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Master thesis

Using additive manufacturing for rapid tooling of obsolete spare parts in the aerospace industry

Final thesis

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List of Abbreviations

- 3D – Three-Dimensional
- AM – Additive Manufacturing
- ASL – Approved Supplier List
- CAD – Computer-Aided Design
- CM – Conventional Manufacturing
- DSS – Decision Support System
- EOL – End of Life
- EOP – End of Production
- EOS – End of Service
- ERP – Enterprise Resource Planning
- FDM – Fused Deposition Modeling
- TCS – The Company Services
- ILS – Inventory Locator Service
- LRU – Line-Replaceable Unit
- LTB – Last Time Buy
- MOV – Minimum Order Value
- MOQ – Minimum Order Quantity
- MRO – Maintenance, Repair and Overhaul
- OEM – Original Equipment Manufacturer
- PC - Polycarbonate
- RT – Rapid Tooling
- SINTAS – Sustainable Innovation of New Technology in the After-sales service Supply chain
- SLA – Stereolithography (StereoLithography Apparatus)
- SLS – Selective Laser Sintering
- VBA – Visual Basic for Applications
- WP – Work Package

MANAGEMENT SUMMARY

In this thesis, we assess the suitability of using rapid tooling (RT) for manufacturing obsