Hengelo use additive manufacturing, in order to decrease life cycle cost of one-off parts?'

With the use of the model, important developments regarding additive manufacturing can be identified as well as important parameters. By monitoring and investigating these developments and characteristics Thales can determine the potential of other parts.

Approach

For the construction of the model, cost factors are identified which benefit from AM processes compared to CM processes. Additionally, literature related to life cycle analysis as well as existing life cycle costing models were reviewed. Besides, the current LCC analysis used by Thales is reviewed to identify important cost factors which are specific to the business in which Thales is operating. After the identification of the relevant cost factors, the model is constructed using the principles of 'stochastic dynamic programming'. This is a modelling method, which uses backwards recursion to determine the optimal solution of a given problem.

The principle of the model, is that the life cycle of a part is divided into multiple periods. At the start of every period, a couple of decisions are taken to minimize the costs associated with the production of one-off parts. The decisions are related to which manufacturing method is used in case production takes place during a period, either CM or AM. The second decision is, the number of parts to produce to put in inventory during a period. The third decision is related to special tooling. In case special tooling is available at the start of a period, a third decision has to be made. Werther to keep the special tooling in

inventory or to discard the special tooling. The last decision is about preparing the AM method or not. The cost factors which are considered regarding the cost calculation are:

- Production costs
- Downtime costs
- Preparation costs of the manufacturing methods
- Costs associated with inventory
- Salvage value of inventory

The model is validated by several experts in the field of AM working at Thales as well as experts from Thales's partners. In addition, the model is verified by means of a discrete event simulation. During this simulation, the demand of parts is simulated and the corresponding costs are calculated. The average results of the simulation are approximately the same of the results of the model.

Results

Based on the result of the analysis of the model, it can be concluded that AM in combination with the use of inventory of parts, can decrease the life cycle cost of one-off parts. Two case studies of different parts, the protection cover and the sunshade, show the impact. The analysis of the protection cover results in cost savings between 16,07% (€67.000) and 17,06% (€72.000). It must be noted, a cost saving of €38.000 (8,42%) is a result of the use of inventory. So, only looking at AM results in a cost saving between €29.000 (7,65%) and €34.000 (8,64%). The analysis of the sunshade results in cost savings between7,14% (€5.500) and 9,55% (€8.000) over a period of 30 years in case we use AM during the after-sales phase. The cost savings of AM are a result of the use of AM, since no parts are put in inventory. The cost savings are dependent on the current way Thales deals with its special tooling. Is special tooling discarded in the optimal way, or does Thales apply their own discarding strategy.

From the sensitivity analysis, four parameters turned out to be sensitive towards the outcome of the model. The most important parameter, is 'the variable production costs of the AM method', the other three are the life cycle length of the analysis, the demand rate of a single part per period, and the acquisition price of special tooling. In case the value of the variable production costs of the AM method becomes almost equal to the variable production costs in case of CM, AM will be used for the production of parts during the after-sales phase as well as for the production of parts within the initial phase. At that moment, AM will replace CM completely for that type of part. Regarding the protection cover, the variable production costs in case of CM have be declined after 6 years to the value of €5.678, where production will only take place by means of AM. This results in cost savings between 23,99% and 24,88%. Regarding the sunshade, the variable production costs in case of CM have be declined after 3 years to the value of €1.135, where production will only take place by means of AM. This results in cost savings between 16,88% and 19,50%.

Regarding the other sensitive parameters, we can conclude that:

- The use of AM results in higher cost savings if the life cycle length of the analysis increase
- The use of AM results in higher cost savings if the demand rate of a single part per period increase
- The use of AM results in higher cost savings if the acquisition price of special tooling increase

List of Abbreviations

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

SINTAS:	Sustainability Impact of New Technologies on After-sales service Supply chains
CM:	Conventional Manufacturing
AM:	Additive Manufacturing
LCC:	Life Cycle Cost
CAD:	Computer-aided design
STL:	Stereolithographic
STIR:	Signal Tracking and Illumination radar
SA:	Sensitivity analysis

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Preface

You have before you the result of my graduation project at Thales Hengelo about the subject: "the impact of Additive Manufacturing on the Life Cycle Cost of one-off parts at Thales Hengelo". This thesis completes my Master Program Industrial Engineering and Management, specialisation track: Production and Logistics Management, at the University of Twente. During the last months of my study I worked with a lot of pleasure at the worldwide leader of the production of the latest and most innovative radar technologies and radar systems.

I would like to thank my coordinators at Thales: Aad van den Berg and Jeroen van der Wel for their support, feedback and guidance throughout my research. Additionally, I want to thank the people within the mechanical design department. They made me feel welcome directly from the start of the research. Also, great thanks towards people within the logistical department, especially Jord Bolhaar and Robert Sauer for the information and insights provided.

I would also like to thank my coordinators form the University of Twente. I would like to thank Matthieu van der Heijden. First because Matthieu brought me into contact with Aad and Jeroen, and because of his support and feedback on my thesis. I also want to thank Nils Knofius for his feedback and opinions with respect to the research. Thank you both very much for this.

Finally, I want to thank the partners within the SINTAS project. During my second day of my graduation project, I was invited to one of their meetings. I think it was a pleasant and informative meeting where I met interesting people and learned a lot of insights with respect to additive manufacturing in the after-sales service supply chains.

Michel Reimert

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1 Introduction

This research is carried out on behalf of Thales Nederland B.V. as part of a project called “Sustainability Impact of New Technologies on After-sales service Supply chains” (SINTAS). The research focusses on the impact of the use of Additive Manufacturing (AM) instead of Conventional Manufacturing (CM) on the Life Cycle Cost (LCC) associated with the production of ‘mechanical one-off parts’ at Thales.

1.1 Thales Nederland B.V.

Thales Nederland B.V. is the Dutch division of the Thales Group. Thales Nederland is specialized in the Defence, Security and Transportation Systems sectors. Thales is focussed on solutions in the field of Safety and Security. In the Netherlands, Thales has five offices, one in Hengelo (OV), one in Huizen, one in Delft, one in Eindhoven, and one in Enschede. This research will be performed in Hengelo (OV), where Thales’s NL head office is located. In addition, since 1922, this location is worldwide leader in the latest and most innovative radar technologies and radar systems for naval ships (Thales Group, 2016). In Hengelo, Thales develops and produces radar systems, command and control systems, and sensor & weapon system integrators for combat management systems. Besides the production, Thales delivers different types of after-sales services to their customer. These after-sales services range from delivering spare parts to customer, to system availability contracts.

1.2 The SINTAS project

Thales is currently involved in a research project conducted by the University of Twente and Eindhoven University of technology, together with partners from the industry and other partners from defence. In the SINTAS project, the possibilities of producing spare parts through AM, popularly known as 3D printing, are examined. The focus is on the impact on failure behaviour and maintainability, and the redesign and planning of spare parts supply chains when 3D printing will (partially) replace CM. Thales participates in this project, because it is interested in the development of innovative production techniques such as AM. Besides, the advantages of improving the functionality and performance of parts is interesting. Thales also expects advantages with respect to the production processes and logistical aspects, particularly in the after-sales service.

1.3 Additive Manufacturing

The SINTAS project focusses on AM. This is a process of joining materials to make objects from 3D model data, usually layer upon layer (American Society for Testing and Materials, 2012). During the manufacturing process layers of material, as finite 2D cross-sections of the 3D model, are added together resulting in a 3D object (Gibson, Rosen, & Stucker, 2010). In this way, it is possible to construct complex parts, which wouldn’t be feasible by using known CM methods. Additionally, there are other benefits because of the transition from CM to AM. On the other hand, there are drawbacks incurred with the transition from CM to AM. For these benefits and drawbacks, we refer to Section 4.1. Regarding the benefits and drawbacks, at this point in time, AM seems particularly useful for the manufacturing of low volume and customer-specific products, since there is no need for high amounts of individual products to refinance the tools, like with traditional manufacturing (Lindemann, Jahnke, Moi, & Koch, 2012).

1.4 Problem description

Thales Hengelo delivers particularly radar systems to its customers all over the world. Radar systems produced by Thales have a lifetime between 40 and 60 years and some systems even over 60 years. In general, radar systems are 5 to 10 years in R&D, followed by 25 to 35 years of first customer use. After the first customer, some systems get a second customer. In some of these cases, the second customer arranges an after-sales service period, which could have a duration of 20 years in which Thales must be able to deliver spare parts. This implies, Thales has a long after-sales service period to cover. During this long period, Thales has to deal with all kind of difficulties as a result of CM processes. While radar systems get older, production through CM may become more expensive. For example, through declining demand, batch size decrease while fixed costs stay constant. Machines become obsolete or are replaced by new ones resulting in a necessity for redesign of existing parts. All kinds of tooling, like casting moulds, have to be produced and stored for a long period of time without knowing if they will be used ever again. All these issues ensure high costs during the life span of spare parts.

As a substitute for CM processes, Thales is looking at options regarding the use of AM processes. Since parts used by Thales must meet high requirements, a lot of parts are not eligible for production by means of AM, at this point in time. However, if at a certain point in time AM processes can meet the requirements, are AM processes in that case interesting for Thales to use for the manufacturing of parts and to what extent. This could be translated into the following problem:

“The impact on the use of Additive Manufacturing processes on several areas (such as failure behaviour, manufacturing capabilities, costs) is partially unknown for a lot of businesses including Thales”.

Since the use of AM has impact on a lot of areas, we will specify our research. From previous research, it turns out that some mechanical parts which fail because of ‘special’ incidents, can be printed at this point in time. ‘Special’ incidents resulting in a failure are random events which can’t be prevented. Examples are extreme weather conditions, imprudence during maintenance, battle damage, etc. Since these parts fail because of random incidents, we don’t have to include the impact of use of AM on subjects like quality and performance. For these mechanical parts, they don’t play an important role. Therefore, we will focus on the impact of the costs on these mechanical parts during the entire life cycle, if AM is used to what extent whatsoever. From now on, the mechanical parts which can be printed are called ‘one-off parts’. Therefore, this research deals with the problem:

“Thales does not know the impact of the use of Additive Manufacturing processes on the Life Cycle Costs of one-off parts”.

1.5 Research goal

The goal of this research is to:

“Construct a model to assess the impact of the use of <u>Additive Manufacturing</u> instead of the use of <u>Conventional Manufacturing</u> at some moment during the life cycle, on the <u>Life Cycle Cost</u> of <u>one-off parts</u> within radar systems at Thales Hengelo”.

<u>Conventional Manufacturing:</u> manufacturing of parts, by means of known processes such as: drilling, milling, casting etc.

Additive Manufacturing: as stated before, AM is a process of joining materials to make objects from 3D model data, usually layer upon layer (American Society for Testing and Materials, 2012).

Life Cycle Cost: during this research, we will define LCC as: "the sum of all costs affected by using AM instead of CM, during the life span of a one-off part". Regarding the life span of these parts we distinguish four different phases: design & development, production, use, and disposal (Asiedu & Gu, 1998), (Fixson, 2004), (Woodward, 1997).

One-off parts: we consider only mechanical one-off parts. Because of technological restrictions concerning AM techniques, electronic spare parts can't by produced at this moment in time, so we only consider mechanical parts. In addition, *One-off parts,* are parts that fail because of external incidents such as extreme weather conditions, damage during inspection, or damage during maintenance instances, battle damage, etc. These parts don't have a predetermined Mean Time To Failure (MTTF). Other characteristics of one-off parts are:

- One-off parts are not subjected to redesign
- One-off parts are mechanical structures which do not need any type of consumable (lubricants, cooling liquids, tapes, fuel, etc.)
- One-off parts do not require human interaction while operating

As part of the SINTAS project, a research has been performed within Thales called 'Additive Manufacturing and Thales' After Sales Service' by Katgert (2015). This research was focussed on the development of a framework to identify interesting spare parts applicable for AM. Parts identified during this research, where mostly parts assembled from a set of subcomponents instead of parts used for the assembly.

The model constructed in this research should be able to assess the impact of AM on the LCC of one-off parts based on data available within Thales and expert opinions. We will perform a LCC analysis to determine the cost factors affected by the transition from CM to AM, so the model can determine the optimal manufacturing strategy for one-off parts during their entire life span.

1.6 Research scope

The focus concerning the model is on the production of parts in new radar systems. Since remodelling of existing parts applicable for AM, can take up to over 100 hours and thus can cost a lot of money, Thales wants to focus on new parts. In order to validate the model, however, we will use parts which are currently produced by means of CM.

Problems concerning certification of one-off parts produced by AM are left out of the scope of this research. Certification focusses on the quality of parts. Determination of the quality of AM produced parts, can be seen as a research on its own. The same holds for the difficulties concerning intellectual property. That is why also these difficulties are left out of the scope of this research.

In addition, we must note that Thales doesn't produce any of the one-off parts itself. All one-off parts are bought at suppliers. Thales is focused on the development, design and assembly of radar systems. Therefore, we assume that production by means of AM will be outsourced to third parties, as is done with CM produced parts as well at this moment in time. We must take this into account, because it will influence the outcome of research.

1.7 Research question

Based on the problem description, and the research goal, we have formulated the following main research question:

"How can Thales Hengelo use <u>Additive Manufacturing</u>, in order to decrease <u>Life Cycle Cost</u> of <u>one-off</u> <u>*parts*</u>*?"*

We will answer the main question by the following research questions.

Chapter 2: Current situation
In Chapter 2, we will analyse the cost factors used to determine the current LCC at Thales. Therefore, we have formulated the following question:

Which cost factors determine the Life Cycle Cost at Thales, at this moment in time?

It is important to understand the current LCC method used by Thales. In order to determine whether AM might be better in terms of LCC in comparison with the current production methods, we have to evaluate the current process. This might be done, based on variables used to determine the current LCC. This question will be answered based on the following sub questions:

1) What are LCC according to Thales?
2) Which variables are used to determining LCC at Thales?

During the first step to answer this research question, we will determine the definition of LCC as it is at Thales at this moment. Hereafter, we will identify the variables that influence the LCC according to Thales. We end with a description of the variables Thales uses for the calculation of their current LCC and we will also mention important variables which are left out of the LCC calculation performed by Thales. We will interview employees to discuss which variables are used.

Chapter 3: Literature study
In order to construct a proper model, we will perform a literature study in order to determine the cost factors which affect the LCC of one-off parts because of the transition in manufacturing method from CM to AM. Therefore, we will discuss the principles of AM. Hereafter, we have to research the principles of LCC, based on literature LCC and determine how LCC is used during this research. The following questions will be discussed in Chapter 3:

1) What is AM?
    a. What are the benefits of AM?
    b. What are the drawbacks of AM?
2) How is the term LCC used during this research?
3) How is a LCC analysis performed according literature?

First we will define AM, give an overview of the most common used AM methods, and outline the general process steps in case of AM. Hereafter, we will define LCC as it will be used during this research. Furthermore, since this research is focused on the fact how AM can be used to decrease LCC of one-off parts within Thales, we will perform a LCC analysis. Therefore, we will describe a strategy to perform a LCC analysis. The questions in this chapter will be answered, based on literature.

In the end, we will describe a LCC model from literature to get an insight in relevant cost factors according literature. We can compare the cost factors used in literature and the cost factors currently used for a LCC analysis according Chapter 2, to see if there are differences. Perhaps, critical cost factors are missing in one of the models. These cost factors may have to be investigated more extensively in Chapter 4, than other more common cost factors.

Chapter 4: Cost factors of Additive Manufacturing affecting Life Cycle Cost
Based on the information in Chapter 3, we will identify the cost factors which are affected within Thales if AM will be used instead of CM on the LCC of one-off parts. We will answer the following question:

> *Which cost factors affect LCC when switching from Conventional Manufacturing to Additive Manufacturing?*

This question will be answered by linking cost factors mentioned in literature to the specific situation as it is at Thales. A lot of studies identify cost factors to determine the LCC in case of AM. During this research, however, we are only interested in the cost factors that affect the cost over the entire life cycle, of one-off parts in case AM is used instead of CM. We will do this by discussing the cost factors of LCC in case of AM, with the benefits and drawbacks of AM.

Chapter 5: Case description
In order to validate the model at the end of our research, we need cases to check the model. Therefore, we have formulated the following research question which will be discussed in Chapter 5:

> *Which parts could be used as a case during this research in order to verify the model?*

For the selecting of potential cases we will use the report of Katgert (2015), as previously mentioned in Section 1.4. The report includes an intensive investigation towards a method to identify the best spare parts available for production by AM. Additionally, the report indicates potential parts, which could be printed despite the current restrictions with respect to AM. We will investigate the parts adduced in the report, and look for similar type of parts. Since the report includes an intensive investigation towards potential parts for AM, the research won't be carried out again.

Chapter 6: Construction of a model specific to Thales

After answering the previous research questions, we have to focus our knowledge on a model which can be used by Thales. Therefore, we will answer following question in Chapter 7:

> *How can a model that assesses the impact of AM on the LCC at Thales be constructed?*

Because the radar systems at Thales have a lifetime of ± 70 years, we have to keep in mind variables which may be different from other models. The goal of the model is to determine the optimal production strategy for the one-off part which is analysed. In order to answer this question, we formulated two question which will be answered in Chapter 6:

1) Which method should be used to construct a model?
2) How is the model formulated to assess the impact of AM?

In the previous questions, we have gathered all variables of interest so now we can construct a model with all relevant parameters on the situation of Thales. A model will be constructed in Excel. The model will describe the difference between CM and AM in terms of variables. The necessary data required for the model will be based on existing data within Thales. This will be data obtained by means of interviews as well as data obtained from databases. If there is a lack for data, we will construct statistical models in order to predict the data. These models are based upon literature and on the opinion of the experts at Thales. For the data related to AM, we will use literature, expert opinions and other available information sources like internet websites.

Chapter 7: Analysis of the model

At last, we will analyse the model. Based on this analysis we will evaluate the potential of AM.

In what situations can Thales use AM, to decrease the life cycle cost?

With the model, we will be able to identify the optimal production strategy which minimizes total LCC associated with the manufacturing of a one-off part. In order to be able to determine other results, we will make use of a simulation model.

Chapter 8: Conclusions and Recommendations

What are the conclusions of this research and what are the recommendations?

Finally, we will end this report with the conclusions of this study. Furthermore, we will come up with recommendations towards the current way Thales handles it after-sales supply chain and with recommendations towards further research.

2 Current situation

In this chapter, we describe the current model which is used by Thales to determine the cost of their systems during the entire life cycle. We start with a short introduction which shows an overview of the costs included and the costs excluded with respect to the model used by Thales. Hereafter, we describe to what extend the model is applied, which assumptions are made regarding the model, and we describe in detail the cost factors which are considered. Finally, based on three cases, we will determine the influence of the different cost factors compared to the total costs. All information is obtained by means of interviews and an internal document used by Thales (Thales Nederland B.V., 2016).

2.1 Life Cycle Cost at Thales at this moment in time

At this moment in time, Thales uses a standard LCC model to analyse the costs of a system during its life cycle. The purpose of this analysis, is to provide their internal and external customers, background cost information in order to evaluate design choices or to identify quick wins to reduce costs. The internal customers are the different design departments within Thales. Costs incurred in this model are the acquisition costs to get the system up and running and the operational costs to keep the system available. The different cost factors considered by Thales regarding the LCC model of a complete system, are described in a cost breakdown structure, see Figure 1. The cost breakdown structure used by Thales, is a by Thales self-developed method based on NATO guidelines to categorize costs for naval radar systems according a fixed procedure. This method is described in (Thales Nederland B.V., 2016). We must note, the costs of every cost element are calculated based on the entire radar system the customer purchases. In order to create more understanding of the costs, we will discuss every cost element included in the standard LCC analysis in more detail in Section 2.2. Some costs are excluded in a standard product LCC analysis. These costs are out of scope of the specific analysis, or the costs can't be estimated with any reasonable accuracy (Thales Nederland B.V., 2016).

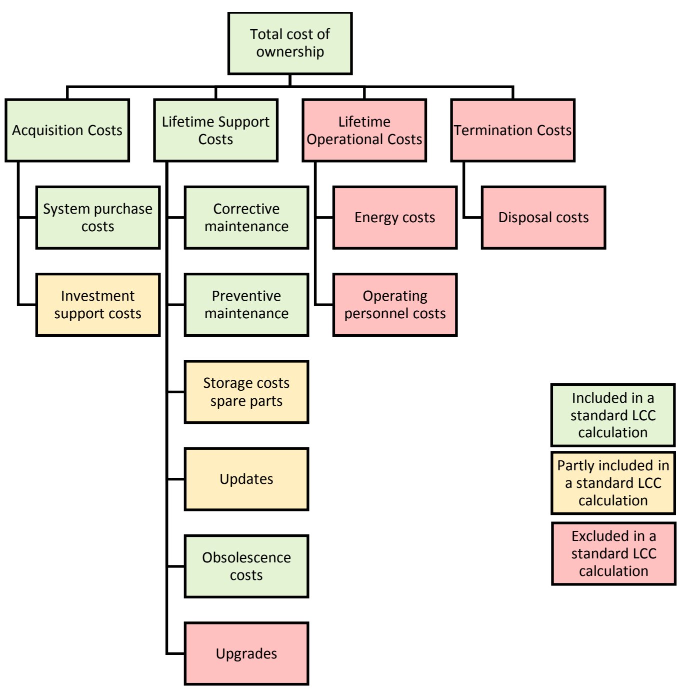

Figure 1: Cost breakdown structure of the life cycle cost, as developed by Thales

2.2 Standard Life Cycle Cost at Thales

The standard LCC analysis at Thales is used to give a customer an indication of the total costs of a system during a certain lifetime. Since every customer has different requirements and preferences concerning the acquisition and use of a system, Thales first constructs a so called 'Navy profile'. This 'Navy profile' contains a default profile in which, on request data could be altered. Hereafter, based on the 'Navy profile' the standard LCC is calculated. In Section 2.2.1 we describe the 'Navy profile'. Additionally, there is a financial profile, which we describe in Section 2.2.2. In Section 2.2.3 we will describe the cost factors used for the calculation of the standard LCC, and in Section 2.2.4 we will discuss cost factors mentioned in the internal document for used by Thales for calculation of the LCC, but are excluded in a standard LCC analysis (Thales Nederland B.V., 2016).

The standard LCC analysis is only used for a 'simple' cost indication for the customer. When a standard LCC analysis is performed, it isn't reviewed or evaluated at a later point in time to determine the level of correctness of the estimates or to determine the correctness of the analysis.

2.2.1 Navy profile *(the numbers are confidential and must be blanked in the public report)*

In the Navy profile, assumptions are made with respect to performance requirements of the system, the navy size of the customer, and operational settings of the system. There are assumptions made with respect to the following data (see Appendix 1 which is confidential, for their associated values):

- Number of bases, and ships per base
- Yearly operational hours per ship
- No lateral transhipments of spares between ships
- Logistical availability target
- Average mission duration
- Average repair turnaround time (TAT)
    - Time between the moment a customer sends a failed part away for repair and the moment the part is returned to the customer
- Purchasing lead times
- Fraction of successful repair of spares of all repairs performed
- The designed Mean Time To Repair (MTTR)
    - The time it takes to repair a failed part. This is different for different echelon levels
- Mean Time Between Failures (MTBF)

Some assumptions are customer specific, these assumptions are described below, the values presented are based on the Dutch naval profile:

- Operational life cycle of the system
- Obsolescence is always covered by last time buy
- Time period between major overhauls, including an estimation of the overhaul costs as a % of the total purchase price of the system
- The time between successive training programmes of personnel

2.2.2 Financial profile

Since the LCC analysis covers a relative long time period, Thales creates a profile with respect to financial assumptions. The following assumptions are made with respect to the model:

- Based on Dutch Navy Unit Selling Prices of items
- No costs on interest
- No yearly discount factors
- No inflation on price
- No reduced prices by multi-buy, larger quantities etc.

2.2.3 Cost factors used during a standard Life Cycle Cost analysis at Thales

The cost factors which Thales uses for their standard LCC calculation are:

Acquisition costs

The acquisition costs, are the costs for the customer that incur before the customer can use the system. Thales distinguishes two types of acquisition costs. One part of the acquisition costs, are the costs incurred with the purchasing of the physical system and to make it operational. These costs consist of the hardware, the software, the delivery, and the installation of the radar system. The second part of the acquisition costs are the initial costs to support the radar system. These support costs consist of an investment in initial spares, an investment in special tooling as well as in common tooling, and an investment in the training of personnel in order to operate the system. The special tooling, as well as the tooling bought by a customer, are both intended for maintenance activities.

Lifetime support costs

The lifetime support costs are broken down into six subcategories. There are two maintenance categories: corrective maintenance and preventive maintenance, the other categories are costs as result of the storage of parts, update and upgrade costs of the system, and costs of obsolescence of parts. The costs of an upgrade of the system is excluded which will be discussed in Section 2.2.4.

Maintenance

In both maintenance categories, personnel of different skill levels perform maintenance tasks such as replenishment of spare parts as well as repair of spare parts. These tasks will be performed by personnel from the navy itself (personnel cost, in Appendix 2). Besides, in some cases parts are send back to the OEM for repair or refurbishment (repair of spares, in Appendix 2). In addition, both categories need spare parts which ensure costs (acquisition, transportation, and storage) (replenishment of spares, in Appendix 2). Preventive maintenance has an extra costs element: costs of an overhaul (overhaul, in Appendix 2). The costs of an overhaul could be seen as the costs of periodically replacement of parts in order to restore the system requirements and ensure the reliability of the system until the next overhaul.

Storage costs

The storage costs of spare parts include, insurance and warehouse building expenses (room, heating/cooling, storage maintenance etc.) (Thales Nederland B.V., 2016).

Updates
Updates are renewals of the system in order to deliver the same performances of the systems on the long term. The costs which are taking into account, are the costs of training of personnel in order to operate the system in the most efficient and most effective way (recurring training).

Costs of obsolescence
The costs of obsolescence consist of costs incurred during obsolescence monitoring, costs of redesign, and the costs of a last time buy. In order to identify the moment to perform a last time buy, Thales monitors supplier disruption of parts (mostly LRU's and SRU's).

The costs incurred as result of a redesign of parts. Thales distinguishes three reasons for a redesign (beyond economic reasons, and malfunction). One reason is that the last time buy option is not (no longer) available. A second reason, is that the last time buy was not sufficient to cover demand during the rest of the lifecycle. A third reason is the large uncertainty in estimating the size of a last time buy thereby introducing too much risk in order to proceed the last time buy option, making a redesign favourable over a last time buy.

The last cost factor of the costs of obsolescence, consists of the costs of the last time buy. These costs are a result of the fact that too many parts are purchased during the last time buy.

2.2.4 Cost factors excluded from a standard Life Cycle Cost analysis at Thales

The cost factors which Thales excludes from their standard LCC analysis are (Thales Nederland B.V., 2016):

Acquisition costs
During the acquisition phase, costs are made to support the radar system. Costs like the investments in consumables and manuals are not taken into account since they are negligible.

Lifetime support costs
The costs of upgrades are completely left out of the LCC analysis. Upgrade costs exist out of improvements on the system in order to realize more/better functions and/or capabilities. Most upgrades are done between 10 and 20 years after the customer purchased the system. Additionally, not every customer wants an upgrade and if they want an upgrade it has to meet their specific requirements. For these two reasons the upgrade costs vary a lot, are subjected to a lot of uncertainties, and thus excluded in a standard LCC analysis. For the same reason, costs of system renewals concerning the updates are excluded as well. Not every customer is interested in the same (level of) updates. Other cost factors which are excluded are part of the storage costs such as invested capital, insurance, depreciation of parts, and costs of deterioration of parts.

Lifetime operational costs
The operational costs during the systems life span consists of the energy costs and the costs for personnel in order to operate the system. The energy costs of a radar system are negligible compared to the energy consumption of the entire ship. For personnel costs, it holds that it is difficult to assign a number of employees to a system. It is for example difficult to assign supportive employees (the doctor, the kitchen staff etc.) on board of a ship to a specific function/system on board. Therefore, the operational costs during the lifetime are completely left out of a standard LCC analysis.

Disposal costs
At the end of the lifecycle systems are disposed. Since the systems were used on a naval ship, in many cases they have to be demilitarized. Thereby, the disposal costs include detoxification, long-term waste storage, and domestic recycling. Therefore, these costs are hard to determine so, none of the disposal costs are included in a standard LCC analysis.

2.3 Example of a standard LCC analysis

Finally, we determine the relative influence of the included cost factors during a standard LCC analysis of a system. Since different systems, consist of complete other technologies, size, etc. we are not interested in absolute numbers. We are interested in relative ratios of the different cost factors in the current situation using CM based on the total costs regarding the current situation. By using relative ratios, we are able to analyse the influence of different cost factors over all systems, instead of analysing the influence of different cost factors per system. We will determine the different cost ratios as an average based on three cases. Because of confidentiality reasons, the cases are excluded in this research. As mentioned before, the standard LCC analysis is customer specific. Since all three examples are based on the Dutch Navy as 'Navy profile', we will use the Dutch Navy as our customer. In Appendix 2, the ratios of all cost factor, as described in Section 2.2.3, are given.

There are a few cost factors which stand out directly in Appendix 2. The costs of overhaul look sky high compared to all other cost factors. Likewise, the obsolescence costs seem to be relatively high compared to other cost factors. On the other hand, the total costs of all costs factors related to the initial spares and replenishment of spare seem relatively low, the same holds for the storage costs of spare parts.

The reason why the costs of overhaul are that high, is because overhauls could be seen as an investment in the system to make it as good as new. This also includes, costs related to preventive spare parts which are replaced after a certain period, as mentioned in Section 2.2.1. Since it includes costs related to preventive spare parts, the relative low costs of the other cost factors of spare parts can be explained.

The low storage costs can be explained by the fact that the invested capital, insurance, depreciation of parts, and costs of deterioration of parts are excluded in the storage costs. It can be argued whether this number is realistic, however, we know the reason why the storage costs are relatively low

The last cost factor, the obsolescence costs, is the cost factor which needs the most attention. We can argue, that systems produced by Thales have a long lifetime, and that manufacturing techniques change over time or are replaced by new ones resulting in costs. However, since obsolescence costs can be seen as non-value added costs, this cost factor should be investigated to determine how it could be lowered in the future.

2.4 Conclusion

The LCC analysis as performed by Thales is focused on a complete radar system. The model constructed during this research, however, is focussed on individual one-off parts (or maybe small assemblies) instead of complete systems. This results in the fact, that parts aren't evaluated as part of a final system. Additionally, the type of parts evaluated (mechanical one-off parts) are because of their characteristics (as described in Section 1.4) not subjected to operational costs in terms of 'energy costs' or 'operating personnel costs' or similar costs.

The cost factors we will focus on, are the cost factors who influence the cost associated with one-off parts. These are the cost factors as a result of the production of new parts (in Figure 1: acquisition costs) and cost factors as a result of the after-sales service (in Figure 1: lifetime support costs). Therefore, we might use the cost factors mentioned during this chapter as cost factor for our own model. In order to develop a broader view with respect to relevant cost factors that might occur during the production phase and the after-sales phase, we will perform a literature study towards LCC analysis in Section 3.2.

Regarding Appendix 2, we can conclude that in the current LCC analysis the costs of obsolescence as result of part monitoring, redesign and last time buy are relatively high compared to other cost factors. This is not surprising, knowing that there is little to no policy formulated for demand of parts other than spare parts. The best possible option, at that moment, is chosen for the 'other parts, which include one-off parts'. This could include redesign, high production costs (because of low production volume and/or high tooling costs). For the one-off parts applies that they can be produced in case they are demanded. The one-off parts are not subjected to a high probability of redesign and because of their relative simple production method there will be a supplier who is able to produce this type of parts. The costs in case only one part is produced can be relative high, since a supplier has to set-up a production process for only one part (including the production of tooling).

A cost factor which is lacking in Appendix 2, is the cost factor 'downtime costs'. If a spare part fails and is not in storage (what is realistic regarding the low storage costs) the radar might not be able to operate. Although a radar system doesn't generate revenue, some kind of costs should be taken into account if a radar isn't able to operate because of a failure. At this moment in time, no downtime costs are taken into account in case a failure occurs.

3 Literature study

In this chapter, we perform a literature study in order to develop a broader view with respect to relevant cost factors with respect to the model. Since, we are focused on the impact on the LCC of one-off parts because of the use of AM, we will first describe the principles of Additive Manufacturing (AM). Hereafter, we will describe the principles of Life Cycle Cost (LCC). In Section 3.1, we will define AM and give an overview of the most common used AM methods. In addition, we will outline the general steps that have to be taken in order to manufacture by means of AM. In the end, we will discuss the benefits and drawbacks of AM compared to CM. Hereafter, we will focus on LCC. In Section 3.2, we will define LCC and outline the different phases during a life cycle. In Section 3.3, we describe a strategy from literature, of the steps that need to be taken to perform a LCC analysis. In Section 3.4, we will describe a LCC model based on models found in literature.

3.1 Principles of Additive Manufacturing

The key to how AM works is that parts are built by adding layers of material together (Ford, 2014), (Gibson, et al, 2010), (Khajavi, Partanen, & Holmstöm, 2014). Each layer is a very thin cross-section of a 3D CAD-model. Since, in the physical world each layer must have a finite thickness to it, the constructed part is an approximation of the original 3D CAD model. The thinner the layer, the closer the final part will be to the original 3D CAD model (Gibson, et al., 2010). The thickness of layers is measured in microns, by adding hundreds or thousands of layers together a 3D object emerges. The raw materials used for AM may be in the form of a liquid, a powder, or a sheet and are typically plastics and other polymers, metals, or ceramics (Ford, 2014).

During this research, we use the definition of AM as it is defined in the American Society for Testing and Materials (ASTM) standard F2792 as "a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies".

The most common AM methods include material extrusion, material jetting, binder jetting, sheet lamination, vat photopolymerization, powder bed fusion, and directed energy deposition (Ford, 2014), (Gibson, 2010), (Goa, et al., 2015). Some of these methods melt or soften materials in order to produce layers, while others cure liquid materials or powder materials layer by layer (Ford, 2014). Every AM method roughly exist out of an eight process steps, as described by Gibson et al. (2010):

- Conceptualization and CAD
- Conversion to stereolithographic (STL) file
- Transfer and manipulation of STL file on AM machine
- Machine setup
- Build
- Part removal and clean-up
- Post-processing of part
- Application

For a detailed explanation of the different process steps, see Appendix 3.

The different methods applied in AM have their own benefits and drawbacks compared to their comparable Conventional Manufacturing (CM) method. However, we won't outline the benefits and drawbacks separately for every AM method. This would result in an extensive overview, while AM is not the main focus of this research. In Table 1, an overview is given which summarizes the benefits and drawbacks of AM compared to CM. For the exact benefits and drawbacks per AM method, see the references of Table 1.

Table 1: Benefits and drawbacks of Additive Manufacturing compared to Conventional Manufacturing (Ford, 2014), (Gibson, et al., 2010), (Goa, et al., 2015), (Holmström, et al., 2009).

Benefits of AM	Drawbacks of AM
• Freedom of design • Ability to combine an assembly/integrate functions of parts into one part • No need for tooling • Lower setup costs • Cost efficient mass customization • Quick response time • Decrease in time to the market • Extra complexity of a part comes at no additional production costs • Reduction of material use and a reduction of the amount of waste • Energy savings (where AM is competitive)	• Lack of standards to ensure quality, repeatability and consistency • High costs of machines • High costs of materials • Low diversity of applicable materials • Post-processing of the final product • Limited dimension of the AM machines • Sensitivity of digital product data (protection of intellectual property)

3.2 Definition of 'Life Cycle Cost'

LCC is in literature defined in several ways, depending on the situation and the kind of research. Dhillon (2010) defined LCC as 'the sum of all costs incurred during the life span of a part or system (i.e., the total cost of procurement and ownership). For our research, however, we are especially interested in the cost factors affected by the transition from CM to AM during the life span of a part, rather than all costs incurred during the life span.

In order to identify cost factors, which are relevant concerning the transition from CM to AM, according a structured method, we will distinguish four different phases regarding the life span of a part: design & development, production, use, and disposal (Asiedu & Gu, 1998), (Fixson, 2004), (Woodward, 1997). During each phase of the life cycle, parts are exposed to different processes and activities which all create costs. These costs occur at different points in time. In Figure 2, an overview of activities resulting in possible cost factors is given including an indication of the phase of the life span in which they might occur. These costs are applicable to the situation of Thales as well. One remark has to be made, Thales has to deal with extensive validation and verification costs during the design phase of its parts/systems.

Although most of the costs occur after the design period, as can be seen in Figure 2, studies reported in Dowlatshahi (1992) argue that the design of a product influences the total costs of a product at over 70% of the total LCC. Therefore, the design phase is an important phase in order to control costs in the end.

Choices made during the design phase concerning the complexity and number of parts, affect the manufacturing and assembly costs of parts during the production phase. To give a better understanding of these principles we will shortly explain the ideas behind design for manufacturing (DFM) and design for assembly (DFA). DFM is focused on simple manufacturing processes, in order to reduce the process variability by which we can produce in higher process rates, resulting lower costs and in higher yields. On the other hand, we have DFA focusing on part count reduction, only one assembly direction and symmetrical parts (Boothroyd, 1994). This results in more simple and more cost-efficient assembly processes. These two principles however, affect each other typically in opposing directions. Using different manufacturing processes in order to reduce part count, can have an impact on assembly time and costs and the other way around (Fixson, 2004). Another choice during the design phase affecting the production phase is focused on the use of common parts across product families. When fixed costs of fabrication and assembly can be divided over a large number of units, the costs per unit will decrease. It is important to ensure the extra costs of design for common parts are cost effective compared to the savings (Fixson, 2004). The choice for common parts also influences the costs during the use phase, since personnel is able to operate different machines/systems without the need for extra training (Fixson, 2004). The choices with respect to DFM and DFA might change dramatically in case of AM, because of the ability to construct complex geometries and integrate assemblies as well as combine functions. This could reduce the total design time and effort of parts or a group of parts.

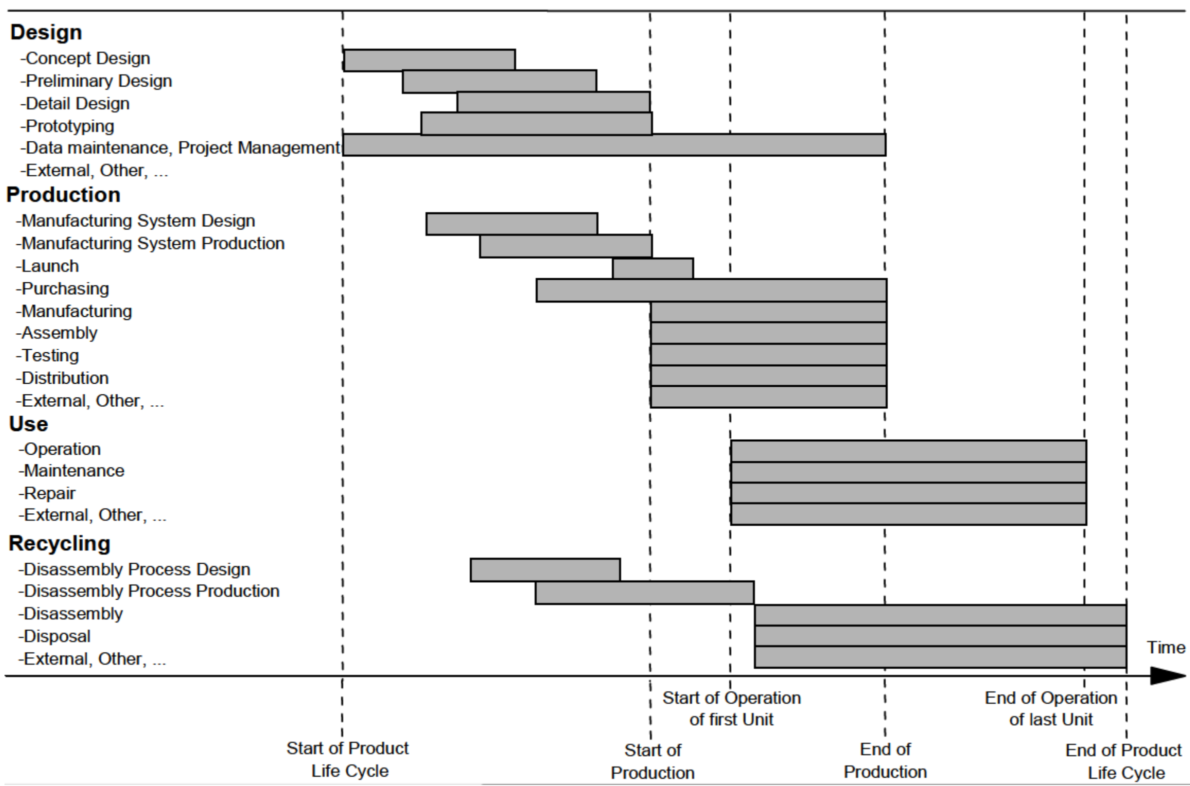

Figure 2: General activities throughout the life cycle (Pine, as cited in Fixson, 2004)

3.3 Performing a Life Cycle Cost analysis

In literature, much has been written concerning models and tools in order to perform a LCC analysis. In order to perform a good analysis, however, the used model and tools are not the only important factors of the analysis. In order to complete a successful LCC analysis, we use a ten steps strategy proposed by Greene & Shaw (1990). The steps are the following:

1. Determine the purpose of the LCC analysis.
2. Define and scope the system/support system.
3. Select the appropriate estimating methodology/LCC models.
4. Gather data and make the appropriate inputs to the methodology/model.
5. Perform sanity checks of inputs and outputs.
6. Perform sensitivity analysis and risk assessment.
7. Formulate the results of the LCC analysis.
8. Document the LCC analysis.
9. Present the LCC analysis.
10. Update the LCC analysis/baseline.

The ten steps mentioned above can be performed in sequence, out of sequence, and some steps can even be performed simultaneously. It doesn't matter in what way they are performed, as long as the analysist ensures all steps are included (Greene & Shaw, 1990).

Determine the purpose of the Life Cycle Cost analysis

The first step regarding a LCC analysis is to determine its purpose. By specifying the purpose, it is more likely that the outcome of the LCC analysis meets the expectations of the requester. The purpose of a LCC analysis may range from a comparative analysis to a cost effectiveness analysis. Other types of LCC analyses are: maintenance concept analysis, LCC estimate, LCC estimate for source selection, trade studies, cost benefit analysis, repair level analysis and provisioning analysis (Greene & Shaw, 1990). This step is already performed in Section 1.5.

Define and scope the system/support system

This is the most difficult step because in the final analysis, the system and subsystems are not fully defined. During this step, we try to identify the following items: statement of need, performance parameters, technical parameters, number of production units and LCC analysis period, schedule parameters and procurement strategy (Greene & Shaw, 1990). This step is performed in Section 3.1 and Section 3.2.

Select the appropriate estimating methodology/LCC models

The selection of which LCC models or methodologies to use, depend on factors such as the type of analysis to be conducted (the purpose of the analysis), the type of system/support system (refers to the number of operating hours of a system) and the life cycle phase of the program (during the different phases different levels of information are available) (Greene & Shaw, 1990). During this research, we will develop a general model to assess the impact of the transition from CM to AM on the LCC of one-off parts. The model should be able to deal with different types of system/support system and different life cycle phases. In Section 3.4, we will introduce a model based on literature which will be used as a guideline/starting point in order to develop a model. In Chapter 4, we will describe relevant cost factors for our model. The model will be constructed in Chapter 6.

Gather data and make the appropriate inputs to the methodology/model
While gathering data for the LCC analysis it is highly likeable some data will be hard to collect. If step 2 is performed thoroughly, we know where to search and whom to talk to (Greene & Shaw, 1990). The collection of data and input will be done throughout the entire research.

Perform sanity checks of inputs and outputs
During this step, incorrect, incomplete, or duplicated data is removed from the collected data to ensure the credibility of the LCC analysis. The most important aspects are to make sure the inputs as well as the outputs are consistent, accurate, valid and complete so no erroneous information is present in the analysis, while at the same time no required information is left out of the analysis (Greene & Shaw, 1990). The same holds as for the previous step. It will be performed throughout the research.

Perform sensitivity analysis and risk assessment
LCC analysis involves making projections, and thus it involves assessing risks and uncertainties. During a LCC analysis all estimates are cost range estimates. There are cost models which express a cost range statistically and there are cost models which provide a point estimate with an automated ability to vary a limited number of parameters, sometimes in combination (without changing inputs) over a range of values (Greene & Shaw, 1990). This will be performed in Chapter 7, where the analysis is described.

Formulate the results of the LCC analysis
At this point, all data is gathered, the methodologies/models are defined, and the sensitivity analysis/risk assessment is performed, so we can process the results. Results can be presented in the form of tables, graphs, data matrices, and data arrays. This can be done in the form of bandwidths or point estimates, because of the high level of uncertainty we will display results in bandwidths. Hereafter, all cross-over areas can be analysed and factors significant influencing the LCC in a positive way or in a negative way can be identified. In the end, the best alternative or set of alternatives will appear (Greene & Shaw, 1990). The results will be formulated in Chapter 7.

Document the LCC analysis
After the LCC analysis is performed it has to be documented. In practice an important step. Even if the analysis excellent, without a proper documentation of the used method and an explanation of the results the analysis is worthless to others (Greene & Shaw, 1990).

Present the LCC analysis
After completion of a LCC analysis, the results may be presented to a group of employees who will serve as a 'jury' who will assess the outcome of the analysis (Greene & Shaw, 1990).

Update the LCC analysis/baseline
The future will ensure changes which should be adapted by the model used during the LCC analysis. After future development of the system, updates will be required. Changes in program/system funding, performance, technical, and schedule parameters might also require updates. Finally, updates may be required because of technical problems or because of erroneous projection of system parameters. When changes are made, it is important they are traceable and trackable back to the initial baseline estimate.

3.4 Life Cycle Cost model

A lot of different LCC models are described in literature. Dhillon (2010), describes six 'General LCC Models' and five 'Specific LCC Models'. For this research, we will construct a LCC model based on these eleven models. With respect to the model, we preserve the distinction between the four separate phases (design & development, production, use, and disposal) during the life cycle of parts. The cost factors taken into account in the model, can be directly related to the activities in every phase as presented in Figure 2.

$$LCC = C_{D\&D} + C_{Production} + C_{Use} + C_{Disposal}$$

Where: LCC is Life Cycle Cost;

$C_{D\&D}$ is costs of Design & Development;
$C_{Production}$ is costs of Production;
C_{Use} is costs of use;
$C_{Disposal}$ is costs of Disposal.

The costs of design & development are composed of the following parameters:

- Costs of the conceptual phase and the definition phase;
- Costs of product planning;
- Costs of product engineering;
- Costs of R&D for tooling;
- Costs of prototyping;
- Costs of test and evaluation;
- Costs of R&D training services and equipment; and
- Costs of design documentation.

The costs of production are composed of the following parameters:

- Costs of manufacturing;
- Costs of quality control;
- Costs of engineering changes; and
- Costs of initial logistics support.

The costs of use are composed of the following parameters:

- Costs of operating personnel;
- Costs of storage of spare parts;
- Costs of transportation of spare parts;
- Costs of handling of spare parts;
- Acquisition costs of spare parts;
- Labour costs of maintenance;
- Costs of downtime of the system;
- Costs of training of personnel (maintenance personnel, operating personnel);
- Consumption costs of liquids, energy, and lubricants; and
- Number of years the system will be in use.

The costs of disposal are composed of the following parameters

- Salvage value of parts;

- Costs of disassembly; and
- Costs of disposal.

3.5 Conclusion

With respect to the cost factors of the different manufacturing methods (CM and AM) we have to take care of the input parameters. As stated in Section 3.2, the price of the machines required for AM and the price of materials required for AM are relatively high compared to the machine and material price in case of CM. However, because of the freedom of design, the principles of DFM and DFA can be ignored resulting in more cost-efficient design & development process. Additionally, the possibility to integrate functions or combine assemblies in case AM is used for production, may influence the total production costs of parts in a positive way. In the end, production by AM is not necessarily (a lot) more expensive than CM. Especially, if one outsources the production, preventing high investment costs as a result of the purchasing of machines.

When we look at the LCC model according literature as described in Section 3.4, we see some cost factors that are included, which are missing in the model of Thales. These cost factors are mainly a result of costs during the after-sales period:

- Costs of transportation of spare parts;
- Costs of handling spare parts; and
- Costs of downtime of the system.

The cost factor 'costs of downtime of the system' was already mentioned in Chapter 2, as a missing cost factor and must be included in our model because one of the benefits of AM is a quicker response time. The use of AM will influence the downtime and thus the cost related to downtime. The costs of transportation and handling of spare parts will influence the cost during the life cycle as well. However, the one-off parts which are taken into account during this research are produced by third parties in case of CM as well as in case of AM. Therefore, the costs of transportation will not differ between the use of CM or AM. So, the costs of transportation of spare parts are not taken into account. Regarding the handling costs of spare parts, we do not take them into account as well. AM may result in less spare parts because of the possibilities to combine an assembly or integrate functions of several parts into one part. However, there are a lot of uncertainties about the practical applicability of these possibilities. In addition, the impact of these possibilities on the total handling costs of spare parts is not known.

The cost factors which are not included in the literature model but which are included in the model of Thales, are the costs of obsolescence and the costs of repair of spares. Especially in the business of Thales, a business of expensive, technological, highly complex systems, it may be preferable to repair expensive parts instead of replacing them by new ones. The costs of obsolescence are of importance as well. The parts used in systems, are often specifically designed and produced for Thales. This ensures only a limited number of suppliers who are capable of manufacturing the parts. This causes small production volumes for suppliers making it unattractive to support production processes during the after-sales service period of these type of parts where demand is low.

4 Cost factors of Additive Manufacturing affecting Life Cycle Cost

In this chapter, we will determine the relevant cost factors which are required to analyse the potential of Additive Manufacturing (AM) for the production of spare parts. Although this research is focussed on a model focussed on one-off parts, we determine the cost factors for spare parts. In Chapter 2, we discussed cost factors which are currently used by Thales to determine the Life Cycle Cost (LCC) of systems, including spare parts. In Chapter 3, we distinguished four different life cycle phases in order to create a structured overview of applicable cost factors used during an analysis of the LCC of parts or systems. This analysis also included spare parts. So, all information required for the determination of the cost factors of spare parts is present. That is why we first will determine all cost factors related to spare parts, where after we will select the cost factors related to one-off parts. In case spare parts can be printed as well, the possible cost factors are already determined. So, only an extension of the model will be required instead of a complete new research in order to identify all relevant cost factors.

We will discuss and select appropriate cost factors according the four phases described in Section 3.2. Section 4.1 is focused on the cost factors during design & development, Section 4.2 is focused on the cost factors during production, Section 4.3 is focused on the cost factors during the use phase, and Section 4.4 is focused on the costs of disposal associated with a part. At the end of every section, we conclude with the cost factors which affect the manufacturing costs of spare parts regarding the entire life cycle.

We will finish this chapter, with an overview of the cost factors which are affected by AM in case of one-off parts. As we shall see, not all cost factors applicable in case of spare parts, are also applicable in case of one-off parts as we have defined them.

4.1 Factors during design & development phase

The first phase of the life cycle is the design & development phase. This phase exists of activities as conceptual and preliminary design, detail design and prototyping, and support functions as data maintenance and project management (Fixson, 2004). From now on, we will call this group of costs 'cost of part design'.

The ability to produce (complex) structures, combine assemblies into one part, and integrate different functions into one part by using AM, will affect the cost of part design. The principles of design for manufacturing (DFM) and design for assembly (DFA) as well as the use of common components across different product families, as discussed in Section 3.2, can be ignored changing the way a part is designed. AM will require a different design approach which may affect the time and effort needed to design a part, resulting in different design costs. According to experts in the field of AM, the design costs can be influenced in a negative way as well as in a positive way in case we will use AM instead of CM.

Changing the manufacturing method from Conventional Manufacturing (CM) to AM will affect the costs associated with 'special tooling' in order to produce a component. A lot of CM processes require special tooling which could only be used for one or a couple of parts. In case of manufacturing by means of AM, these special tools aren't required any longer (Gibson, et al., 2010). For some CM processes the special tooling can be quite expensive compared to the rest of the production costs. An example, is the construction of an expensive mould for an injection moulding process (Gibson, et al., 2010). In case of low-volume or highly specialized parts, AM could be more cost-efficient over CM, even during the initial production phase. This as a result of the fact that there is no need to refinance all costs associated with special tooling (Ford, 2014). In addition, in case a part is expected to be produced in a high-volume during its initial production phase CM may be more cost-efficient during this phase, while during the use phase (including the after-sales period) AM may be more cost-efficient because of all kind of cost benefits. More about this topic in Section 4.3.

As a result of a new production method and a new design approach, problems may occur with respect to the current way parts are certified. The use of AM may result in a much higher certification costs because of new processes, materials, and material properties. On the other hand, since assemblies and different parts may be integrated into one part, less part needs to be certified. This might reduce the costs of certification.

These factors can be translated into the cost factors: costs of part design, design/production costs of special tooling, and the costs of certification.

4.2 Factors during production phase

AM methods are more expensive than their CM equivalent in a lot of situations (Ford, 2014). Because of higher costs of machines and materials used during AM compared to CM and the costs of post-processing in case of AM. On the other hand, the setup costs of manufacturing by AM are in a lot of situations lower than the setup costs of manufacturing by CM. This makes it more interesting to manufacture relatively small batches using AM instead of using CM. This results in a decrease of the minimum order quantity. Thales however, is focussed on the design & development and assembly of radar system instead of the production of all parts. A lot of production processes are outsourced to third parties. This results in the fact that Thales isn't directly affected by a change in production costs because of the use of AM. Suppliers however, which have to deal with possible different production costs of parts, caused by AM, will charge different prices for their parts to Thales.

Additionally, benefits mentioned in Section 3.1 were the ability to construct complex structures, combine an assembly of parts into one part, and integrate functions from different parts into one part. These benefits can affect the assembly process, since the process might change (less assembly steps, no necessity of highly skilled employees because of simplified assembly steps). Additionally, the number of parts, Stock Keeping Units (SKU's), will be affected (Holmström, et al., 2009). As a consequence of a change in the number of SKU's, all kind of internal logistical aspects, made before production, might change as well. Additionally, inventory and transportation costs of subassemblies may change as well.

The last cost factors concerning production are related to the costs of obsolescence of production processes. The use of CM methods to manufacture a part during a lifespan of 30 years, can result in the necessity of use of outdated production processes. This requires a redesign of that part, so it can be produced by current production processes. Although the standards for AM are not formulated, it is highly likeable, component data (3D CAD models) will be compatible with future machines. Therefore, components can be produced in the same way as they were produced 40 years ago. Perhaps small changes will be required, because of advanced technology and/or improved materials. Experts expected, these small changes with respect to AM will lead to cost-savings compared to a complete redesign in case of CM.

The cost factors affected during the production phase are: costs of parts, labour costs of assembly, costs of internal handling (receiving, packaging, labelling), storage costs (invested capital, warehousing), and the labour costs of potential redesigns.

4.3 Factors during use phase

The use phase as we consider in this part, corresponds with the Lifetime Support Costs and Lifetime Operational Costs as described in Section 2.1. The factors affected by a change of manufacturing method are all related to maintenance and associated activities.

The quality of the components produced by AM might differ from the quality of components produced by CM (Gibson, et al., 2010), (Gao, et al., 2015). This can cause a change in the Mean Time To Failure (MTTF) of parts. This will influence the maintenance policy during the use phase and so the costs related to maintenance and the costs related to repair of parts. A change in MTTF might affect the expected number of components needed during the life span and the downtime of a system. In addition, the ability to produce complex structures might change the effort (in terms of tools, time, and knowledge) needed to repair or replace a failed part. The effort needed to perform a maintenance action, will also affect the downtime.

Other factors that might be affected, are factors related to after-sales service of parts. Since AM has the ability to manufacture parts in a faster way than CM (Gibson, et al., 2010), the costs of inventory might change because of a reduction in the production lead time. This might affect the inventory levels required to guarantee a specific availability level. Additionally, manufacturing by means of AM can be performed all over the world, in theory. This might affect the transportation lead time in case a component is ordered. Direct on-site production will reduce the transportation time, and prevents the necessity of emergency shipments in case no part is available on stock. These points will result in a change in the costs of inventory during the after-sales period. In addition, all aforementioned points will directly affect the availability of systems.

During the after-sales period, the set-up costs are of importance. Some parts required in the after-sales period, are only required in relative low amounts. While some CM methods have high set-up costs, high costs as a result of the storage of special tooling, or fixed batches sizes in case of demand (otherwise it isn’t profitable for the supplier). In the last case, Thales gets more parts than needed, resulting in inventory. Manufacturing by AM doesn’t have the special tooling or the fixed batch size problem, what could result in lower costs. However, if we use both manufacturing methods, we might have extra costs as a result of design and certification. The CM part has to be designed and certified as well as the AM part.

Finally, we have the costs of obsolescence of spare parts during the use phase. These costs arise, as described in de model of Thales in Chapter 2, as a result of the monitoring of obsolescence, the costs of redesign, and the costs of the last time buy if too many parts are purchased.

With respect to the use phase we can identify the following costs factors: costs related to the production of replacement parts (these include the same cost factors as during the production phase). Additionally, there are labour costs of preventive/corrective maintenance, costs of inventory (capital invested in spare parts, spare part handling, warehousing, etc.), repair costs of broken parts, costs of downtime including lead time of spare parts (as a result of: production, transportation, special tooling, preparation of AM method), costs of special tooling, costs of design for the AM method, costs of certification for AM, and costs of obsolescence (obsolescence monitoring, redesign, and last time buy).

The cost factor, cost of downtime, is a difficult factor which requires a detailed research during the construction of the LCC model in Chapter 6. Since radar systems don't generate revenues, it will be hard to determine costs in case of a failure. However, it won't be realistic to completely ignore this factor.

We have to make a remark regarding the acquisition costs of parts. In the future, acquisition cost of AM components may drop significantly. Over time, the technology of AM will improve and the production numbers in this sector will rise. Two examples of decreasing production costs over time are described in Bhasin & Bodha (2014). Their research shows that the production costs of RFID decreased by 76% in a time period between 2007 and 2014. Additionally, the production costs of LED decreased over 65% in a time period between 2009 and 2013. The last few decades, AM already followed the digital technology progress model, in that more capable and cheaper machines are introduced year after year (Khajavi, et al., 2014). So, we are also dealing with a certain factor that describes the development of the machine and material costs of AM processes.

4.4 Factors during disposal phase

This research is focussed on parts used for radar systems of Thales. These radar systems are produced for naval ships and air defence systems. When these systems come to their end-of-life, the systems have to be demilitarized. Costs of this demilitarization process are unknown. In addition, it is likeable that the disposal costs of a system produced by AM has the same disposal cost as a system produced by CM, the same holds for the individual components of the system. Therefore, we won't include the disposal costs of parts in our research.

However, next to the parts which have to be disposed, we also have to dispose special tooling in case this is required for production. Since special tooling might be produced especially for the production of the part(s) only used at Thales, disposing may cost money. Nevertheless, in theory it is possible that special tooling as a salvage value at the moment it isn't needed anymore. Therefore, we will take the disposal costs of special tooling or the salvage value of special as a cost factor in our model.

4.5 Cost factors related to one-off parts

In this section, we make a selection of cost factors which are relevant with respect to this research, see Table 2. Since one-off parts a slightly different from spare parts, some cost factors will be excluded.

With respect to the production phase, we exclude the storage costs as well as the costs of redesign. As argued in Section 1.4 and Section 1.5, we focus our model especially on one-off parts. Because of their characteristics, one-off parts are not subjected to redesign. Regarding the storage costs during production, we found out no intermediate parts are stored with respect to one-off parts. If they are produced to put in inventory, they are produced in one run. This results in inventory costs during the use phase and not in storage costs during the production phase.

As stated before, we might have to reconsider inventory costs of parts. In principal are one-off parts, parts which are not put in inventory. However, it may turn out that it is cost-efficient to keep one-off parts in stock, for example because of long lead times or high set-up costs. Concerning one-off parts, they can't be repaired, for that reason we exclude the repair costs of broken parts. As mentioned in

Chapter 3, one of the drawbacks of AM are the difficulties concerning intellectual property. Therefore, Thales wants production by known suppliers. This implies the transportation lead time of parts won't change, and is therefore excluded at this point in time.

Table 2: Overview of cost factors affected by the conversion from CM to AM

Design & development	**Useful**	**Useless**
Costs of part design	x	
Costs of certification	x	
Costs of tooling	x	
Production		
Acquisition costs of parts	x	
Assembly costs	x	
Costs of internal handling	x	
Storage costs		x
Costs of redesign		x
Use		
Costs of replacement parts	x	
Corrective maintenance	x	
Inventory costs	x	
Repair costs of broken parts		x
Production lead time of parts	x	
Lead time of transport		x
Lead time of tooling	x	
Lead time preparation AM method	x	
Costs of downtime	x	
Costs of obsolescence	x	
Cost development factor of AM	x	
Disposal		
Salvage value of parts	x	
Salvage value special tooling	x	

4.6 Conclusion

We have determined the cost factors that affect the LCC of spare parts at Thales, when AM will be used at a certain point during the life cycle of a part. Because of the practical difficulties regarding manufacturing by means of AM and the fact we are focused on one-off parts instead of spare parts, some of the identified cost factors are left out of the model. In Table 2, an overview is given of the useful cost factors for our model and the ones which are useless for our model, regarding the assessment of the impact of AM on the LCC with respect to one-off parts within Thales.

5 Potential cases

In this chapter, we will discuss three possible parts which could be used as a case during the analysis in Chapter 7. As stated in Section 1.7, a research towards the identification of potential spare parts suited for Additive Manufacturing (AM), has been performed within Thales. Although an extensive research, no useful spare parts where identified at that point in time. However, some suggestions were made with respect to the type of parts which might be interesting to be produced by AM. In Section 1, a short summary of the results from previous research will be discussed. In the sections which follow, we describe potential cases which could be used during the analysis of the model developed in this research.

5.1 Previous research

The research we review in this section is performed by Katgert (2015). The goal of his research was: 'to develop a framework to analyse what type of spare parts could be suited for AM, while striving for an improvement of Thales' services'. During his research, he encountered the difficulties of the restricted production capabilities of AM at that point in time. Those restrictions still hold, why we choose in this research to analyse one-off parts instead of spare parts.

By the end of the research, Katgert (2015) concluded that there is one part which is interesting for the use of AM and that there are 3 other parts of which some subcomponents may be interesting for the use of AM. We have to note that all parts adduced by Katgert are assemblies of multiple components. However, in his remarks, Katgert notices that the real parts applicable for AM are the mechanical structure/housing of those parts. These mechanical structures/housings are not regarded as being spare parts. Though, mechanical structures/housings are mechanical parts which might fail because of rare incidents. Those type of parts, are seen as one-off parts which can be used for the analysis in this research. Additionally, waveguides turned out to be interesting parts to be produced by means of AM based on the research of Katgert (2015). It is an interesting type of part, because they have a high impact on the functioning of the radar system and are produced by means of a complex production process, which ensures long lead times. In the remainder of this chapter, we will focus on mechanical one-off parts which are exposed to incidents.

5.2 Mechanical one-off parts

After discussions with several employees from the assembly department, we conclude that mechanical structures/housings in principle don't fail because of use. However, in some extreme situations, they might crack. In that case, mechanical structures/housings will be repaired. In consultation with experts we concluded, that covers are a better type of mechanical part to analyse. Think about closing covers, covers for protection, and stealth/esthetical covers. Those types of covers are often directly exposed to the outside world and thus directly affected (damaged) in case of incidents.

At the moment we were identifying potential cases, an expert of the STIR showed interesting parts. The parts he mentioned, are subjected to the kind of incident, resulting in a failed part, where we are looking for (extreme weather conditions and imprudence during maintenance). The expert advised to investigate the protection cover for the STIR, the sunshade for the STIR and the radome for the STIR. The radome, however, is made out of combination of special material which can't be printed at this point in time. Therefore, we won't discuss this option any further.

5.2.1 Protection cover for the STIR

The Stir has a protection cover that forecloses a part of the electrical components within it. This cover consists of a hood made out of carbon epoxy within it an aluminium mounting ring. The carbon epoxy hood, is shaped by the use of a mould, where after the aluminium ring is placed. Because of weather influences and the use of two different materials, in some cases cracks appear around the outside of the cover. When those cracks become too big, the cover has to be replaced by a new one. Additionally, it is possible someone may damage the cover during activities. Mechanical experts at Thales expect to need between five to fifteen of these covers in order to replace failed ones during the entire life cycle. At this point in time, the covers are still produced since the Stir is still in production. Therefore a failure at this point in time is solved be producing a new cover with the existing mould. However, as mentioned in Section 2.4, there is no strict policy how to deal with a failure in case. It is highly likeable, that new parts are produced by the same method in case CM is used even if the mould has been discarded. In that case, a failure results in the construction of a new mould to produce the cover. This results in high costs and long lead times. (This holds for all parts produced by means of a mould.) Therefore, it might be cost-efficient to produce this component by means of AM instead of CM in the future. The protection cover is presented in Figure 3.

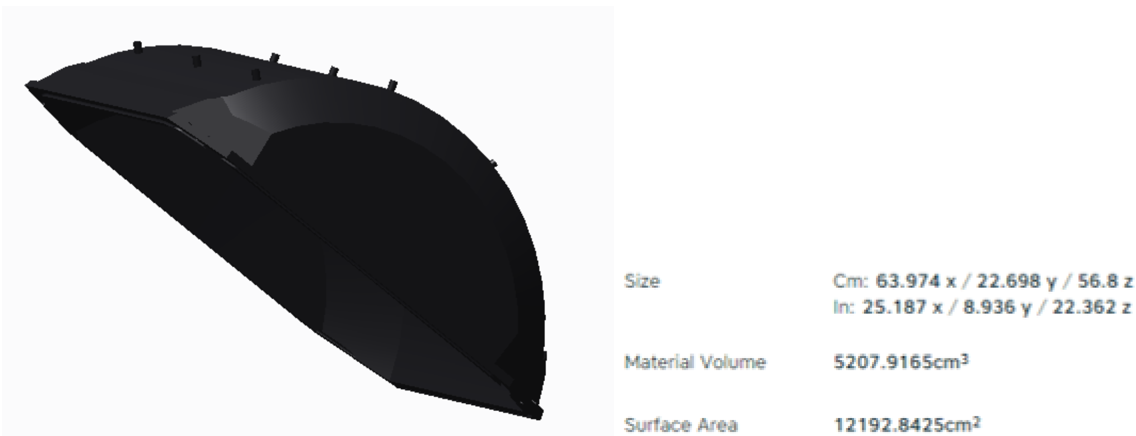

Figure 3: Representation of the protection cover for the STIR *Source: shapeways.com*

Based on the specifications and opinions of mechanical experts, we conclude that it is feasible to actually print the protection cover. It might be necessary to make some adjustments in the design. By adding material in certain areas, it should be possible to create a part consisting of only one material. On the internet, we have found a material 'glass filled polyamide (nylon)', which should be suitable to produce the protection cover by means of AM. In Table 3, the specific input parameters of the protection cover are given. More information about the input values can be found in Appendix 4.

Table 3: Input parameters of the sunshade

Part input	**CM method**	**AM method**
Costs of preparation	P_{CM} = €10.000	P_{AM} = €10.000
Variable production costs per piece	c_{CM} = €5.768	$c_{AM}(0)$ = €13.331
Production lead time	L_{CM} = 192 days	L_{AM} = 10 days
Preparation lead time AM method		$L_{AM(prep)}$ = 28 days
Salvage value	s_{parts} = -€57,68 (disposal costs)	
Holding costs	h_{parts} = 10%	
Special tooling (mould) input		
Acquisition costs of special tooling	ST = *€5.900*	
Salvage value	s_{ST} = -€295,00 (disposal costs)	
Holding costs	h_{ST} = 10%	
Production lead time special tooling	L_{ST} = 65 days	

5.2.2 Sunshade for the STIR

The sunshade for the STIR, is an extra hood to protect the protection cover mentioned in the previous section from the exposure to the sun. This part is made out of carbon epoxy and glass epoxy. The same characteristics holds for the sunshade as are defined for the protection cover. Additionally, the sunshade is also produced by the use of a mould. In case it is demanded in the future, production by means of CM will hold the same principles as production of the protection cover. Also for the sunshade is the expected number of parts needed to replace failed ones between five and fifteen units. An image of the sunshade is presented in Figure 4.

Figure 4: Representation of the sunshade for the STIR *Source: shapeways.com*

Experts expect the sunshade to be a useful case as well. The material used to produce the sunshade, is the same as for the protection cover 'glass filled polyamide (nylon)'. In Table 4, the specific input parameters of the sunshade are given. More information about the input values can be found in Appendix 4.

Table 4: Input parameters of the protection cover

Part input	**CM method**	**AM method**
Costs of preparation	P_{CM} = €5.000	P_{AM} = €5.000
Variable production costs per piece	c_{CM} = €1.086	$c_{AM}(0)$ = €2.062
Production lead time	L_{CM} = 197 days	L_{AM} = 10 days
Preparation lead time AM method		$L_{AM(prep)}$ = 28 days
Salvage value	s_{parts} = -€10,86 (disposal costs)	
Holding costs	h_{parts} = 10%	
Special tooling (mould) input		
Acquisition costs of special tooling	ST = €2.800	
Salvage value	s_{ST} = -€140,00 (disposal costs)	
Holding costs	h_{ST} = 10%	
Production lead time special tooling	L_{ST} = 65 days	

5.2.3 Waveguides

We investigated the possibility to produce waveguides by means of direct laser melting. In cooperation with partners of Thales we printed a waveguide in order to test its performance. Based on the results from the tests, experts within Thales concluded it won't be feasible to produce qualitatively useful waveguides which can be used without the necessity of a lot of post-processing. The current methods can't reach the required surface finish to make direct production by means of AM interesting. For this reason, we don't discuss the case of waveguides any further during this research.

5.3 Conclusion

In order to perform an analysis of an actual part using the model which will be developed in the next chapter, we have selected two cases: the protection cover and the sunshade both used for the STIR. Although the materials used at this point in time for both parts might not be printable, mechanical experts within Thales are sure they can be modified in such a way they can be printed. An important remark with respect to the modification is, that the function and incident rate won't change as a result of the conversion in manufacturing method from CM to AM

6 Cost model

In this chapter, we develop a model which is able to determine the optimal production strategy for one-off parts. The model will result in an expected total minimum cost incurred with the production (and associated activities) of one-off parts, during their entire life cycle. As discussed in Section 4.1, manufacturing by means of Additive Manufacturing (AM) has some benefits compared to Conventional Manufacturing (CM). Therefore, using AM instead of CM at a certain point in time may be cost-efficient. Since cost factors of different parts, can have different values, a model is developed during this research which is able to analyse one part/assembly at the time. So, it is possible to analyse an assembly of multiple parts.

We will start with the assumptions made with respect to the model in Section 1. In Section 2, we give a description of the method used to develop the model. Followed by the input parameters and model variables in Section 3. In Section 4, we formulate our mathematical model. In Section 5, we formulate the expression used for the model.

6.1 Model assumption

The model constructed during this research, should determine if the production of one-off parts using AM is cost-efficient over just using CM at a certain point in time. One-off parts have in contrast to 'spare parts' not a failure behaviour because of use (it is not subjected to wear). One-off parts only have an 'incident rate', resulting in possible failures. Those incidents arise as a result of random events. For example, extreme weather conditions or imprudence during maintenance activities. These incidents are random events which may happen with the same probability over a predetermined period. Based on these facts, we conclude the incident rate of one-off parts is constant over time. From this, we can conclude that the lifetime of one-off parts follows an exponential distribution. Due to the exponential distribution, we assume the demand for one one-off parts follows a Poisson process with rate λ per period. In addition, because incidents arise because of random events, the incident rate of CM produced parts is approximately equal to the incident rate of AM produced parts (Rausand & Hoyland, 2004).

Assumption 1: the demand for one one-off part follows a Poisson process with rate λ per period.

Assumption 2: the incident rate of CM produced parts is equal to the incident rate of AM produced parts.

For developing the model, we can distinguish two separate phases. First, we have the initial production phase. In this phase, a total of N parts is manufactured by either CM or AM. All N parts are produced before entering the second phase, which is defined as the after-sales phase (called after-sales) which consists of $t = 1, \ldots, T$ periods. At the end of the after-sales phase, after period T, all parts are taken out of the field at once. Therefore, we assume the number of parts, N, is constant over time and all parts are installed and taken into operation during the initial production phase, which is equal to period $t = 0$. Second, we assume the costs incurred with the production of the initial one-off parts, preparation costs of the used manufacturing method as well as the incurred variable production costs of the parts, are incurred in period $t = 0$. Third, we assume failed parts must be replaced by a new part during the entire life cycle. The costs considered to produce a part are the costs which apply during the period a part is demanded. So, if parts fail during the last day of a period, we take into account the costs of that period not the costs of the following period.

Assumption 3: the number of parts, N, is constant over time and all parts are installed and taken into operation in period $t = 0$

Assumption 4: the costs as a result of the production of the initial one-off parts are incurred at period $t = 0$

Assumption 5: failed parts must be replaced by a new part during the entire life cycle at the costs of the period in which the part fails.

With respect to every period t, we have to make a consideration between which manufacturing method to use, either CM or AM. Both methods have their benefits and drawbacks, as discussed in Section 3.1. In case we choose for CM, we might have to take into account costs as a result of special tooling. This could be costs as a result of the acquisition of new tooling, or costs because of the fact we have special tooling in inventory. If we account for the costs of special tooling separately in the model, the special tooling is dedicated to only one part (this special tooling could be one or more tools). The costs of tooling which is dedicated to multiple parts, is included in the acquisition price of the parts.

Assumption 6: only one manufacturing method is used during one period

Assumption 7: special tooling is dedicated to only one part

Regarding the cost development of the CM and AM manufacturing methods, we assume that the costs of CM will be constant over time. Because of technological development concerning AM, we assume those costs will decrease over time. This decrease in costs, will be taken into account in the cost expression of the model in Section 6.5. However, these assumptions result in the fact, that if we have chosen to use AM in period t, we will use AM during the remaining life cycle.

Assumption 8: as soon as the AM method is used during a period, AM will be used during the remaining life cycle

Although we don't focus on 'spare parts', we include the option to produce one-off parts to put them in inventory. As described in Chapter 2, it isn't investigated by Thales if it is cost-efficient to put one-off parts in inventory. However, the storage of parts could have benefits compared to the situation in which only is produced in case of demand. With respect to parts which are put in inventory, we assume constant inventory costs during the entire life cycle. Additionally, the costs are assumed to incur at the beginning of every period. So, even if a part from inventory is demanded the first day of the period, the fixed inventory costs are included in the costs.

Assumption 9: holding costs of parts are fixed and incurred at the start of a period.

Two other assumptions with respect to the model, are the fact that all parts produced during one period, can be produced by using one unit of special tooling, if applicable. And no inventory costs are considered during the period in which the parts are produced.

Assumption 10: all part produced during one period, can be produced by one unit of special tooling.

Assumption 11: no holding costs of parts are accounted during the period they are produced.

The goal of the model is to determine the optimal production strategy in terms of which manufacturing method should be used during which period in order to minimize the total Life Cycle Cost associated with the manufacturing of a one-off part. Other trade-offs are how should be dealt with special tooling in case this is applicable. Is it cost-efficient to store special tooling or is it better to discard them and purchase new special tooling in case it is needed? Besides, we have to focus on the preparation of the AM method. Should this method be prepared in advance, so it can be used directly at the moment it is required, or is it more cost-efficient to do nothing and only prepare this method in case it is actually needed? The final trade-off is concerned with the number of parts that should be produced to put in inventory every period.

With respect to financial aspects, we take into account the same financial assumptions as made during the current LCC analysis of Thales, as discussed in Section 2.2.2:

- Based on Dutch Navy Unit Selling Prices of items
- No costs on interest
- No yearly discount factors
- No inflation on price
- No reduced prices by multi-buy, larger quantities etc.

6.2 Method used to develop a model

The nature of the above described model can be seen as a problem with a certain structure in which, during every period t, decisions have to be made. At the start of every period t, we have to determine which manufacturing method we should use, what we should do with special tooling and should we prepare the AM method or not, in order to minimize total costs over the entire life cycle from $t = 0$ until $t = T + 1$. Although the after-sales phase ends at the end of period *T*, we have to take into account period *T + 1* as well. It could be possible we still have parts or special tooling in inventory. In that case, we have discard the remaining inventory, which could cause costs or benefits.

A method used to solve this type of sequential optimization problem is dynamic programming. Given the nature of our problem and the fact demand of one-off parts follows a Poisson process (so demand is stochastic), we can conclude that we are dealing with a stochastic optimization problem. Therefore, we use Stochastic Dynamic Programming (SDP) to develop a model.

6.3 Input parameters

In Table 5, we describe the model variables. In Table 6, we describe the input parameters required for the model. All parameters are related to the costs factors described in Chapter 4.

Table 5: Model variables

$c_{AM}(t) =$	variable production costs of the AM method per piece in period t.
$E[P(s,i)] =$	expected number of backorders during a period in order to fulfil demand in that period, if (s) parts are in stock and *i* parts are produced for inventory at the beginning of a period.
$P_{prod}(s) =$	probability that parts are produced during a period in order to fulfil demand in that period, if (s) parts are in stock at the beginning of a period, $P(demand \geq s+1)$.

Table 6: Model input parameters

Parameters related to CM	
$P_{CM} =$	costs of preparation of the CM method to use this method from the start of period $t = 0$.
$c_{CM} =$	variable production costs of the CM method per piece (constant over time).
$ST =$	acquisition price of special tooling (constant over time).
$L_{ST} =$	mean special tooling production lead time in days.
$L_{CM} =$	mean component production lead time when CM is used in days.
$h_{ST} =$	holding cost rate of special tooling per period as % of the acquisition costs of special tooling.
$s_{ST} =$	salvage value of special tooling if discarded at the start of period 1 (may be positive, zero or negative in case of disposal costs).
Parameters related to AM	
$P_{AM} =$	costs of preparation of the AM method if prepared in period 0.
$c_{AM}(0) =$	variable production costs of the AM method per piece in period 0.
$L_{AM} =$	mean component production lead time when AM is used in days.
$L_{prep} =$	preparation lead time of the AM method in days.
$cf =$	cost development factor of the variable production costs of AM (see Appendix 5).
Other parameters	
$d =$	costs of downtime per time unit (days) (see Appendix 6).
$\lambda =$	demand rate of a single part per period.
$N =$	total number of installed parts in the field.
$T =$	life cycle length of the analysis (number of periods).
$h_{parts} =$	holding cost rate of parts per period as % of c_{CM}.
$s_{parts} =$	salvage value of parts in inventory in period T+1 (may be positive, zero or negative in case of disposal costs).
$L_{period} =$	length of one period in days.

6.4 Stochastic Dynamic Programming model

In this section, we formulate our SDP model. As stated in Section 1 of this chapter, we consider a total of $t = T + 1$ periods, starting from period $t = 0$.

6.4.1 Model formulation

Phase: start of period *t = 0, …, T+1*

At the beginning of every period, we find ourselves in one of the following states:

State: [*w, s*]. Variable w stating whether special tooling is available or not and the fact if the AM method is prepared or not, at the start of each period t … T: $w \in W_t = \{0, 1, 2, 3\}$. Variable s stating there are *s* part(s) in stock, at the start of each period *t … T*: $s \in \mathbb{N}_0$. In theory, *s* can go to infinity. In practice, however, we see *s* won't go higher than a specific upper bound because of the relatively low demand rate of the one-off parts. Therefore we have developed a method to determine an upper bound for *s*, based on the value of the input parameters, see Appendix 7.

$(w = 0)$: special tooling is available and the AM method hasn't been prepared. $(w = 1)$: Special tooling is available and the AM method has been prepared. This might seem to be a cost-ineffective state at this moment in time, however, since the AM method can be prepared in advance we can prevent high downtime costs because of the preparation lead time of the AM method. $(w = 2)$: Special tooling isn't available and the AM method hasn't been prepared. $(w = 3)$: Special tooling isn't available and the AM method has been prepared.

Given the state we are in at the beginning of a period, we can make different decision how to continue, that ensures that we will end up in a certain state the next period

Decision: (1) use the CM method $(x = 0)$ or use the AM method $(x = 1)$ for the production of one-offs in this period. (2) Do nothing concerning special tooling $(y = 0)$ discard special tooling $(y = 1)$. (3) Do nothing concerning the AM method $(z = 0)$ prepare the AM method in advance $(z = 1)$. (4) Produce *i* part(s) to put in inventory ($i \in \mathbb{N}_0$), possible in case of CM as well as in case of AM.

$D(w, s) =$ set of possible decision {*x, y, z, i*} given state (*w, s*).

$D(0, s) = \{x = 0\text{: } use\ CM\ method, x = 1\text{: } use\ AM\ method; y = 0\text{: } do\ nothing\ special\ tooling,\ y = 1 : discard\ special\ tooling; z = 0\text{: } do\ nothing\ AM, z = 1\text{: } prepare\ AM\ in\ advance; i = number\ of\ parts\ for\ inventory\}$
$D(1, s) = \{x = 1\text{: } use\ AM\ method; y = 1 : discard\ special\ tooling;\ z = 0\text{: } do\ nothing\ AM;\ i = number\ of\ parts\ for\ inventory\}$
$D(2, s) = \{x = 0\text{: } use\ CM\ method, x = 1\text{: } use\ AM\ method;\ y = 0\text{: } do\ nothing\ special\ tooling;\ z = 0\text{: } do\ nothing\ AM, z = 1\text{: } prepare\ AM\ in\ advance;\ i = number\ of\ parts\ for\ in\ inventory\}$
$D(3, s) = \{x = 1\text{: } use\ AM\ method;\ y = 0\text{: } do\ nothing\ special\ tooling;\ z = 0\text{: } do\ nothing\ AM;\ i = number\ of\ parts\ for\ inventory\}$

Value function: $V_t(w, s)$ is the minimum expected costs during period *t, t+1, …, T+1*, given that period t started with state *(w, s)*. The minimum is taken, over the expected costs, $c_t([w, s]; [x, y, z, i])$, as a result of all actions, $x, y, z, i \in D(w, s)$, that are feasible when starting period t with state *(w, s)*. In addition, we sum up over the expected costs from period *t+1* to the end of the phase *T+1*, multiplied with the state transition probability, $p_t([j, a]|[w, s]; [x, y, z, i])$. The state transition probability, is the probability that decision [*x, y, z, i*] in state (*w, s*), where $w \in W_t$ and ($s \in \mathbb{N}_0$), in period t results in state (*j,a*), where $j \in W_t$ and $a = (\max\{0, s - D\} + i)$, in period *t + 1*, where *D* is the demand during period *t*. Since the demand is a stochastic process: $D \in \mathbb{N}_0$.

For the period, after the last period of the after-sales phase, *T+1*, we have to include the salvage value in case a decision is made in which the special tooling is put in inventory or might have to be purchased during period *T*, due to the probability a part is demanded. Additionally, parts which are still in inventory have to be scrapped, resulting in a salvage value of parts.

$$V_t(w,s) = \min_{x,y,z,i \in D(w,s)} \{c_t([w,s];[x,y,z,i]) + \sum_{\substack{j \in W_{t+1} \\ a=(\max\{0,s-D\}+i)}} p_t([j,a]|[w,s];[x,y,z,i]) * V_{t+1}(j,a)\}$$

$$V_{T+1}(0,\mathrm{s}) = -s_{ST} - s * s_{parts}$$
$$V_{T+1}(1,\mathrm{s}) = -s_{ST} - s * s_{parts}$$
$$V_{T+1}(2,s) = -s * s_{parts}$$
$$V_{T+1}(3,\mathrm{s}) = -s * s_{parts}$$

During the initial phase, the costs as result of production are different from the costs during the periods in the after-sales. Therefore, the value function for period $t = 0$ is given separately. However, the result of the value function at period $t = 0$ is most interesting, since this includes the minimum expected costs over all periods.

$$V_0(2,0) = \min_{i \in \mathbb{N}_0} \{P_{CM} + ST + c_{CM} * (N + i) + V_1(0,i);\ P_{AM} + c_{AM}(0) * (N + i) + V_1(3,i)\}$$

6.5 Expressions

In this section the expressions used for the model are formulated, described, and explained. Most cost factors are dependent on the state we are in at the beginning of a period combined with the decisions taken. Therefore, we will first formulate we expressions for the model and describe in which situation they will arise. Finally, we give the expected costs, $c_t([w,s];[x,y,z,i])$, as a result of all actions, $x, y, z, i \in D(w,s)$, in terms of the different costs expressions.

Variable production costs

The variable production costs during a period are dependent upon the number of parts produced. There are production costs associated with the production of parts produced to put in inventory and costs of parts to directly fulfil demand in case the inventory is insufficient. The number of parts to put in inventory is an integer number, which is dependent upon the decisions made. The production of parts for inventory starts at the beginning of the period. Therefore, these parts can be used during the same period as they are produced in order to fulfil demand. Therefore, the number of parts produced during a period to fulfil demand, is dependent upon the demand during a period, the number of parts in inventory at the beginning of a period, and the number of parts produced for inventory during a period. The number of parts extra produced during a period, in order to fulfil demand which could not be delivered from inventory, can be seen as the number of parts in backorder. Therefore, we will use the formula to calculate the expected number of backorders, as described in Sherbrooke (2004), to calculate the expected number of part produced during a period. We have formulated $E[P(s,i)]$, as the expected number of parts produced, to fulfil demand, during a period if *s* parts are stocked at the beginning of a period and *i* parts are produced for inventory.

$$E[P(s,i)] = \sum_{q=s+i}^{\infty} (q-(s+i)) * \frac{(\lambda N)^q}{q!} e^{-\lambda N}$$

$$E[P(s,i)] = \lambda N * \sum_{q=s+i}^{\infty} \frac{(\lambda N)^q}{q!} e^{-\lambda N} - (s+i) * \sum_{q=s+i+1}^{\infty} \frac{(\lambda N)^q}{q!} * e^{-\lambda N}$$

The variable production costs in case of CM are determined by:

$$if\ x = 0, \qquad (E[P(s,i)] + i) * c_{CM}$$

With respect to the variable production costs in case of AM, the same conditions apply as for CM. The only addition, is that we have to take into account the costs development of the variable production costs per piece of AM. Therefore, we formulate for the variable production costs in case of AM the following expression:

$$if\ x = 1, \qquad (E[P(s,i)] + i) * c_{AM}(t)$$

For the formula of $c_{AM}(t)$, see Appendix 4.

Downtime costs

In case demand can't be fulfilled from inventory, parts have to be produced resulting in different types of possible lead times, which causes extra downtime and thus downtime costs. With respect to the lead time, we distinguish two different types of lead time. Dependent on the manufacturing method and the state we are in at the start of a period, there is possible lead time with respect to the production of special tooling in case we use CM. Or there is possible lead time with respect to the preparation of the AM method. On the other hand, we have lead time as result of the production lead time of the parts themselves. Therefore, we distinguish four different scenarios concerning downtime costs. The scenario which is applicable during a period, is dependent upon the state (*w,s*) at the beginning of a period and the decisions made. The costs of the different scenarios are as follow:

Scenario 1: *we have special tooling available or the AM method is prepared and no parts are produced to put in inventory.*

In this scenario, we only have to deal with possible downtime as a result of the production lead time of parts in order to fulfil demand during timespan I, in Figure 5. This is equal to the expected number of parts produced to fulfil demand during a period if *s* parts are stocked at the beginning of a period, multiplied with the production lead time and the cost per unit downtime.

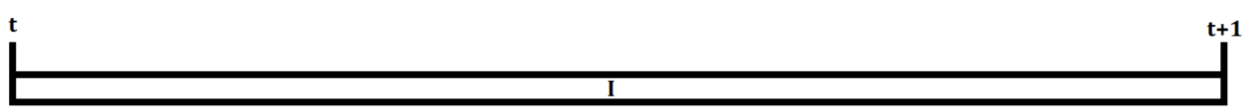

Figure 5: Downtime overview in case special tooling is available or the AM method is prepared and no parts are produced to put in inventory

The downtime costs in case of this scenario, are given by the following expressions:

$$E[P(s,i)] * L_{CM} * d, \quad if\ x = 0, w = 0\ or\ 1, y = 0, and\ i = 0 \quad [1]$$
$$E[P(s,i)] * L_{AM} * d, \quad if\ x = 1, w = 1\ or\ 3, and\ i = 0 \quad [2]$$

Scenario 2: special tooling isn't available or the AM hasn't been prepared yet and no parts produced to put in inventory

In this scenario, we are dealing with possible downtime costs as result of the production lead time of parts in order to fulfil demand, as in scenario 1 [1] and [2]. Additionally, we have to deal with probable downtime caused by the production lead time of special tooling (or the lead time to prepare the AM method). These last costs, will occur only with the probability that the demand is higher than the number of parts in inventory ($Demand\ > s+1$). In case this is applicable, the first part demanded which can't be delivered from inventory has to deal with the entire lead time of special tooling production/AM preparation, this happens at point A in Figure 6. The downtime costs in case are:

$$\begin{aligned} &P(Demand\ > s+1) * L_{ST} * d, &&if\ x=0 \quad [3] \\ &P(Demand\ > s+1) * L_{prep} * d, &&if\ x=1 \quad [4] \end{aligned}$$

It is possible that demand occurs during the production lead time of special tooling or AM preparation. This time period is equal to 'timespan II' in Figure 6. During 'timespan II' we will have on average a downtime of half the production lead time of special tooling/AM preparation in case demand occurs. Since we assumed demand follows a Poisson process, demand will arrive evenly distributed over the timespan. These downtime costs only occur with the probability that demand is higher than the number of parts in inventory ($Demand\ > s+1$). The expected number of parts demanded during this period is equal to:

$$E[P(s+1,\mathrm{i})] * \frac{L_{ST}}{L_{period}}, \quad if\ x=0$$
$$E[P(s+1,\mathrm{i})] * \frac{L_{prep}}{L_{period}}, \quad if\ x=1$$

The associated downtime costs during the production lead time of special tooling or AM preparation is equal to:

$$P(Demand\ > s+1) * E[P(s+1,\mathrm{i})] * \frac{L_{ST}}{L_{period}} * \frac{L_{ST}}{2} * d, \quad if\ x=0 \quad [5]$$
$$P(Demand\ > s+1) * E[P(s+1,\mathrm{i})] * \frac{L_{prep}}{L_{period}} * \frac{L_{prep}}{2} * d, \quad if\ x=0 \quad [6]$$

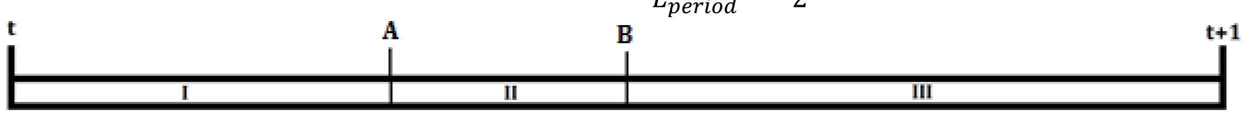

Figure 6: Downtime overview in case special tooling is not available or the AM method is not prepared and no parts are produced to put in inventory

If we combine all expression in case of scenario 2 [1], [2], [3], [4], [5], [6], the total downtime costs are given by the following expressions:

$$\left(\begin{array}{c} E[P(s,i)] * L_{CM} * d + \\ \sum_{q=s+1}^{\infty} \frac{(\lambda N)^q}{q!} e^{-\lambda N} * \left(L_{ST} + E[P(s+1,i)] * \frac{L_{ST}}{L_{period}} * \frac{L_{ST}}{2} \right) * d \end{array}\right), \quad if\ x=0, w=2, and\ i=0$$

$$\left(\begin{array}{c} E[P(s,i)] * L_{AM} * d + \\ \sum_{q=s+1}^{\infty} \frac{(\lambda N)^q}{q!} e^{-\lambda N} * \left(L_{prep} + E[P(s+1,i)] * \frac{L_{prep}}{L_{period}} * \frac{L_{prep}}{2} \right) * d \end{array}\right), \quad if\ x=1, w=0\ or\ 2, and\ i=0$$

Scenario 3: *we have special tooling available or the AM method is prepared and i parts are produced to put in inventory*

In this scenario, we are dealing with possible downtime costs as result of the production lead time of parts in order to fulfil demand which can't be delivered from inventory (including the parts produced from inventory during this period). This is equal to:

$$E[P(s,i)] * L_{CM} * d, \quad if\ x = 0 \quad [7]$$
$$E[P(s,i)] * L_{AM} * d, \quad if\ x = 1 \quad [8]$$

During the production meant for inventory, 'timespan I' in Figure 7, it may occur demand exceeds the number of finished parts in inventory. In that case, we have to include the applicable downtime costs as a result of the production lead time of parts as well. In this case, it holds the average lead time if demand occurs is equal to half the production lead time of parts. Since we assumed demand follows a Poisson process. The expected number of parts subjected to this lead time is equal to:

$$(E[P(s,0)] - E[P(s,i)]) * \frac{L_{CM}}{L_{period}}, \quad if\ x = 0$$
$$(E[P(s,0)] - E[P(s,i)]) * \frac{L_{AM}}{L_{period}}, \quad if\ x = 1$$

The associated the downtime costs are equal to:

$$(E[P(s,0)] - E[P(s,i)]) * \frac{L_{CM}}{L_{period}} * \frac{L_{CM}}{2} * d, \quad if\ x = 0 \quad [11]$$
$$(E[P(s,0)] - E[P(s,i)]) * \frac{L_{AM}}{L_{period}} * \frac{L_{AM}}{2} * d, \quad if\ x = 1 \quad [12]$$

Figure 7: Downtime overview in case special tooling is available or the AM method is prepared and i parts are produced to put in inventory

The total downtime costs in case of scenario 3 is a combination of [7], [8], [9], [10], and are given by the following expressions:

$$\begin{pmatrix} E[P(s,i)] * L_{CM} * d + \\ (E[P(s,0)] - E[P(s,i)]) * \frac{L_{CM}}{L_{period}} * \frac{L_{CM}}{2} * d \end{pmatrix} \quad if\ x = 0, w = 0\ or\ 1, y = 0, and\ i > 0$$
$$\begin{pmatrix} E[P(s,i)] * L_{AM} * d + \\ (E[P(s,0)] - E[P(s,i)]) * \frac{L_{AM}}{L_{period}} * \frac{L_{AM}}{2} * d \end{pmatrix} \quad if\ x = 1, w = 1\ or\ 3, and\ i > 0$$

Scenario 4: special tooling isn't available or the AM hasn't been prepared yet and i parts are produced to put in inventory

In this scenario, we are dealing with possible downtime costs as result of the production lead time of parts in order to fulfil demand which can't be delivered from inventory (including the parts produced from inventory during this period), as in scenario 3 [7] and [8]. Since, we produce parts to put in inventor, we start at the beginning of the period with the production of special tooling/the preparation of the AM method, 'timespan I' in Figure 8. During timespan I, demand that occurs is on average subjected to half the production lead time of special tooling/AM preparation. The expected demand during this timespan is equal to:

$$E[P(s,0)] * \frac{L_{ST}}{L_{period}}, \quad if\ x = 0$$
$$E[P(s,0)] * \frac{L_{prep}}{L_{period}}, \quad if\ x = 1$$

The associated downtime costs as a result of special tooling/AM preparation are:

$$E[P(s,0)] * \frac{L_{ST}}{L_{period}} * \frac{L_{ST}}{2} * d, \qquad if\ x = 0 \quad [13]$$
$$E[P(s,0)] * \frac{L_{prep}}{L_{period}} * \frac{L_{prep}}{2} * d, \quad if\ x = 0 \quad [14]$$

With respect to the downtime costs related to the production lead time of parts meant to put in inventory, consist of the lead time in timespan I and timespan II in Figure 8. The downtime costs of timespan II are equal to costs in timespan I in scenario 3 [11] and [12]. The downtime costs during timespan I are given by the following expressions:

$$(E[P(s,0)] - E[P(s,i)]) * \frac{L_{ST}}{L_{period}} * L_{CM} * d, \quad if\ x = 0 \quad [15]$$
$$(E[P(s,0)] - E[P(s,i)]) * \frac{L_{prep}}{L_{period}} * L_{AM} * d, \quad if\ x = 0 \quad [16]$$

Figure 8: Downtime overview in case special tooling is not available or the AM method is not prepared and i parts are produced to put in inventory

The downtime costs in case of scenario 4, are given by the following expressions:

$$\left(\begin{array}{c} E[P(s,i)] * L_{CM} * d + E[P(s,0)] * \frac{L_{ST}}{L_{period}} * \frac{L_{ST}}{2} * d + \\ (E[P(s,0)] - E[P(s,i)]) * \left(\frac{L_{ST}}{L_{period}} * L_{CM} * d + \frac{L_{CM}}{L_{period}} * \frac{L_{CM}}{2} * d \right) \end{array} \right) \quad if\ x = 0, w = 2, and\ i > 0$$

$$\left(\begin{array}{c} E[P(s,i)] * L_{AM} * d + E[P(s,0)] * \frac{L_{prep}}{L_{period}} * \frac{L_{prep}}{2} * d + \\ (E[P(s,0)] - E[P(s,i)]) * \left(\frac{L_{prep}}{L_{period}} * L_{AM} * d + \frac{L_{AM}}{L_{period}} * \frac{L_{AM}}{2} * d \right) \end{array} \right) \quad if\ x = 1, w = 0\ or\ 2, and\ i > 0$$

Possible costs of the acquisition of special tooling
In case there is no special tooling available or if we have discarded special tooling at the beginning of a period, we need to purchase special tooling if we have to produce by means of CM. The probability we need purchase special tooling is given by:

$$P_{prod}(s) = \sum_{q=s+1}^{\infty} \frac{(\lambda N)^q}{q!} e^{-\lambda N}$$

The costs are calculated by:

$$\begin{array}{ll} ST * P_{prod}(s), & \left\{ \begin{array}{c} if\ x = 0, w = 2, and\ i = 0 \\ or \\ if\ x = 0, w = 0, y = 1, and\ i = 0 \end{array} \right. \\ ST, & \left\{ \begin{array}{c} if\ x = 0, w = 2, and\ i > 0 \\ or \\ if\ x = 0, w = 0, y = 1, and\ i > 0 \end{array} \right. \end{array}$$

Possible costs of the preparation in order to prepare the AM method
The preparation costs of the AM method will occur in case the AM method isn't prepared already at the start of the period and we produce by means of AM or if we decide to prepare the AM method in advance.

$$\begin{array}{ll} P_{AM} * P_{prod}(s), & if\ x = 1, w = 0\ or\ 2, z = 0\ and\ i = 0 \\ P_{AM} & \left\{ \begin{array}{c} if\ \ x = 1, w = 0\ or\ 2, z = 0\ and\ i > 0 \\ or \\ if\ z = 1 \end{array} \right. \end{array}$$

Possible holding costs of special tooling
If we have special tooling available at the beginning of a period and we decide to put it inventory, we have to include holding costs. These costs are dependent upon the acquisition costs of the special tooling and the holding cost rate of special tooling and is expressed by:

$$ST * h_{ST}, \quad if\ w = 0\ or\ 1\ and\ y = 0$$

Salvage value of special tooling
If we decide to discard special tooling, this will result in a salvage value or disposal costs. Therefore, we will include these costs in the model by:

$$-s, \quad if\ y = 1$$

Holding costs of parts
Finally, in case we have parts in inventory at the beginning of a period, we have to include the holding costs of these parts. These costs are expressed by:

$$s * c_{CM} * h_{parts}$$

Final cost expression as used in the model
Now we will give an overview of all expression followed by the indication when they occur.

$$c_t([w, s], [x, y, z, i]) \underset{\substack{w \in W_t \\ s \in \mathbb{N}_0 \\ x,y,z,i \in D(w,s)}}{=} \{all\ above\ mentoined\ expressions\}$$

6.5.1 State transition probabilities

In this section, we outline the applicable state transition probabilities which are given by: $p_t([j,a]|[w,s];[x,y,z,i])$, as the probability that decision [*x, y, z, i*] in state (*w,s*), where $w \in W_t$ and $s \in S$ in period t results in state (*j,a*), where $j \in W_t$ and

$$a = \max\{0, s + i - D\}$$

in period *t + 1*. *D* is the demand during period *t*, which follows a Poisson process as mentioned in Section 6.1.

The value of variable *j*, is dependent on the value of *w*, the decisions *x, y, z*, and the fact if production takes place during period *t* or not. In case demand can be fulfilled from stock $(D \leq s)$ and no parts are produced to put in inventory in period *t*, no production takes place in period *t*. In all other situations production takes place, resulting in different states as in case of no production.

Table 7: State transition probabilities

• ([w=0,s];[x=0, y=0, z=0, i]) in period t gives state (w=0, a) at the start of period t + 1: $$\mathrm{p_t([0,a]|[0,s];[0,0,0,i])} = \frac{(\lambda N)^D}{D!}e^{-\lambda N},\ \ for\ D = 0, \dots, (s+i-1)$$ $$\mathrm{p_t([0,0]|[0,s];[0,0,0,i])} = 1 - \sum_{d=0}^{s+i-1}\frac{(\lambda N)^d}{d!}e^{-\lambda N},\ \ if\ D \geq s+i$$
• ([w=0,s];[x=0, y=1, z=0, i=0]) in period t gives state (w=2, a) at the start of period t+1 if no production takes place in period t and (w=0, a) if production takes place in period t: $$\mathrm{p_t([2,a]|[0,s];[0,1,0,0])} = \frac{(\lambda N)^D}{D!}e^{-\lambda N},\ \ for\ D = 0, \dots, s$$ $$\mathrm{p_t([0,0]|[0,s];[0,1,0,0])} = 1 - \sum_{d=0}^{s}\frac{(\lambda N)^d}{d!}e^{-\lambda N},\ \ if\ D > s$$ • ([w=0,s];[x=0, y=1, z=0, i>0]) in period t gives state (w=0, a) at the start of period t+1: $$\mathrm{p_t([0,a]|[0,s];[0,1,0,i>0])} = \frac{(\lambda N)^D}{D!}e^{-\lambda N},\ \ for\ \ for\ D = 0, \dots, (s+i-1)$$ $$\mathrm{p_t([0,0]|[0,s];[0,1,0,i>0])} = 1 - \sum_{d=0}^{s+i-1}\frac{(\lambda N)^d}{d!}e^{-\lambda N},\ \ if\ D \geq s+i$$
• ([w=0,s];[x=1, y=1, z=0, i=0]) in period t gives state (w=2, a) at the start of period t+1 if no production takes place in period t and (w=3, a) if production takes place in period t: $$\mathrm{p_t([2,a]|[0,s];[1,1,0,0])} = \frac{(\lambda N)^D}{D!}e^{-\lambda N},\ \ for\ D = 0, \dots, s$$ $$\mathrm{p_t([3,a]|[0,s];[1,1,0,0])} = 1 - \sum_{d=0}^{s}\frac{(\lambda N)^d}{d!}e^{-\lambda N},\ \ if\ D > s$$ • ([w=0,s];[x=1, y=1, z=0, i>0]) in period t gives state (w=3, a) at the start of period t+1: $$\mathrm{p_t([3,a]|[0,s];[1,1,0,i>0])} = \frac{(\lambda N)^D}{D!}e^{-\lambda N},\ \ for\ D = 0, \dots, (s+i-1)$$ $$\mathrm{p_t([3,0]|[0,s];[1,1,0,i>0])} = 1 - \sum_{d=0}^{s+i-1}\frac{(\lambda N)^d}{d!}e^{-\lambda N},\ \ if\ D \geq s+i$$
• ([w=0,s];[x=0, y=0, z=1, i]) in period t gives state (w=1, a) at the start of period t+1:

$$\mathrm{p_t}([1,\mathrm{a}]|[0,\mathrm{s}];\ [0,0,1,\mathrm{i}]) = \frac{(\lambda N)^D}{D!}e^{-\lambda N},\ \ for\ \ for\ D = 0,\dots,(s+i-1)$$

$$\mathrm{p_t}([1,0]|[0,\mathrm{s}];[0,0,1,\mathrm{i}]) = 1 - \sum_{d=0}^{s+i-1}\frac{(\lambda N)^d}{d!}e^{-\lambda N},\ \ if\ D \geq s+i$$

- ([w=0,s];[x=0, y=1, z=1, i=0]) in period t gives state (w=3, a) at the start of period t+1 if no production takes place in period t and (w=1, a) if production takes place in period t:

$$\mathrm{p_t}([3,\mathrm{a}]|[0,\mathrm{s}];[0,1,1,0]) = \frac{(\lambda N)^D}{D!}e^{-\lambda N},\ \ for\ D = 0,\dots,s$$

$$\mathrm{p_t}([1,\mathrm{a}]|[0,\mathrm{s}];[0,1,1,0]) = 1 - \sum_{d=0}^{s}\frac{(\lambda N)^d}{d!}e^{-\lambda N},\ \ if\ D > s$$

- ([w=0,s];[x=0, y=1, z=1, i>0]) in period t gives state (w=1, a) at the start of period t+1:

$$\mathrm{p_t}([1,\mathrm{a}]|[0,\mathrm{s}];[0,1,1,\mathrm{i}>0]) = \frac{(\lambda N)^D}{D!}e^{-\lambda N},\ \ for\ D = 0,\dots,(s+i-1)$$

$$\mathrm{p_t}([1,0]|[0,\mathrm{s}];[0,1,1,\mathrm{i}>0]) = 1 - \sum_{d=0}^{s+i-1}\frac{(\lambda N)^d}{d!}e^{-\lambda N},\ \ if\ D \geq s+i$$

- ([w=0,s];[x=1, y=1, z=1, i]) in period t gives state (w=3, a) at the start of period t+1:

$$\mathrm{p_t}([3,\mathrm{a}]|[0,\mathrm{s}];\ [1,1,1,\mathrm{i}]) = \frac{(\lambda N)^D}{D!}e^{-\lambda N},\ \ for\ D = 0,\dots,(s+i-1)$$

$$\mathrm{p_t}([3,0]|[0,\mathrm{s}];[1,1,1,\mathrm{i}]) = 1 - \sum_{d=0}^{s+i-1}\frac{(\lambda N)^d}{d!}e^{-\lambda N},\ \ if\ D \geq s+i$$

- ([w=1,s];[x=1, y=1, z=0, i]) in period t gives state (w=3, a) at the start of period t+1:

$$\mathrm{p_t}([3,\mathrm{a}]|[1,\mathrm{s}];\ [1,1,0,\mathrm{i}]) = \frac{(\lambda N)^D}{D!}e^{-\lambda N},\ \ for\ D = 0,\dots,(s+i-1)$$

$$\mathrm{p_t}([3,0]|[1,\mathrm{s}];[1,1,0,\mathrm{i}]) = 1 - \sum_{d=0}^{s+i-1}\frac{(\lambda N)^d}{d!}e^{-\lambda N},\ \ if\ D \geq s+i$$

- ([w=2,s];[x=1, y=0, z=0, i=0]) in period t gives state (w=2, a) at the start of period t+1 if no production takes place in period t and (w=3, a) if production takes place in period t:

$$\mathrm{p_t}([2,\mathrm{a}]|[2,\mathrm{s}];[1,0,0,0]) = \frac{(\lambda N)^D}{D!}e^{-\lambda N},\ \ for\ D = 0,\dots,s$$

$$\mathrm{p_t}([3,\mathrm{a}]|[2,\mathrm{s}];[1,0,0,0]) = 1 - \sum_{d=0}^{s}\frac{(\lambda N)^d}{d!}e^{-\lambda N},\ \ if\ D > s$$

- ([w=2,s];[x=1, y=0, z=0, i>0]) in period t gives state (w=3, a) at the start of period t+1:

$$\mathrm{p_t}([3,\mathrm{a}]|[2,\mathrm{s}];[1,0,0,\mathrm{i}>0]) = \frac{(\lambda N)^D}{D!}e^{-\lambda N},\ \ for\ D = 0,\dots,(s+i-1)$$

$$\mathrm{p_t}([3,0]|[2,\mathrm{s}];[1,0,0,\mathrm{i}>0]) = 1 - \sum_{d=0}^{s+i-1}\frac{(\lambda N)^d}{d!}e^{-\lambda N},\ \ if\ D \geq s+i$$

- ([w=2,s];[x=0, y=0, z=1, i=0]) in period t gives state (w=3, a) at the start of period t+1 if no production takes place in period t and (w=1, a) if production takes place in period t:

$$\mathrm{p_t}([3,\mathrm{a}]|[2,\mathrm{s}];[0,0,1,0]) = \frac{(\lambda N)^D}{D!}e^{-\lambda N},\ \ for\ D = 0,\dots,s$$

$$\mathrm{p_t}([1,\mathrm{a}]|[2,\mathrm{s}];[0,0,1,0]) = 1 - \sum_{d=0}^{s}\frac{(\lambda N)^d}{d!}e^{-\lambda N},\ \ if\ D > s$$

- ([w=2,s];[x=0, y=0, z=1, i>0]) in period t gives state (w=1, a) at the start of period t+1:

$$\mathrm{p_t}([1,\mathrm{a}]|[2,\mathrm{s}];[0,0,1,\mathrm{i}>0]) = \frac{(\lambda N)^D}{D!}e^{-\lambda N},\ \ for\ D = 0,\dots,(s+i-1)$$

$$\mathrm{p_t}([1,0]\|[2,s];[0,0,1,\mathrm{i}>0]) = 1-\sum_{d=0}^{s+i-1}\frac{(\lambda N)^d}{d!}e^{-\lambda N},\ \ if\ D \geq s+i$$
• ([w=2,s];[x=1, y=0, z=1, i]) in period t gives state (w=3, a) at the start of period t+1: $$\mathrm{p_t}([3,\mathrm{a}]\|[2,\mathrm{s}];\ [1,0,1,\mathrm{i}]) = \frac{(\lambda N)^D}{D!}e^{-\lambda N},\ \ for\ D = 0,\dots,(s+i-1)$$ $$\mathrm{p_t}([3,0]\|[2,\mathrm{s}];[1,0,1,\mathrm{i}]) = 1-\sum_{d=0}^{s+i-1}\frac{(\lambda N)^d}{d!}e^{-\lambda N},\ \ if\ D \geq s+i$$
• ([w=3,s];[x=1, y=0, z=0, i]) in period t gives state (w=3, a) at the start of period t+1: $$\mathrm{p_t}([3,\mathrm{a}]\|[3,\mathrm{s}];\ [1,0,0,\mathrm{i}]) = \frac{(\lambda N)^D}{D!}e^{-\lambda N},\ \ for\ D = 0,\dots,(s+i-1)$$ $$\mathrm{p_t}([3,0]\|[3,\mathrm{s}];[1,0,0,\mathrm{i}]) = 1-\sum_{d=0}^{s+i-1}\frac{(\lambda N)^d}{d!}e^{-\lambda N},\ \ if\ D \geq s+i$$

6.6 Validation and verification of the model

The model as described before, is implemented in Excel. The model constructed is new and can't be checked, verified, and validated by comparing it to an existing system. However, in order to increase validity and credibility of the model, we have used several techniques during construction of the model and to verify the model, as adduced by Law (2015).

Prior to the construction of the model, we have visited a supplier of Thales which is focused on the development of AM. During this visit, we spoke with AM experts specialised in the machine capabilities and material properties. They were willing to give a lot of information about these subjects. Additionally, they gave their opinion about the use of AM in the future and the cost development of AM. Besides, for this research we went to 'Formnext', an international exhibition in Frankfurt on the next generation of manufacturing technologies mainly focussed on AM. During the exhibition, we spoke experts out of all fields of AM. From machine builders, to consultants who advice companies how to use AM in an effective way. We discussed subjects related to the development of the costs of AM, the difference in design costs between CM and AM, and production lead times associated with AM processes.

With all this information and knowledge gathered in different ways we started to develop a model. During the development period, we have consulted people from different disciplines within Thales, about their opinion on several points which are of importance regarding the model.

Finally, we presented the model to people with knowledge of additive manufacturing as well as knowledge of the parts produced for Thales. They concluded, the model seems to be valid given the assumptions. Additionally, we have consulted Thales's supplier who is working on the development of AM, to give their opinion about the model. They concluded, the model seems to be valid as well.

Besides these qualitative techniques, we have constructed a spreadsheet in which we can simulate the number of one-off parts demanded as discrete events. With the use of a random number generator between 0 and 1, and the probability that a specific number of parts demand will occur we simulated the number of parts demanded during every period of the life cycle. The number of parts demand during each period is simulated as follows:

$$\sum_{q=0}^{x}\frac{(\lambda N)^q}{q!}*e^{-\lambda N} > random\ number \leq \left(1-\sum_{q=x+1}^{\infty}\frac{(\lambda N)^q}{q!}*e^{-\lambda N}\right)$$

The value of *x*, for which this holds is the expected number of parts demanded during that period. In addition, all applicable costs subject to the specific number of parts demanded can be easily calculated. Besides, based on the simulation we can simulate several life cycles in order to determine all kind of results with respect to the average number of parts in inventory, the average period in which AM is used for the first time in case it is applied. Therefore, we will use this simulation in Chapter 7, where we make an analysis of the model.

In order to verify the model, we have cut the model into different components. First we have analysed the production costs during the life cycles. Since we assume, demand follows a Poisson distribution we can calculate the expected demand during the life cycle. By means of a simulation model, we can determine the average period in which CM is replaced for AM. Based on these numbers, we are able to determine the average production costs. Hereafter, we included the preparation costs of the two methods and compared the results of the model, with those of the simulation. Thirdly, we added the costs of special tooling. Finally, we added the costs of inventory together with the costs as a result of downtime. Since these two cost components are dependent on each other, we can't check them separately.

We will run 10.000 life cycles for this simulation for different values of different parameters. In this way, we are able to check different components of the model separately, as adduced by Law (2015). We start with input values, causing that only CM will be used during the entire life cycle. Hereafter, we adjust the input in such a way only AM will be used. Finally, we will run a simulation in which AM might start at a random moment during the life cycle. The settings for the simulation are based on average values of parts within Thales, as described in Appendix 3. If we compare the costs of our simulation runs, with those of the costs according the model we find no differences greater than 0,48%, see Appendix 8. Based on this difference, we conclude that the model is implemented properly in excel and it gives the same results as the SDP model.

6.7 Conclusion

In this this chapter, we constructed a model which is able to determine the optimal period to start with AM as manufacturing method. Additionally, the model determines the optimal number of parts which should be produced to put in inventory, in order to minimize costs. The total life cycle of a part is divided into multiple periods. At the start of every period, decisions have to made at the beginning of every period. The method to solve such an optimization problem is stochastic dynamic programming, which is used for the construction of the model. The cost factors taken into account are:

- Production costs
- Downtime costs
- Preparation costs of the manufacturing methods
- Costs associated with inventory
- Salvage value of inventory

The model is validated using experts in the field of additive manufacturing. Besides, with the use of a discrete simulation model, we have verified the working of the model.

7 Analysis

In this chapter, we analyse the model constructed in order to evaluate the potential of Additive Manufacturing (AM). The model described in Chapter 6 is able to identify the optimal production strategy which minimizes total Life Cycle Cost (LCC) associated with the manufacturing of a one-off part. If use of AM, at a certain point in time (this could be at the start of a parts lifespan or at a certain point in time during the parts use phase), saves costs compared to the situation in which only of CM is used, the model will result in lower overall costs compared to the overall costs in case only CM is applied for production.

The goal of this research is to assess the impact of the use of AM concerning the production of one-off parts. Since the model will determine the minimal total LCC, we are interested in the cost savings of the optimal production strategy compared to the situation in which only CM is applied for production:

- The expected cost savings during the life cycle: $E[cost\ savings]$. We calculate the expected cost savings as a percentage of the costs saved according the model using the optimal production strategy, compared to the costs in case of CM.

Besides the expected cost savings, we are interested under which circumstances AM will be used and during which periods. As described in Chapter 6, we constructed a stochastic model. Therefore, we aren't able to determine fixed production strategies, since decision during a period are dependent upon the results of previous periods except for period *t=0*. Therefore, we will use the simulation model as described in Section 6.6 in order to simulate different life cycle runs in order to generate output results in terms of:

- The expected probability that AM is used at some point during the life cycle: $E[P(AM\ used)]$
- The expected period in which production by means of AM is started: $E[start\ period\ AM]$
- The expected average inventory level of spare parts per period: $E[stock]$

During every analysis performed in this chapter, we simluated 10.000 life cycle runs per analysis in order to determine the average value of aforementioned output results.

In Section 1 of this chapter, we perform a sensitivity analysis (SA) to determine the relationship between uncertain parameters of the model and the associated outcomes. In Section 2, we perform two case studies of parts which are described in Section 5.2 if we decide to use AM from this point in time. In Section 3, we perform two case studies of the same parts, as studied in Section 7.2, if we decide to use AM in the future.

7.1 Sensitivity analysis

In this section, we perform a SA in order to investigate the relations between uncertain parameters of the model and the observable outcome. Regarding the model, there are in total seven input parameters which are subjected to uncertainty:

- Life cycle length of the analysis (T): as described in Chapter 1, the life cycle of systems delivered by Thales can have a useful life between 30 and 50 years. This is dependent upon the quality of the system. Therefore, we will analyse the impact of AM in case of several life cycle lengths. During the SA, we vary the value of *T* from 30 to 50 years.

- Total number of installed parts in the field (N): the marketing and sales department within Thales forecasts the expected number of systems to be sold. However, this forecast can be inaccurate, therefore we take this variable into account during the SA. Together with the marketing and sales department, an estimation error of ±20% is taken into account, ranging *N* from 40 till 60.
- Demand rate of a single part per period (λ): the demand of one-off parts is dependent upon the number of failures. The number of failure is uncertain, therefore we will analysis this parameter for the values: $\lambda = 0{,}004, \lambda = 0{,}006, \lambda = 0{,}008, \lambda = 0{,}01, \lambda = 0{,}012$. Where $\lambda = 0{,}012$ is the maximum value to consider.
- Cost development factor of the variable production costs of AM (cf): as described in Appendix 5, it is hard to determine the right value for cf. In order to determine the impact of a changing value of *cf*, we analyse this value for -50% till +50% of the base value.
- Variable production costs of the AM method per piece in period 0 $\left(c_{AM}(0)\right)$: we determine $c_{AM}(0)$ as a fraction of c_{CM}, as described in Appendix 9. This fraction is based on the results of Appendix 4, where we determine $c_{AM}(0)$ of two cases based on the size and material used for the parts. This way of determining $c_{AM}(0)$, can cause imperfections. In addition, in the future $c_{AM}(0)$ will decrease, as discussed in Appendix 5. Therefore, we vary the costs of $c_{AM}(0)$ over a range of -50% till +50% of the base value.
- Acquisition price of special tooling (ST): the acquisition price of special tooling is based on average values derived from the supplier. Therefore, this parameter can be different than calculated. So, this parameter is taken into account with respect to the SA for a range of -50% till +50% of the base value.
- Costs of downtime per time unit (d): with respect to the downtime costs, we distinguish four different scenarios in which downtime costs may occur. Within these scenarios, the value of d will be varied over a set of values:
  - *Scenario 1:* a failure doesn't result in standstill of the radar. Some one-off parts only have an esthetical function. In case these type of parts fails, the radar system is still able to perform its tasks.
  - *Scenario 2:* for other type of one-off parts, it holds that a failure doesn't result in a standstill of the radar, however, a temporarily fix is needed to prevent damage of other parts until a new part is available. After the part is fixed, the radar can perform its tasks again. In this scenario, the costs of the temporarily fix are taken into account as the costs of downtime.
  - *Scenario 3:* a failure results in a standstill of the radar system with a certain probability. Regarding the SA, we will vary this probability over several values (1%, 2%, 3%, 4%, 5%, 10%, 50%).
  - *Scenario 4:* a failure of a part results always in a standstill of the radar. These kind of parts are critical to the radar systems. In case of a failure, the radar system won't be able to operate until the failed part is replaced by a new one.

All other input parameters can be estimated with certainty and will not be analysed in this section. With respect to the SA we will vary one parameter at a time, while assuming all other input parameters are fixed. The fixed parameters are given in Table 8.

Table 8: General input parameter overview

System input		
Life cycle of the analysis	T = 30 (years)	
Total number of installed parts	N = 50	
Demand per period per part	λ = 0.004	
Cost development factor of AM	cf = 25,8%	
Costs per unit of downtime (€/day)	d = €27.000	
Length of one period	L_{period} = 365 (days)	
Part input	**CM method**	**AM method**
Costs of preparation	P_{CM} = €15.000	P_{AM} = €15.000
Variable production costs per piece	c_{CM} = €1.260	$c_{AM}(0)$ = €2.646
Production lead time	L_{CM} = 93 (days)	L_{AM} = 10 (days)
Preparation lead time AM method		$L_{AM(prep)}$ = 28 (days)
Salvage value	s_{parts} = €-12,60	
Holding costs	h_{parts} = 10%	
Special tooling input		
Acquisition costs of special tooling	ST = *€4.350*	
Salvage value	s_{ST} = €-217,50 (costs of discarding)	
Holding costs	h_{ST} = 10%	
Production lead time special tooling	L_{ST} = 65 (days)	

With respect to the SA of the downtime costs, we adjust more parameters than only the value of d in case of scenario 2. Since we are dealing with fixed downtime costs in this scenario, we set $L_{CM} = 10$, $L_{AM} = 1$, $L_{AM(prepP} = 5$, $L_{ST} = 0$, and $d = €500$. In case the part can be produced directly by means of AM, the temporarily fix has to hold for a short period, resulting in repair costs of only €500,00. A fix that has to hold for a longer period, is more expensive. These values have been established in consultation with people of the mechanical design department.

For the SA of the different parameters, we take 5 values of each parameter which are equally spread over the value range of that parameter. The results of the analysis of the parameters can be found in Table 9 till Table 15.

Table 9: Results of the SA of the life cycle length of the analysis

T	30	35	40	45	50
E[cost savings]	2,95%	5,51%	7,92%	10,14%	12,20%
E[P(AM used)]	45,83%	99,90%	99,92%	99,92%	100,00%
E[start period AM]	10	6	6	7	7
E[stock]	3,68	2,86	2,85	2,85	2,79

Table 10: Results of the SA of the total number of installed parts in the field

N	40	45	50	55	60
E[cost savings]	2,24%	3,03%	2,95%	3,39%	3,77%
E[P(AM used)]	19,55%	30,38%	45,83%	99,53%	99,93%
E[start period AM]	12	11	10	6	5
E[stock]	3,81	3,83	3,68	2,86	2,85

Table 11: Results of the SA of the demand rate of a single part per period

λ	0,004	0,006	0,008	0,01	0,012
E[cost savings]	2,95%	5,49%	5,76%	8,89%	14,78%
E[P(AM used)]	45,83%	100,00%	100,00%	100,00%	100,00%
E[start period AM]	10	5	5	5	4
E[stock]	3,68	2,80	3,52	3,74	3,64

Table 12: Results of the SA the cost development factor of the variable production costs of AM

cf	12,9%	19,4%	25,8%	32,3%	38,7%
E[cost savings]	1,92%	2,40%	2,95%	4,00%	4,88%
E[P(AM used)]	17,73%	35,15%	45,83%	99,58%	99,58%
E[start period AM]	14	10	10	7	7
E[stock]	3,94	3,77	3,68	2,85	2,86

Table 13: Results of the SA of the variable production costs of the AM method per piece in period 0

Cam(0)	€ 1.323,00	€ 1.984,50	€ 2.646,00	€ 3.307,50	€ 3.969,00
E[cost savings]	18,67%	3,95%	2,95%	2,56%	2,24%
E[P(AM used)]	100,0%	99,8%	45,83%	40,8%	31,0%
E[start period AM]	0	6	10	11	11
E[stock]	2,76	2,86	3,68	3,73	3,80

Table 14: Results of the SA of the acquisition price of special tooling

ST	€ 2.175,00	€ 3.262,50	€ 4.350,00	€ 5.437,50	€ 6.525,00
E[cost savings]	0,56%	1,54%	2,95%	4,77%	6,51%
E[P(AM used)]	2,5%	31,6%	45,83%	99,6%	99,5%
E[start period AM]	23	10	10	6	6
E[stock]	3,80	3,80	3,68	2,85	2,85

Table 15: Results of the SA of the downtime costs per time unit (d is set at €27.000,00 concerning scenario 3)

	Scenario 1	Scenario 2	scenario 3		
d	€ -	FIXED	1%	2%	3%
E[cost savings]	0,25%	0,33%	2,06%	1,74%	1,58%
E[P(AM used)]	32,88%	30,89%	99,56%	99,84%	37,44%
E[start period AM]	7	8	6	6	9
E[stock]	0,75	1,55	0,85	0,85	2,47
	scenario 3				Scenario 4
d	4%	5%	10% of d	50% of d	€ 27.000,00
E[cost savings]	1,83%	2,10%	2,40%	2,63%	2,95%
E[P(AM used)]	44,92%	46,24%	99,60%	39,76%	45,83%
E[start period AM]	10	11	6	10	10
E[stock]	2,62	2,66	1,86	3,67	3,68

For Thales, the most important reason to introduce AM is to save costs during the life cycle of a part. Therefore, we will focus on the expected cost savings, $E[cost\ savings]$, for different values of the investigated parameters. Based on the expected cost savings regarding the SA's, we conclude that the expected cost savings by using AM are sensitive to the following parameters:

- Life cycle length of the analysis (T)
- Demand rate of a single part per period (λ)
- Variable production costs of the AM method per piece in period 0 $\left(c_{AM}(0)\right)$
- Acquisition price of special tooling (ST)

7.1.1 Life cycle length of the analysis *(T)*

In Figure 9, we depicted the relation between $\mathrm{E[cost\ savings]}$ in case we use AM and T. As aforementioned, an extension of the life cycle length is realistic. From Figure 9, we see a clear pattern where $\mathrm{E[cost\ savings]}$ are sensitive to an increase of T. As T increases, the total number of parts demanded during the life cycle increase as well. Additionally, the variable production costs of the AM method decrease as more periods expire. Since we assumed, demand follows a Poisson process, the average the variable production costs of the AM method decrease as well leading to higher cost savings in case AM is used.

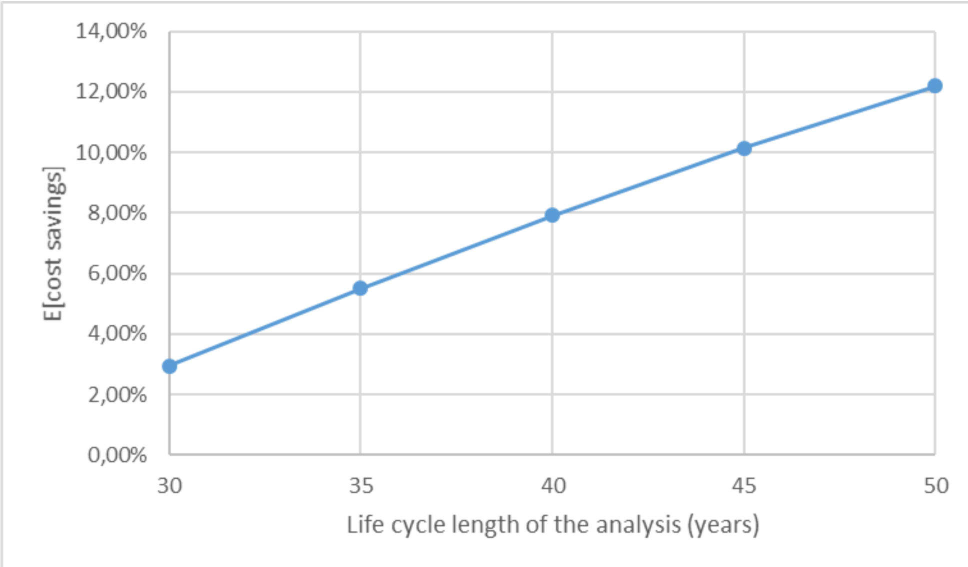

Figure 9: Sensitivity of the expected cost savings to T

7.1.2 Demand rate of a single part per period *(λ)*

Figure 10 depicts the relation between $\mathrm{E}[\text{cost savings}]$ in case we use AM and λ. We conclude that $\mathrm{E}[\text{cost savings}]$ are sensitive to an increase of λ. Given the current cost development characteristics (where cost decrease relatively quick in the near future), parts demanded after five to ten years are cheaper to produce by means of AM instead of CM. If λ increases, the demand of parts produced by AM increase relatively more, than parts produced by means of CM. Therefore, an increase of λ will result in higher cost savings in case AM is used.

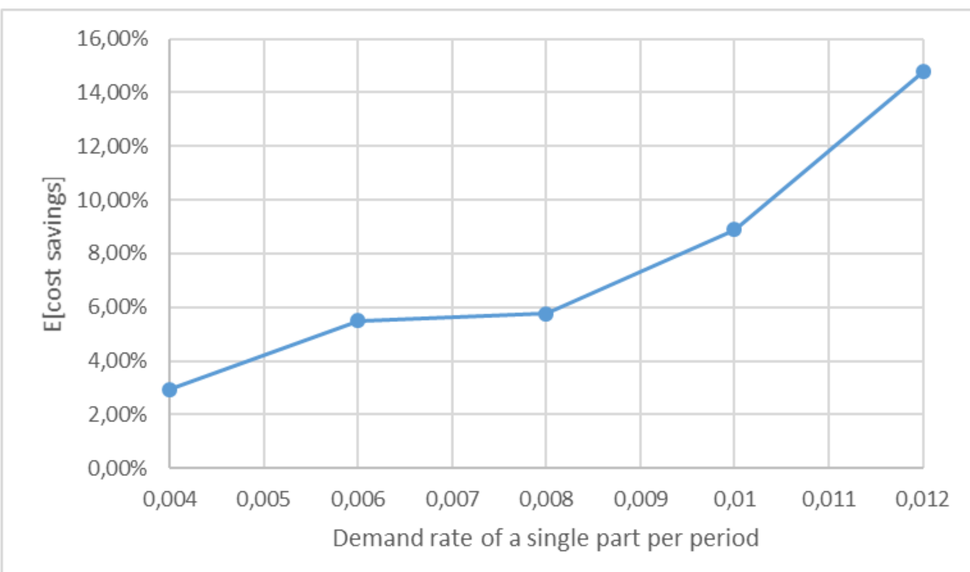

Figure 10: Sensitivity of the expected cost savings to λ

7.1.3 Variable production costs of the AM method per piece in period 0 *($c_{AM}(0)$)*

From Figure 11, we identify the relation between $\mathrm{E}[\text{cost savings}]$ in case we use AM and $c_{AM}(0)$. We conclude that $\mathrm{E}[\text{cost savings}]$ are sensitive to an increase of $c_{AM}(0)$. In Figure 11, we see an interesting behaviour. In case $c_{AM}(0)$ is low (in this particular situation only 50% of the original $c_{AM}(0)$), we see relatively high cost savings. From Table 13, we conclude AM is started in period 0, $E[start\ period\ AM]$ is equal to zero. This ensures, the initial production phase is performed by means of AM. Causing CM isn't used at all, so no preparation costs of the CM method are included and no special tooling has to be purchased at all. From this we conclude, if $\frac{c_{AM}(0)}{c_{CM}}$ goes to one (or drops below one), the use of AM causes relatively high cost savings during the LCC.

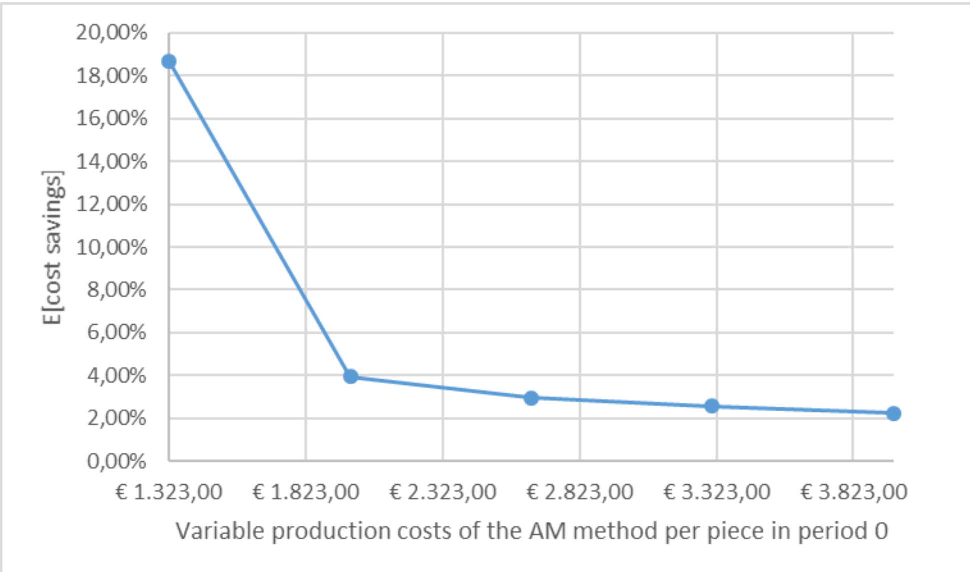

Figure 11: Sensitivity of the expected cost savings to Cam(0)

7.1.4 Acquisition price of special tooling *(ST)*

Based on Figure 12, which depicts the relation between $\mathrm{E}[\text{cost savings}]$ in case we use AM and ST, we conclude that $\mathrm{E}[\text{cost savings}]$ are sensitive to an increase of ST. If ST increases, also the inventory costs associated with special tooling increase. This makes production by means of AM during an earlier period more interesting, since inventory costs are omitted. Therefore, an increase of ST will result in higher cost savings in case AM is used.

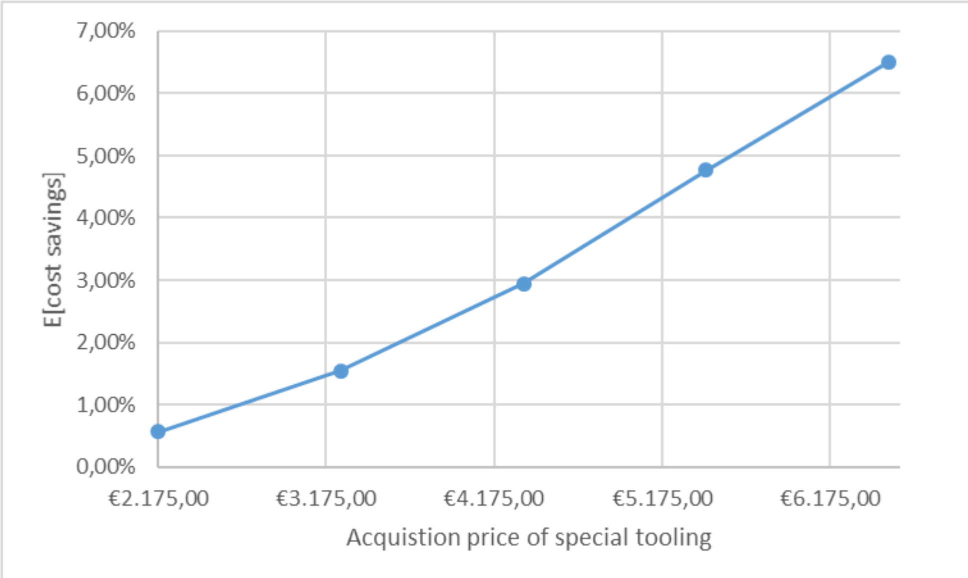

Figure 12: Sensitivity of the expected cost savings to ST

7.2 Case studies: analysis is performed in 2017

In this section, we perform a case study of the protection cover for the STIR and a case study for the sunshade for the STIR, which are described in Section 5.2. With respect to these two cases, we analyse the following output results:

- The expected cost savings during the life cycle: $E[cost\ savings]$
- The expected probability that AM is used at some point during the life cycle: $E[P(AM\ used)]$
- The expected period in which production by means of AM is started: $E[start\ period\ AM]$
- The expected average inventory level of spare parts per period: $E[stock]$

Regarding the SA, we analysed the expected cost savings in case of the optimal production strategy using AM compared to the optimal strategy using CM. However, in the current situation, Thales holds no inventory regarding spare parts and there is no strict policy with respect to storing or discarding special tooling. Therefore, we distinguish four different expected cost savings:

- The expected cost saving of the optimal strategy using AM, compared to the optimal strategy using CM: $E_1[cost\ savings]$
- The expected cost saving of the optimal strategy using AM, compared to the strategy using CM without inventory of parts using the optimal policy regarding special tooling: $E_2[cost\ savings]$
- The expected cost saving of the optimal strategy using AM, compared to the strategy using CM without inventory where special tooling is discarded in case it hasn't been used for a period of 10 years: $E_3[cost\ savings]$
- The expected cost saving of the optimal strategy using AM, compared to the strategy using CM without inventory where special tooling is discarded in case it hasn't been used for a period of 5 years: $E_4[cost\ savings]$

The costs associated with the strategy where we use CM and discard tooling after a period of 5/10 years it isn't used are derived by means of the simulation model.

7.2.1 Protection cover for the STIR

We first analyse the protection cover for the STIR, the input values used for the analysis, can be found in Table 16. In case of a failure of a protection cover, we are dealing with downtime costs as described in scenario 2. The cover is meant to protect electrical components within it. A failure results in a temporarily fix to prevent the electrical components from damage. Dependent upon the lead time of a new part, the failed part is repaired. A temporarily fix in case of AM when the AM method is prepared is set at €1.000. A fix in case of AM when AM is not prepared is set at €6.000. A fix in case of CM is set at €10.000. Therefore, we use $d = €1.000$, $L_{CM} = 10$, $L_{AM} = 1$, $L_{AM(prep)} = 5$, and $L_{ST} = 0$ during the analysis.

Table 16: Input values protection cover for the STIR

P_{CM}=€10.000	C_{CM}=€5.768	L_{CM}=10 (days)	ST=€5.900	L_{ST}=0 (days)	h_{ST}=10%	s_{ST}=€-295
P_{AM}=€10.000	$c_{AM}(0)$=€13.331	L_{AM}=1 (days)	L_{prep}=5 (days)	cf=25,8%		
d=€1.000	λ=0,004	N=50	T=30 (years)	h_{parts}=10%	s_{parts}= €-57,68	L_{period}=365 (days)

As described in Section 6.6, it is hard to determine the optimal period to start with the use of AM for the first time. Therefore, a complete overview of which decision must be taken during each period given a certain state at the beginning of the period is given in Appendix 10. With these particular values, it is optimal to prepare the AM method in advance during period $t = 0$. In addition, we conclude from Appendix 10 that we produce one part to put in inventory during period $t = 0$ and that we discard special tooling at the beginning of the first period. So, in case parts must be produced to fulfil demand, production will take place by means of AM. So, if demand during the entire after-sales phase is less or equal to one, AM won't be used. On average, AM will be used in 98,38% of the simulation runs. The average period in which AM is used for the first time is period 10. An overview of the percentage of runs that start regarding the different periods is given in Appendix 10.

The total costs associated with the input values as given in Table 16, and the optimal production strategy are equal to approximately €350.000. In case we use only CM, the costs are approximately €379.000. Regardless of the use of AM or not, in the optimal situation parts are put in inventory. At this moment, Thales doesn't put one-off parts in inventory. The costs of this strategy, where no parts are put in inventory while using the optimal strategy to discard special tooling, results in total costs of approximately €417.000. The costs of the strategy where we only use CM, no parts are put in inventory, and special tooling is discarded if it isn't been used for a period of 10 years, results in total costs of approximately €419.000. The costs of the strategy where we only use CM, no parts are put in inventory, and special tooling is discarded if it isn't been used for a period of 5 years, results in total costs of approximately €422.000.

Table 17: Results of the analysis of the protection cover for the STIR

$E_1[cost\ savings]$	7,65%
$E_2[cost\ savings]$	16,07%
$E_3[cost\ savings]$	16,47%
$E_4[cost\ savings]$	17,06%
$E[P(AM\ used)]$	98,38%
$E[start\ period\ AM]$	10
$E[stock]$	0,80

Based on the analysis, we conclude that Thales can use AM in order to decrease the life cycle costs of the protection cover for the STIR by 7,65%. In addition, we see high cost savings if parts are put in inventory. If stock is applied, cost savings of $16{,}07\% - 7{,}65\% = 8{,}42\%$ are realized. Dependent on the current strategy of discarding tooling, the use of AM in combination with the storage of parts can save Thales between 17,12% and 16,04%. This is equal to cost savings between €67.000 and €72.000 over a period of 30 years.

By using AM in order to fulfil demand during the after-sales phase, Thales can decline costs by more than 16%, which results in a saving between €72.000 and €67.000 over a period of 30 years. This saving is caused by the use of AM for an amount of at least $€379.000 - €350.000 = €29.000$. In addition, we conclude that Thales can save costs of $€417.000 - €379.000 = €38.000$ if protection covers are put in inventory.

7.2.2 Sunshade for the STIR

We first analyse the sunshade for the STIR, the input values used for the analysis, can be found in Table 18. As described in Section 5.2.2, the sunshade is an extra hood to protect the protection cover. In case it fails, no downtime costs are applicable. This is scenario 1 of the downtime costs, so $d = €0{,}00$.

Table 18: Input values sunshade for the STIR

P_{CM}=€5.000	C_{CM}=€1.086	L_{CM}=192 (days)	ST=€2.800	L_{ST}=65 (days)	h_{ST}=10%	s_{ST}=€-140
P_{AM}=€5.000	$c_{AM}(0)$=€2.062	L_{AM}=10 (days)	L_{prep}=28 (days)	cf=25,8%		
d=€0,00	λ=0,004	N=50	T=30 (years)	h_{parts}=10%	s_{parts}= €-10,86	L_{period}=365 (days)

Regarding the sunshade for the STIR, a complete overview of which decision must be taken during each period given a certain state at the beginning of the period is given in Appendix 11. From this Appendix, we conclude that we use CM during the initial production phase and we don't produce parts to put in inventory during any period of the life cycle. At the start of the first period special tooling is discarded and in case parts must be produced we use AM. However, if during the after-sales phase, from period 1 until period 26 no parts are demanded, demand during the last four periods will be fulfilled be means of CM. If during one of the periods 1 until 26 at least one part is demanded, AM is used during the entire after-sales phase. In case of the sunshade, AM is used in 99,33% of the simulation runs. The average period in which AM is used for the first time is period 5. An overview of the percentage of runs that start regarding the different periods is given in Appendix 11.

The total costs associated with the input values as given in Table 18, and the optimal production strategy are equal to €71.500. In case we use only CM, the costs are €77.000. With these particular values, in case only CM is used no parts are put in inventory. So, the costs of Thales at this moment are equal to those of the situation in which we only use CM if we use the optimal strategy to discard special tooling. The costs of the strategy where we only use CM, no parts are put in inventory, and special tooling is discarded if it isn't been used for a period of 10 years, results in total costs of €78.000. The costs of the strategy where we only use CM, no parts are put in inventory, and special tooling is discarded if it isn't been used for a period of 5 years, results in total costs of €79.500.

Table 19: Results of the analysis of the sunshade for the STIR

$E_1[cost\ savings]$	7,14 %
$E_2[cost\ savings]$	7,14%
$E_3[cost\ savings]$	8,33%
$E_4[cost\ savings]$	9,55%
$E[P(AM\ used)]$	99,33%
$E[start\ period\ AM]$	5
$E[stock]$	0

Based on the analysis, we conclude that Thales can use AM in order to decrease the life cycle costs of the sunshade for the STIR by 7,14%. In contrast with the protection cover, we see no influence of putting parts in inventory on the cost savings. This can be explained, since the costs of downtime are determined at $d = €0{,}00$. Therefore, inventory won't decline the cost savings. Dependent on the current strategy of discarding tooling, the use of AM in combination with the storage of parts can save Thales between 9,55% and 7,14%. This is equal to cost savings between €5.500 and €8.000 over a period of 30 years.

7.3 Case studies: analysis is performed in the future

As described during the SA in Section 7.1.3, the variable production costs of the AM method per piece in period 0, have a great impact on the cost savings regarding the LCC. In this section, we perform an analysis of the two cases in which the values of $c_{AM}(0)$ are chosen in such a way that the initial production phase is performed by means of AM as well as the after-sales phase.

7.3.1 Protection cover for the STIR

According the cost development method described in this research, the costs of $c_{AM}(0)$ of the protection cover will be the same as the costs of c_{CM} after a period of 6 years from now (2017). In that case, only AM will be used and the cost savings as a result of the use of AM instead of CM will be higher. For this analysis we use the input data as in Table 16, except that we set $c_{AM}(0) = €5.768$. The costs associated with this production strategy are approximately €317.000.

Table 20: Analysis results if protection cover is produced only by means of AM

$E_1[cost\ savings]$	16,36 %
$E_2[cost\ savings]$	23,99%
$E_3[cost\ savings]$	24,34%
$E_4[cost\ savings]$	24,88%

If we compare the results of Table 20 to the results of Table 17, we see great cost savings if we use AM for the production of protection covers for the STIR over 6 years.

7.3.2 Sunshade for the STIR

According the cost development method described in this research, the costs of $c_{AM}(0)$ will be the same as the costs of c_{CM} after a period of 3 years from now (2017). In that case, only AM will be used and the cost savings as a result of the use of AM instead of CM will be higher. For this analysis we use the input data as in Table 18, except that we set $c_{AM}(0) = €1.135$. The costs associated with the this production strategy are approximately €64.000

Table 21: Analysis results if sunshade is produced only by means of AM

$E_1[cost\ savings]$	16,88 %
$E_2[cost\ savings]$	16,88%
$E_3[cost\ savings]$	17,95%
$E_4[cost\ savings]$	19,50%

If we compare the results of Table 21 to the results of Table 19, we see great cost savings if we use AM for the production of sunshades for the STIR over only 3 years.

7.4 Conclusion

Based on the performed analysis, we can conclude that the use of AM has a significant impact on the life cycle costs of one-off parts at Thales. The most important conclusion based on the analysis is the fact that the cost saving potential of AM significant increases in case the variable production costs of the AM method per piece in period 0 decreases. If $\frac{c_{AM}(0)}{c_{CM}}$ goes to one (or drops below one), parts required during the initial production phase will be produced by means of AM as well as the parts produced during the after-sales phase. If this happens, CM isn't used at all, so no preparation costs of the CM method are included and no special tooling has to be purchased at all, and AM is used to it full potential. For one-off parts, it is realistic to assume that this is possible within the next 3 till 10 years.

Additionally, parts which are produced by means of special tooling, benefit from using AM in terms of costs during the life cycle. In addition, the effect of AM has more impact on the cost savings as the life cycle length of systems increases, and the demand rate per part per period increases.

With respect to the costs of downtime, we conclude AM has no significant impact regarding one-off parts. Since, one-off parts are demanded in relatively low volumes, costs of downtime are prevented by putting extra parts in inventory. By using AM the production lead time to refill inventory levels become shorter, which results in lower overall inventory levels, however, this has no significant effect on the cost savings.

If we would analyse the case studies point in time (2017), we see a cost reduction of between 16,07% and 17,06% (protection cover) and almost between 7,14% and 9,55% (sunshade) if we introduce AM in combination with inventory compared to the current way of handling one-off parts. This results in saving between €67.000 and €72.000 for the protection cover, were a saving of €38.000 is realized by putting parts in inventory. Regarding the sunshade, we can save between €5.500 and €8.000 over a period of 30 years entirely caused by the use of AM.

If we would perform an analysis of both case studies in the future, we can come up with other results. Because developments concerning AM lower prices, AM becomes much more attractive in the future. If we perform an analysis of the sunshade, 3 years from now, we end up with cost savings between

16,88% and 17,95%. The same holds for the protection cover. If we perform an analysis, 6 years from now, we end up with cost savings between 23,99% and 24,88%.

8 Conclusions and Recommendations

This Chapter includes the conclusion and recommendations of the research. We start with the main conclusions of the research, where after we will discuss the limitations of the research. Based on this information, we continue with the recommendations and finally end up with suggestions for further research regarding this report.

8.1 Conclusions from the research

This research is initiated since Thales Hengelo wants to determine the impact of the use of Additive Manufacturing (AM) methods as a substitute for their current Conventional Manufacturing (CM) methods, during some point in the life cycle of parts. Therefore, the following goal was established:

'Construct a model to assess the impact of the transition from CM to AM on the LCC of one-off parts within radar systems at Thales Hengelo'.

With the use of a model to assess the impact of AM, we can answer the main research question:

´How Thales Hengelo use Additive Manufacturing, in order to decrease Life Cycle Cost of one-off parts?'

We defined several research questions in order to answer this research question. We present the answers shortly in this section.

The first tasks, was to identify cost factors which are affected when we use AM instead of CM. Based on an analysis of the current life cycle cost method used by Thales and literature, we identified the following cost factors regarding the model:

- Preparation costs related to design & development of parts
- Variable production costs of parts
- Downtime costs in case a part is demanded
- Costs related to special tooling if applicable (only in case of CM production)
- Costs related to parts in inventory

The model constructed during this research must determine if the use of AM, is cost efficient over the use of CM during the life cycle of a one-off part. Additionally, the option to produce parts to put in inventory is included. Therefore, the model could be seen as a problem with a structure where during different moments in time, decisions must be made regarding which manufacturing method to use and if parts must be produced for inventory. In our model, decisions are made at the beginning of every period of the life cycle. Such problem structure could be seen as a sequential optimization problem. In order to solve this problem, we use dynamic programming. Given the nature of the problem and the fact we analysis one-off parts which demand follows a Poisson process, a model is constructed based on 'Stochastic Dynamic Programming'. The model is verified by consulting experts within Thales and Thales's partners to give their insights and opinions about the model. Based on the expert opinions we conclude we take the important cost factors into account in the right way. So, according experts, the model is valid. In order to verify the model, we created a simulation model in which we simulate the moment at which demand occurs in practice. Based on this 'actual' demand we can directly calculate all relevant cost applicable. The difference between the average of the simulation runs and the value from the SDP model is less than 0.5%. Therefore, we concluded that the results of the model are similar to the results as they will be in real life.

The most important parameter of the model, is the variable production costs of the AM method per piece in period 0, $c_{AM}(0)$. Because of the cost developments in the future, $c_{AM}(0)$ will decrease over time. As soon as, $\frac{c_{AM}(0)}{c_{CM}}$ goes to one (or drops below one), AM will be used towards its full potential. The initial production phase is performed by means of AM as well as the after-sales production phase. Causing CM isn't used at all, so no preparation costs of the CM method are included and no special tooling has to be purchased at all. For one-off parts, it is realistic to assume that this is possible within the next 5 till 10 years.

Additionally, the acquisition costs of special tooling, the life cycle length of systems, and the demand rate per part per period are parameters that strongly influence the output of the model. The expected cost savings caused by AM, increase in case the acquisition costs of special tooling increase, the life cycle length of systems increase, or the demand rate per part per period increase.

Regarding the costs of downtime, we conclude AM has only limited impact regarding one-off parts. One-off parts are demanded seldom. Therefore, it is better to put them in inventory to prevent for costs of downtime then use AM for production. By using AM the production lead time to refill inventory levels become shorter, which results in lower overall inventory levels, however, this has no significant effect on the cost savings.

Based on the case studies performed in research, we see a cost reduction of between 16,07% and 17,06% (protection cover) and almost between 7,14% and 9,55% (sunshade) if we analyse the use of AM in combination with inventory compared to the current way of handling one-off parts in 2017. This results in saving between €72.000 and €67.000 for the protection cover, were a saving of €38.000 is realized by putting parts in inventory. Regarding the sunshade, we can save between €8.000 and €5.500 over a period of 30 years entirely caused by the use of AM. If we analyse the use of AM in combination with inventory compared to the current way of handling one-off parts in the future we find higher cost savings. If we start the analysis of the protection cover 6 years from now (2023), we find cost savings between 23,99% and 24,88%. Additionally, if we start the analysis of the sunshade only 3 years from now (2020), we find cost savings between 16,88% and 17,95%. The cost savings in the near future, between 3 till 6 years from now, are significantly higher than the costs savings at this point in time.

8.2 Recommendations towards the after-sales supply chain

As we concluded in Section 7.2.1, there is a difference between the costs in case CM is used in combination with the option to put parts in inventory, and the costs in case CM is used without the option to put parts in inventory. Thales must revaluate its parts and look towards the storage of parts which have a very low demand, but cause downtime costs. By these means, Thales is able to save costs in the long run in an easy way.

Additionally, Thales must start with a couple spin-offs with respect to producing parts by means of AM. In this way, Thales is able to determine the effect in real-life and Thales becomes familiar with the pros and cons of the manufacturing in case of AM.

8.3 Recommendations for further research

In this section, we provide the recommendations for further research in order to take the full advantage of the use of AM.

One-off parts are parts which are demanded seldom. Therefore, only a limited number of parts are produced by AM since CM is preferable at this point in time because of the relatively high production costs of AM. However, the development in the technology of AM processes is going fast. Besides, the potential of AM within the next five till ten years is shown. Therefore, Thales should do research towards methods/frameworks which are able to identify parts applicable for production by means of AM.

At the same time, Thales should research the impact of AM on the physical characteristics of parts. For example: AM might change the failure behaviour of a part, resulting in a changing demand pattern in case of electronical spare parts. Additionally, if AM has impact on the physical characteristics of parts, to what level could Thales take advantage of the benefits with respect to the integration of function of different parts, or the integration of subassemblies into one part. Then AM is used, the way it’s meant to be used.

Bibliography

American Society for Testing and Materials. (2012). *ASTM F2792-12a, Standard Terminology for Additive Manufacutring Technologies.* West Conshohocken: ASTM International.

Asiedu, A., Gu, P. (1998). Product life cycle cost analysis: State of the art review. *International Journal of Production Research, 36*(4), 883-908.

Bhasin, V., Bodla, M. R. (2014). *Impact of 3D printing on global supply chains by 2020* (Doctoral dissertation, Massachusetts Institute of Technology).

Boothroyd, G. (1994). Product design for manufacture and assembly. *Computer-Aided Design, 26*(7), 505-520

Bourrel, D. L, Leu, M. C., Rosen, D. W. (2009). Roadmap for additive manufacturing: identifying the future of freeform processing. *The University of Texas at Austin, Austin, TX.*

Dhillon, B. S. (2010). *Life cycle costing for engineers.* Boca Raton: CRC Press.

Dowlatshahi, S. (1992). Product design in a concurrent engineering environment: an optimization approach. *The International Journal of Production Research, 30*(8), 1803-1818.

D'Auria, M., Otter, W. J., Hazell, J., Gillatt, B. T., Long-Collins, C., Ridler, N. M., & Lucyszyn, S. (2015). 3-D printed metal-pipe rectangular waveguides. *IEEE Transactions on Components, Packaging and Manfacturing Technology, 5*(9), 1339-1349.

Ellram, L. M. (1995). Total cost of ownership: An analysis approach for purchasing. *International Journal of Physical Distribution & Logistics Management, 25*(8), 4-23.

Fixson, S. K. (2004). Assessing product architecture costing: Product life cycles, allocation rules, and cost models. In *ASME 2004 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference* (pp. 857-868). American Society of Mechanical Engineers.

Ford, S. L. N. (2014). Additive manufacturing technology: Potential implications for U.S. manufacturing competitiveness. *Journal of International Commerce and Economics,* 1-35. Retrieved from http://www.usitc.gov/journals.

Gibson, I., Rosen, D. W., Stucker, B. (2010). *Additive manufacturing technologies: Rapid prototyping to direct digital manufacturing*. New York: Springer.

Gao, W., Zhang, Y., Ramanujan, D., Ramani, K., Chen, Y., Williams, C. B.,…Zavattieri, P. D. (2015). The status, challenges, and future of additive manufacturing in engineering. *Computer-Aided Design, 69,* 65-89.

Greene, L. E., Shaw, B. L. (1990). The steps for successful life cycle cost analysis. In *Aerospace and Electronics Conference, 1990. NAECON 1990., Proceedings of the IEEE 1990 National* (pp 1209-1216). IEEE.

Groes-Petersen, P. (2011, January 21). SMxxx Family – SM50. Hengelo: Thales Hengelo.

Holmström, J., Partanen, J., Tuomi, J., Walter, M., (2009). Rapid manufacturing in the spare parts supply chain: Alternative approaches to capacity deployment. *Journal of Manufacturing Technology Management, 21*(6), 687-697.

Katgert, A. (2015). *Additive Manufacturing and Thales' After Sales Service.* Hengelo: Thales.

Khajavi, S. H., Partanen, J., Holmström, J. (2014). Additive manufacturing in the spare parts supply chain. *Computers in Industry, 65*(1), 50-63.

Langefeld, B. (2014). *Marktchancen un Potentiale des Additive Manufacturing.* Denkendorf: VDMA.

Law, A. M. (2015). *Simulation modeling and analysis*. New York: McGraw-Hill.

Lindemann, C., Jahnke, U., Moi, M., & Koch, R. (2012, Augustus). Analyzing product lifecycle costs for a better understanding of cost drivers in additive manufacturing. In *23th Annual International Solid Freeform Fabrication Symposium-An Additive Manufacturing Conference. Austin Texas USA 6th-8th August.*

Rausand, M., Hoyland, A. (2004). *System reliability theory: models, statistical methods, and applications.* NJ: Wiley-Interscience.

Sherbrooke, C. (2004). *Optimal inventory modeling of systems: Multi-echelon techniques.* Boston: Kluwer Academic Publishers.

Sullivan, W., Wicks, E., & Koelling, C. (2015). *Engineering economy.* New Jersey: Pearson Prentice Hall.

Thales Group. (2016, June 22). *Wie zijn wij?* Consulted on 6 22, 2016, from Thales group: https://www.thalesgroup.com/en/worldwide/careers/wie-zijn-wij

Thales Nederland B.V. (2016, November 8). Standard Product LCCs: Master Data Assumption List. Hengelo, Overijssel, Netherlands.

Woodward, D. G. (1997). Life cycle costing – theory, information acquisition and application. *International Journal of Project Management, 15*(6), 336-344.

Appendix 1: Navy Profile

– Confidential –

Appendix 2: Standard LCC analysis: cost factor ratios

– Confidential –

Appendix 3: Additive manufacturing process steps

As mentioned in Section 3.1, every AM method involve, at least to some degree, eight process steps. In this section, we will describe what is done in every process step (Gibson, et al., 2010).

Step 1: CAD

The first step of the process is to form a software model, which describes the external geometry. This can be done by the use of almost any professional CAD modelling software, as long as the output is a 3D solid or surface representation.

Step 2: Conversion to STL

The next step is to convert the CAD-model in a file format which will be accepted by the AM machine. At this moment STL file format is a standard which is accepted by nearly every AM machine. Besides, almost every CAD system is able to output a STL format.

Step 3: Transfer to AM machine and STL and STL file manipulation

The third step is the transfer of the STL file to the AM machine. During this step, the file may be manipulated in order to ensure the right size, position, and orientation for building.

Step 4: Machine setup

In order to produce a proper part, machine settings related to build parameters have to be set properly. Build parameters are material constraints, energy source, layer thickness, timings, etc.

Step 5: Build

The construction of the part is an automated process which doesn't need a lot supervision. Only little monitoring is required at this time, in order to ensure no errors occur like the machine running out of material, power or software glitches, etc.

Step 6: Removal

After a part is completed, it has to be removed out of the machine. AM machines can have safety locks in order to ensure for example operating temperatures are sufficiently low or no moving parts are active anymore.

Step 7: Post processing

A lot of part produced by AM, require additional cleaning up before the can be used, once they are removed from the machine. Parts may have supporting structures that has to be removed, or parts may be weak resulting in manipulation of the part.

Step 8: application

The final step of the AM process may be an additional treatment in order to get the part acceptable for use. This may include priming and painting in order to give an acceptable finish of the part. Additionally, they can be assembled together with other components to form a final part.

Appendix 4: Input parameters for the cases

In this section, we will describe how we have determined the input parameters of the protection cover and the sunshade of the STIR. The data of parts with respect to CM are extracted from documents within Thales. The costs of AM are based on information subtracted from websites which print parts for the commercial sector. We used this method to determine the costs of AM, because it is a fast way to determine prices, using all kind of materials. Data with respect to special tooling is based on information obtained from one of Thales' suppliers.

Part input

As stated before, input data related to CM is directly retrieved from documents within Thales, with the exception of the preparation costs. These costs are estimated at €5.000 for the sunshade and at €10.000 for the protection cover, in consultation with people of the mechanical design department.

With respect to the preparation costs of the AM method, we estimate these costs to be the same as those of the preparation costs of CM. Some modification will be needed for the AM model and AM machines have to be set-up in order to build a good part. However, expert expect no significant change of the preparation time associated with the CM method compared to the preparation time associated with the AM method. The time for the preparation of the AM method is estimated at 28 days. This is sufficient to create/adjust a model and set-up the AM machine in case of one-off parts.

At this moment in time, one-off parts, are not stored. Therefore, we can't retrieve salvage values from the information within Thales. However, the parts taken into account, are specific parts which are only suitable for the STIR. Since we assume all systems are taken out of the field at the same time, we have to discard parts if there are parts left in inventory after the systems lifetime. The costs of discarding are estimated to be 10% of the acquisition costs in case of CM in period 0. Additionally, the costs of inventory are determined at 10% of the acquisition costs in case of CM in period 0, per period.

In order to determine the variable production costs of the AM produced parts, we made use of 3dhubs.com. It is an online 3D printing service where you can upload a part, choose the desired material, and directly see potential producers including prices and lead-time. At this point in time, we used the lead-time as indicated at 3D hubs which is 10 days. In case Thales would use professional partners for AM, this time may decline to 1 or 2 days depending on the AM method used, the material used, and the size of the part.

Since the parts, considered are too big to order at 3D hubs in the desired material (glass filled polyamide). Therefore, we scaled both parts to smaller dimension which could be printed. For both parts, we determined the costs of 6 different scaled dimensions and plotted those costs in the Figure 14, 15, 16, and 17.

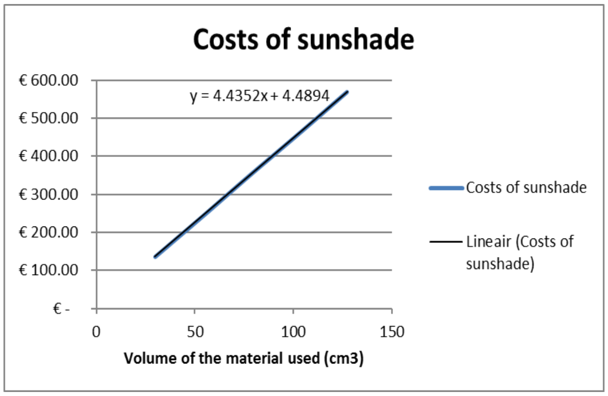

Figure 15: Cost of sunshade (A)

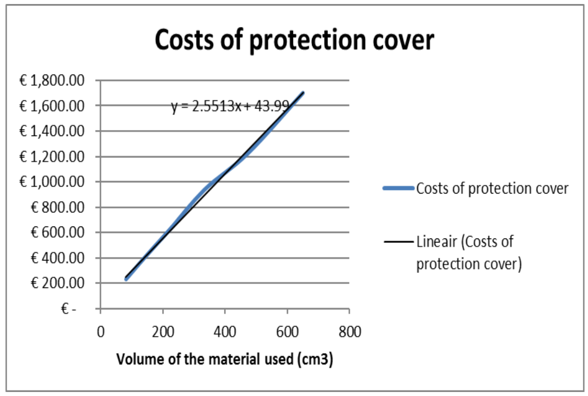

Figure 14: Costs of protection cover (A)

What stands out in the Figures 14 and 15, is that the costs of AM seem increase according a linear line as the volume of material used, increases. Based in these results, we constructed a linear trend line to be able to estimate the costs of the parts in case they are produced by AM. The scaling and volume calculation is done by use of SolidWorks.

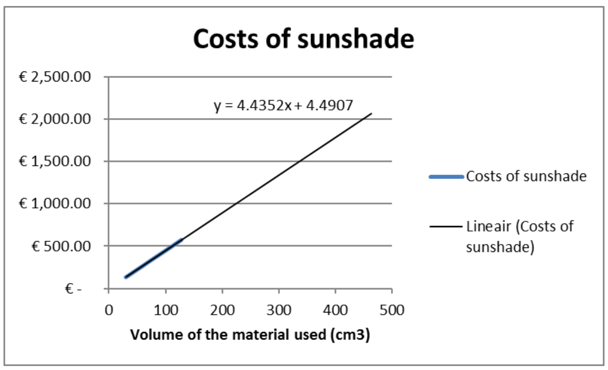

Figure 17: Costs of sunshade (B)

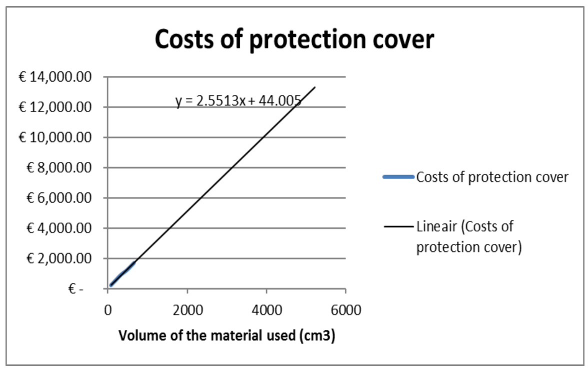

Figure 16: Costs of protection cover (B)

The total material volume used for the sunshade is 463,8 cm^3, resulting in total costs of €2.062. The total material volume used for the protection cover is 5207,9 cm^3, resulting in total costs of €13.331.

Table 22: Sunshade input parameters

Sunshade	**CM method**	**AM method**
Costs of preparation	P_{CM} = €5.000	P_{AM} = €5.000
Variable production costs per piece	c_{CM} = €1.086	$c_{AM}(0)$ = €2.062
Production lead time	L_{CM} = 197 days	L_{AM} = 10 days
Preparation lead time AM method		$L_{AM(prep)}$ = 28 days
Salvage value	s_{parts} = -€10,86	
Holding costs	h_{parts} = 10%	

Table 23: Protection cover input parameters

Protection cover	**CM method**	**AM method**
Costs of preparation	P_{CM} = €10.000	P_{AM} = €10.000
Variable production costs per piece	c_{CM} = €5.768	$c_{AM}(0)$ = €13.331
Production lead time	L_{CM} = 192 days	L_{AM} = 10 days
Preparation lead time AM method		$L_{AM(prep)}$ = 28 days
Salvage value	s_{parts} = -€57,68	
Holding costs	h_{parts} = 10%	

Special tooling input

The costs of special tooling exist out of 3 components, the acquisition costs of new tooling, inventory costs in case special tooling is stored and the costs or revenue when the special tooling is no longer necessary. The inventory costs are 10% of the acquisition costs of special tooling per period. The special tooling used for the sunshade as well as for the protection cover is a mould. The moulds can't be used for other products, so discarding will result in costs. The costs of discarding are dependent upon the size of the moulds, which we estimate at 1% of the acquisition costs of the special tooling €250.

We weren't able to retrieve direct costs of the moulds. However, we have got information about the average costs of a mould per square meter. With the use of SolidWorks, we determined the size of the products and used this to calculate the acquisition costs of the moulds. A mould exists out of a 'plug' and a 'mould'. The costs of a plug are between €1.200 and €1.500 per square meter, while the costs of a mould are between €2.000 and €5.000 per square meter. For our parts, we took the average of these costs. The size of the sunshade is approximately 0,58 square meter (see Figure 4) and the protection cover is approximately 1,22 square meter (see Figure 3)

Table 24: Sunshade special tooling input parameters

Special tooling for the sunshade	
Acquisition costs of special tooling	ST = €2.800
Salvage value	s_{ST} = -€295,00
Holding costs	h_{ST} = 10%
Production lead time special tooling	L_{ST} = 65 days

Table 25: Protection cover special tooling input parameters

Special tooling for the protection cover	
Acquisition costs of special tooling	$ST = €5.900$
Salvage value	s_{ST} = -€140,00
Holding costs	h_{ST} = 10%
Production lead time special tooling	L_{ST} = 65 days

As described in Chapter 7, there are different scenarios associated with downtime. The protection cover is a part that belongs to scenario 2. Therefore, we use $L_{ST} = 0$ during the analysis in Chapter 7.

Appendix 5: Description of the cost factor development value

In the model, we make use of a cost development factor, cf, which is used to describe future costs of AM. Since Thales, will outsource the AM processes, the costs of AM can be translated into the variable production costs per piece. Based on current trends and expert opinions, we can conclude that the costs of AM will decrease in future. However, to what extend and how fast this decrease will be, is highly uncertain.

According various researchers and experts, the costs will decrease as a result of economies of scale. In the future, the market of AM will grow. This will result in lower prices of materials used for different AM processes and the production costs of machines will decrease. Additionally, the build rate of AM processes will increase in the future, resulting in more efficient production processes. Experts expect that the costs of AM will drop by 50% within the next five to ten years. Dr. Bernhard Langefeld from Roland Berger Strategy Consultants, carried out a research in 2014 commissioned by VDMA about the expected future cost development of AM. In his research Langefeld (2014), states that during the period from 2013 to 2018 costs can be cut with 49%. Additionally, he states that during the period from 2018 to 2023 costs can be cut with another 32% (in total a decrease of more than 65%). Although we have little information, based on these statements we can conclude that the costs of AM in the near future (five to ten year) will decrease faster than the costs of AM in the far future (more than ten year). This is in line the expected cost development according AM experts. Such a decrease can be displayed by an exponential function, such as:

$$c_{AM}(t) = c_{AM}(0) * cf^{t}$$

Where,

$c_{AM}(t) =$	variable production costs of the AM method per piece in period t.
$c_{AM}(0) =$	variable production costs of the AM method per piece in period 0.
$cf =$	cost factor to describe future cost developments for the variable production costs per piece of the AM method.
$t =$	period of the life cycle where are taken into account.

Such a formulation however, ensures an extreme decrease of costs in the far future. If we take into account a realistic decrease in the near future as opposed by Langefeld of parts demanded by Thales which have to meet high requirements, the values will become unrealistically low at a certain point, see Figure 18. People within Thales assume that the minimum costs after 50 years will be somewhere between 15%-25% of the costs at this moment in time. Therefore, we have sought a more appropriate function to model the cost development of AM.

We will use the ‘learning curve’ to model the cost development in the future. A learning curve is a mathematical model to express the phenomenon of increased efficiency and improved organizational performance with repetitive production of a good or service (Sullivan, Wicks, Koelling (2015). The concept is that some input parameter decreases, on a per-output-unit basis, as the number of units produced increase. Most learning curves are based on the assumption that a constant percentage reduction occurs as the number of output doubles. In our case, however, we won’t model on a per-output-unit basis, but on a per-period basis and thus we assume a constant reduction of cf % as the number of periods doubles. The function used is as follows:

$$c_{AM}(t) = c_{AM}(0) * t^{n}$$

Where $n = \frac{\log cf}{log2}$ = the learning curve exponent

cf = % reduction of the variable production costs per piece of the AM method every time the analysed period is doubled

t = is the period of the life cycle analysis

The reason, we take a per-period basis is that we have to make decisions at the beginning of a period for the rest of that period. Cost adjustments during a period will be translated into an average number resulting in another type of function rather than a complement to the cost function. The value for cf can be determined by solving the following equations, where x is de % cost decrease of AM over t periods:

$$c_{AM}(t) = c_{AM}(0) * t^n$$

$$(1 - x) = t^n$$

$$(1 - x) = t^n$$

$$\log_t(1 - x) = \log_t(t^n)$$

$$n = \log_t(1 - x)$$

$$n = \frac{\ln(1 - x)}{\ln(t)}$$

In order to calculate cf:

$$n = \frac{\log(1 - cf)}{\log 2}$$

$$\log(1 - cf) = n * \log 2$$

$$cf = 1 - 2^n$$

By filling in n, in the previous expression we get:

$$cf = 1 - 2^{\frac{\ln(1-x)}{\ln t}}$$

Now, we can calculate cf based on an expected decrease of the costs of AM during a certain period.

Value of the cost development factor

Based on the numbers provided by Langefeld (2014), we are able to determine a value which could be used as cf. This number is based on the period from 2018 until 2023 in which the costs will decrease with 32%. So, x will be 32% and t = 5 periods:

$$cf = 1 - 2^{\frac{\ln(1-0.32)}{\ln 5}} = 15{,}3\%$$

If we fill in this value in the function, we get the following line as presented in Figure 18. In consultation with several people within Thales, we conclude that this development curve is quite a conservative one. The experts within Thales who are dealing with AM in some way, expected that the production costs of AM will decrease by 50% within the next 5 to 10 years. Therefore, we also plotted the cost curve presenting a reduction of 50% in 5 years and the cost curve presenting a reduction of 50% in 10 years in Figure 18 in order to compare them easily.

Decrease of 50% in 5 years

$$cf = 1 - 2^{\frac{\ln(1-0.5)}{\ln 5}} = 25{,}8\%$$

Decrease of 50% in 10 years

$$cf = 1 - 2^{\frac{\ln(1-0.5)}{\ln 10}} = 18{,}8\%$$

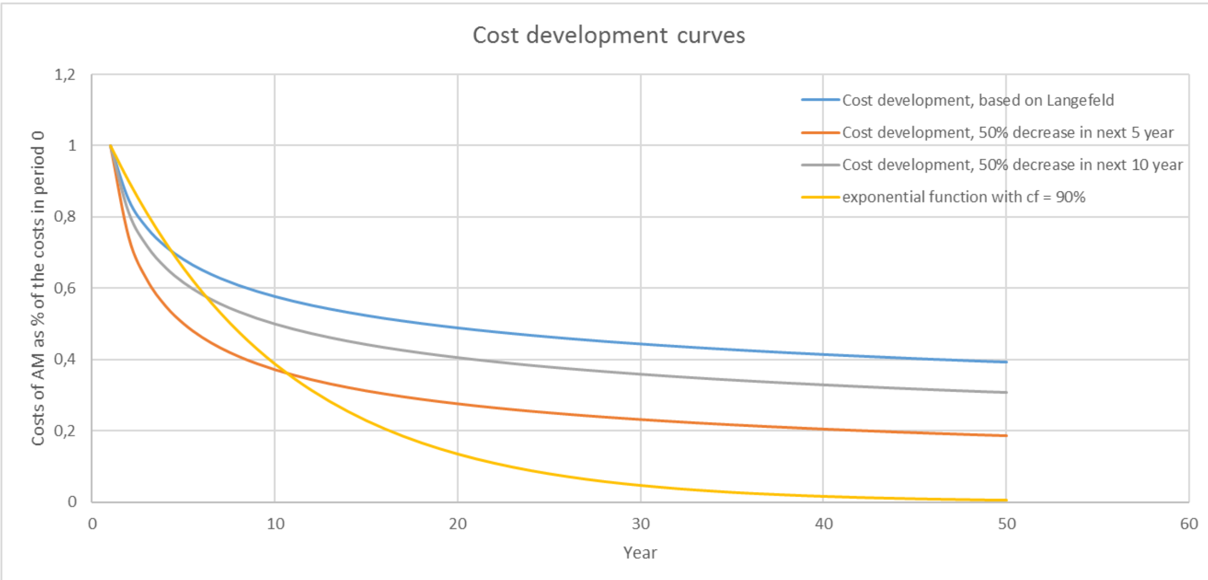

Figure 18: cost development curves

Based on these curves, and the expectation that costs after 50 years will be somewhere between 15%-25% of the costs at this moment in time. We conclude that the cost development will be described in the best way if we take cf 25,8%. This corresponds with a decrease of 50% over 5 years from now.

Appendix 6: Costs of downtime per time unit

– Confidential –

Appendix 7: Upper bound for the inventory level

As mentioned in Section 6.4, the inventory level *s* with respect to the possible states we are in at the start of a beginning goes to infinity in theory. Because of the low demand rate of the one-off parts, we determine an upper bound for *s*, with respect to this research.

Regarding the model, the reasons to put parts in inventory are to prevent for high costs as a result of downtime and to lower inventory costs associated with special tooling. Although inventory is used to prevent for inventory costs associated with special tooling, we will determine an upper bound, based on the downtime costs compared to the costs associated with inventory. Because, in a worst case scenario the costs of downtime will be significant higher than the costs of inventory of special tooling. We will first describe the costs of downtime, where after we describe the inventory costs. Finally, we describe a method to determine the upper bound for the inventory level *s* with respect to the one-off parts.

Downtime costs

For the worst case scenario, we set three input parameters to their maximum value. This holds for the demand rate of a single part per period, the downtime costs per time unit, and the lead time in case a part is demanded.

The expected downtime costs exist of the expected number of backorders, multiplied with the downtime costs in case of a backorder. The expected number of backorders, is dependent upon the number of parts in inventory and the number of parts produced to put in inventory. Since we consider a worst case, we assume parts produced during this period won't be ready until the next period. Therefore, the expected number of backorders is as follows:

$$E[P(s,0)] = \sum\nolimits_{q=s}^{\infty} (q-s) * \frac{(\lambda N)^q}{q!} e^{-\lambda N}$$

With respect to the worst case, we set λ to its maximum realistic value. In case of this research (concerning one-off parts) the maximum value of $\lambda = 0{,}012$. The expected number of backorders are subjected to downtime costs. In the worst case scenario, we assume the failure of one part can result in the maximum fine Thales must pay in case a certain availability level isn't met during a year.

Additionally, in the worst case scenario we have to pay the maximum costs per calendar day in case a system is down, this is $d = x$. Besides, in the worst case we assume we have to pay downtime costs during an entire period of 365 days. So, downtime costs in case a backorder occurs is assumed to be equal to $365x$.

Inventory costs

For the costs associated with inventory, we apply the same rules as we apply with respect to the model constructed in Chapter 6. The inventory costs are calculated as a percentage of the acquisition costs of a part in case it is produced by means of CM. So, the inventory costs of are equal to:

$$Inventory\ costs = s * h * c_{CM}$$

Upper bound determination

In order to determine an upper bound, we have to compare the expected downtime costs with the inventory costs. We take the expected downtime costs per period, since we can produce parts for inventory during every period. Therefore, the upper bound for s, is the value for which applies:

$$s * h * c_{CM} > \left(\sum_{q=s}^{\infty} (q - s) * \frac{(\lambda N)^q}{q!} e^{-\lambda N}\right) * 365x$$

It is not beneficial to put more parts in inventory, if the inventory costs exceed the costs of downtime in case a failure occurs.

Appendix 8: Simulation model evaluation

In this section we will evaluate our simulation model of different parameter values. In Chapter 7, we used different four scenarios, including nine different acquisition costs of special tooling values per scenario. We will use these input parameters to determine the difference between the SDP model and the simulation model. We use the input values as given in Table 27. We compare the costs of the model with the average costs of 10.000 life cycles.

Table 26: Input values for the validation of the model

P_{CM}=€15.000	C_{CM}=€1.260	L_{CM}=93 (days)	ST=€4.350	L_{ST}=65 (days)	h_{ST}=10%	s_{ST}=€-217,50
P_{AM}=€15.000	$c_{AM}(0)$=€2.646	L_{AM}=10 (days)	L_{prep}=28 (days)	cf=25,8%		
d=€26.800	λ=0,004	N=50	T=30 (years)	h_{parts}=10%	s_{parts}=€0	L_{period}=365 (days)

Scenario 1

We use the input values as given in Table 28, except that we have set $d = €0{,}00$ and vary the value of ST between €0,00 and €8.700.

Table 27: Model evaluation based on scenario 1

ST	Model costs	Simulation costs	Relative difference (%)
€0,00	€85.560	€85.544	0,019
€1.087,50	€89.964	€89.978	0,016
€2.175	€94.369	€94.519	0,159
€3.262,50	€98.773	€98.904	0,132
€4.350	€102.210	€102.218	0,008
€5.437,50	€104.133	€104.177	0,042
€6.525	€105.525	€105.557	0,030
€7.612,50	€106.788	€106.717	0,067
€8.700	€107.945	€107.957	0,011

Scenario 2

We use the input values as given in Table 29, except that we have set $d = €1.000$, $L_{CM} = 10$, $L_{ST} = 0$, $L_{AM} = 1$, $L_{prep} = 5$, and vary the value of ST between €0,00 and €8.700.

Table 28: Model evaluation based on scenario 2

ST	Model costs	Simulation costs	Relative difference (%)
€0,00	€94.174	€94.055	0,127
€1.087,50	€98.260	€98.100	0,163
€2.175	€101.872	€101.766	0,104
€3.262,50	€104.753	€104.339	0,397
€4.350	€107.188	€106.759	0,402
€5.437,50	€108.849	€108.859	0,009
€6.525	€109.991	€110.005	0,013
€7.612,50	€111.132	€111.161	0,026
€8.700	€112.274	€112.246	0,025

Scenario 3
We use the input values as given in Table 30, except that we have set $d = €268$ and vary the value of ST between €0,00 and €8.700.

Table 29: Model evaluation based on scenario 3

ST	Model costs	Simulation costs	Relative difference (%)
€0,00	€95.859	€95.473	0,404
€1.087,50	€100.057	€99.730	0,328
€2.175	€104.121	€103.909	0,204
€3.262,50	€107.396	€107.351	0,042
€4.350	€108.864	€108.800	0,059
€5.437,50	€110.006	€109.976	0,027
€6.525	€111.147	€111.102	0,041
€7.612,50	€112.289	€112.246	0,038
€8.700	€113.431	€113.437	0,005

Scenario 4
We use the input values as given in Table 31, except that we vary the value of ST between €0,00 and €8.700.

Table 30: Model evaluation based on scenario 4

ST	Model costs	Simulation costs	Relative difference (%)
€0,00	€104.747	€104.660	0,083
€1.087,50	€108.874	€108.419	0,420
€2.175	€112.850	€112.559	0,259
€3.262,50	€115.790	€115.289	0,435
€4.350	€117.687	€117.905	0,185
€5.437,50	€118.897	€119.358	0,386
€6.525	€120.039	€120.623	0,484
€7.612,50	€121.181	€121.740	0,459
€8.700	€122.323	€122.910	0,478

Based on all Tables mentioned above, we see the maximum difference between our SDP model and our simulation model is 0,484%. Based on this value, we conclude our model is correctly implemented.

Appendix 9: Average input values of the model

In order to verify, validate and analyse the model, we will determine a set of input values which will be used during these three activities. In this section, we will describe how we have determined the input parameters of a 'general' situation of one-off parts. Information with respect to the system input is determined in consultation with people of the mechanical design department. The input data of parts with respect to CM are extracted from documents within Thales. The costs of AM are based on information subtracted from websites which print parts for the commercial sector. Data with respect to special tooling is based on information obtained from one of Thales' suppliers.

System input

The length of the contracts in which Thales must be able to deliver parts for its systems is in general 30 years. For our method, we take one year as one period. Therefore, we get a life cycle length of the analysis, T, of 30 periods. The number of systems installed in the field is expected to be around 50. Since we assume every system consist of one part, the number of parts is 50. Since failure occur because of incidents, we have agreed an incident rate resulting in a failure once every 250 years per part. This corresponds with a demand rate of $\frac{1}{250} = 0.004$ parts per part per period. As value for the cost development factor we take 25,8%.

Table 31: General system input parameters

System input	
Life cycle of the analysis	T = 30 (years)
Total number of installed parts	N = 50
Demand per period per part	λ = 0.004
Cost development factor of AM	cf = 25,8%
Costs per unit of downtime	d = € 26.800
Length of one period	L_{period} = 365 (days)

Part input

The input values for the CM method of parts, are retrieved from the databases at Thales. Since the model is focussed on one-off parts, we derived input values based on only those types of parts which could be seen as one-off parts. Input values for the AM method are based on information retrieved from the website: www.3dhubs.com. The variable production costs per piece, however, are dependent upon the method used during AM, the material used and the size of a part. Therefore, we will analyse different parameters input given different variable production costs per piece using the AM method. However, we will multiply the variable production costs per piece of CM with a factor 2.1 in order to create a start value. The factor 2.1 is based on the average of costs differences of the cases as described in Chapter 5.

Table 32: General part input parameters

Part input	CM method	AM method
Costs of preparation	P_{CM} = €15.000	P_{AM} = €15.000
Variable production costs per piece	c_{CM} = €1.260	$c_{AM}(0)$ = €2.646
Production lead time	L_{CM} = 93 (days)	L_{AM} = 10 (days)
Preparation lead time AM method		$L_{AM(prep)}$ = 28 (days)
Salvage value	s_{parts} = €-12,60	
Holding costs	h_{parts} = 10%	

Special tooling input

The costs of special tooling exist out of 3 components: the acquisition costs of new tooling, inventory costs in case special tooling is stored and the costs or revenues when the special tooling is no longer necessary. Based on the two cases described in Chapter 5, we calculate an average value with respect with respect to the acquisition costs of special tooling. The acquisition costs of the special tooling required for the protection cover are estimated at €5.900 and for the sunshade they are estimated at €2.800. If we take the average of these two values, we end up with €4.350 as average value for the acquisition costs for special tooling. The inventory costs are 10% of the acquisition costs of special tooling per period. Special tooling produced for one-off parts are in most cases only useful for the specific part, which results in the fact we have to take into account discarding costs. These are set at 5% of the acquisition costs of the special tooling.

Table 33: General special tooling input parameters

Special tooling input	
Acquisition costs of special tooling	ST = €4.350
Salvage value	s_{ST} = €-217,50
Holding costs	h_{ST} = 10%
Production lead time special tooling	L_{ST} = 65 (days)

Appendix 10: Results of the protection cover for the STIR

This appendix includes the decision overview of the analysis of the protection cover performed in Section 7.2.1. At the start of every period, we are in a certain state *(w,s)*. Based on the period, and the state we are at the start of that period, an optimal decision is made based on schedule below. To illustrate: in period 0, we produce by means of CM *(x=0)*, we prepare the AM method *(y=1)*, and we produce 1 part to put in inventory *(y=1)*. Then we end up in state *(1,1)* at the beginning of period 1.

Table 34: Decision overview of the protection cover

Period\State	0,0	0,1	1,0	1,1	1,2	2,0	2,1	3,0	3,1	3,2
30	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0
29	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0
28	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0
27	X=0 Y=0 Z=0 i=1	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0
26	X=0 Y=0 Z=0 i=1	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0
25	X=0 Y=0 Z=0 i=1	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0
24	X=1 Y=1 Z=1 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=0 Z=1 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0
23	X=1 Y=1 Z=1 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=0 Z=1 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0
22	X=1 Y=1 Z=1 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=0 Z=1 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0
21	X=1 Y=1 Z=1 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=0 Z=1 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0
20	X=1 Y=1 Z=1 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=0 Z=1 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0
19	X=1 Y=1 Z=1 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=0 Z=1 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0
18	X=1 Y=1 Z=1 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=0 Z=1 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0
17	X=1 Y=1 Z=1 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=0 Z=1 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0
16	X=1 Y=1 Z=1 i=0	X=1 Y=1 Z=1 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=0 Z=1 i=0	X=1 Y=0 Z=1 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0
15	X=1 Y=1 Z=1 i=0	X=1 Y=1 Z=1 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=0 Z=1 i=0	X=1 Y=0 Z=1 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0
14	X=1 Y=1 Z=1 i=0	X=1 Y=1 Z=1 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=0 Z=1 i=0	X=1 Y=0 Z=1 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0
13	X=1 Y=1 Z=1 i=0	X=1 Y=1 Z=1 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=0 Z=1 i=0	X=1 Y=0 Z=1 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0
12	X=1 Y=1 Z=1 i=0	X=1 Y=1 Z=1 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=0 Z=1 i=0	X=1 Y=0 Z=1 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0
11	X=1 Y=1 Z=1 i=0	X=1 Y=1 Z=1 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=0 Z=1 i=0	X=1 Y=0 Z=1 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0
10	X=1 Y=1 Z=1 i=0	X=1 Y=1 Z=1 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=0 Z=1 i=0	X=1 Y=0 Z=1 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0
9	X=1 Y=1 Z=1 i=0	X=1 Y=1 Z=1 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=0 Z=1 i=0	X=1 Y=0 Z=1 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0
8	X=1 Y=1 Z=1 i=0	X=1 Y=1 Z=1 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=0 Z=1 i=0	X=1 Y=0 Z=1 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0
7	X=1 Y=1 Z=1 i=0	X=1 Y=1 Z=1 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=0 Z=1 i=0	X=1 Y=0 Z=1 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0
6	X=1 Y=1 Z=1 i=0	X=1 Y=1 Z=1 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=0 Z=1 i=0	X=1 Y=0 Z=1 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0
5	X=1 Y=1 Z=1 i=0	X=1 Y=1 Z=1 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=0 Z=1 i=0	X=1 Y=0 Z=1 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0
4	X=1 Y=1 Z=1 i=0	X=1 Y=1 Z=1 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=0 Z=1 i=0	X=1 Y=0 Z=1 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0
3	X=1 Y=1 Z=1 i=0	X=1 Y=1 Z=1 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=0 Z=1 i=0	X=1 Y=0 Z=1 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0
2	X=1 Y=1 Z=1 i=0	X=1 Y=1 Z=1 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=0 Z=1 i=0	X=1 Y=0 Z=1 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0
1	X=0 Y=0 Z=1 i=1	X=1 Y=1 Z=1 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=0 Z=1 i=0	X=1 Y=0 Z=1 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0
0						X=0 Y=0 Z=1 i=1				

Figure 19: Overview of the % of simulations runs started per period: protection cover case

Appendix 11: Results of the sunshade for the STIR

This appendix includes the decision overview of the analysis of the sunshade performed in Section 7.2.2. At the start of every period, we are in a certain state *(w,s)*. Based on the period, and the state we are at the start of that period, an optimal decision is made based on schedule below. For example, in period 1 we are in state *(0,0)*. The optimal decisions are 1) to produce by means of AM in case production is required, 2) discard special tooling, 3) don't prepare the AM method in advance, and 4) don't produce any parts to put in inventory. In this case, we end up in state *(2,0)* if no demand occurs and we end up in state *(3,0)* if at least one part is demanded, at the beginning of period 2.

Table 35: Decision overview of the sunshade

Period\State	0,0	0,1	1,0	1,1	1,2	2,0	2,1	3,0	3,1	3,2
30	X=0 Y=0 Z=0 i=0	X=0 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=0 Y=0 Z=0 i=0	X=0 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0
29	X=0 Y=0 Z=0 i=0	X=0 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=0 Y=0 Z=0 i=0	X=0 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0
28	X=0 Y=0 Z=0 i=0	X=0 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=0 Y=0 Z=0 i=0	X=0 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0
27	X=0 Y=0 Z=0 i=0	X=0 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=0 Y=0 Z=0 i=0	X=0 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0
26	X=0 Y=0 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0
25	X=0 Y=0 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0
24	X=0 Y=0 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0
23	X=0 Y=0 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0
22	X=0 Y=0 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0
21	X=0 Y=0 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0
20	X=0 Y=0 Z=0 i=1	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0
19	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0
18	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0
17	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0
16	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0
15	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0
14	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0
13	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0
12	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0
11	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0
10	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0
9	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0
8	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0
7	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0
6	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0
5	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0
4	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0
3	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0
2	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0
1	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=1 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0	X=1 Y=0 Z=0 i=0
0						X=0 Y=0 Z=0 i=0				

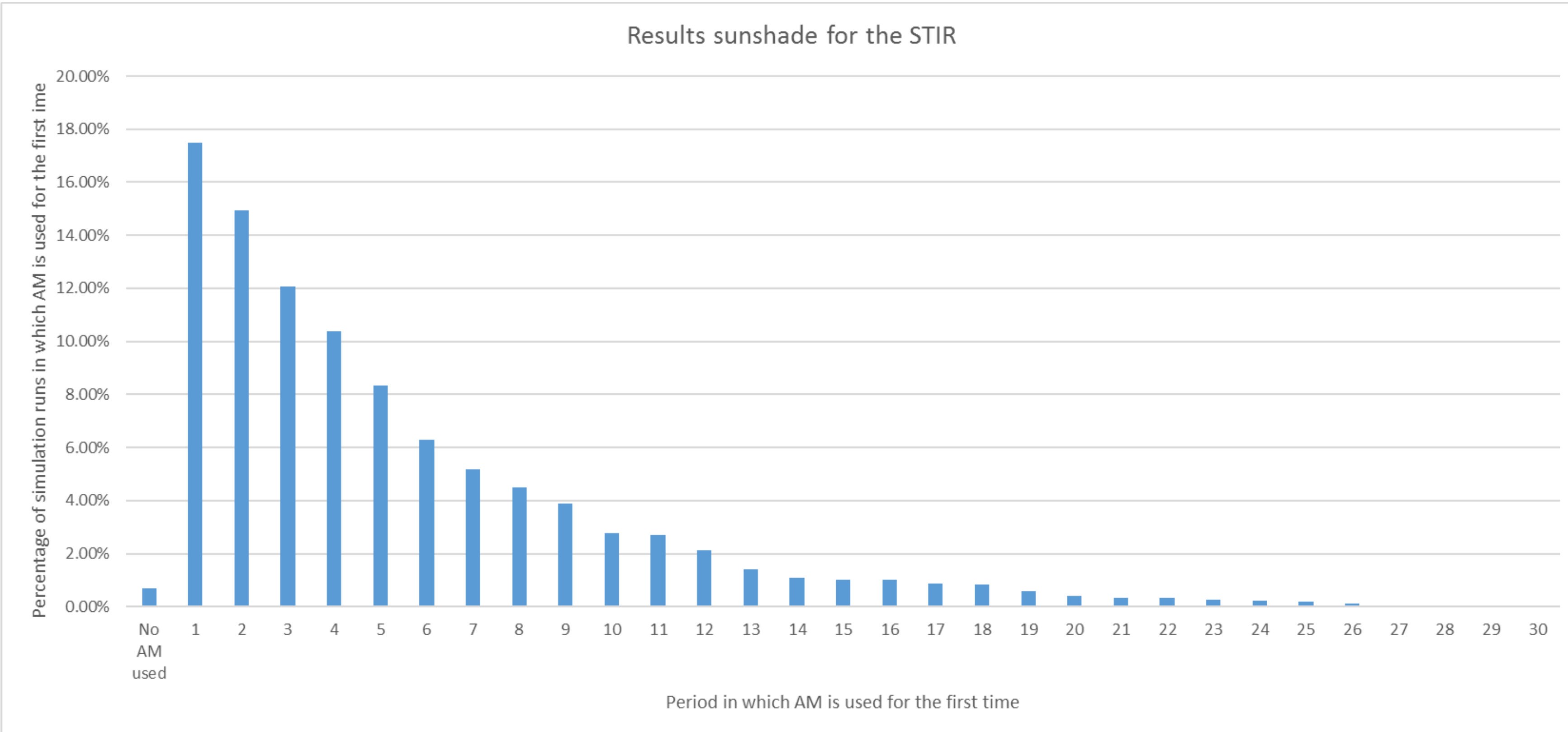

Figure 20: Overview of the % of simulations runs started per period: sunshade case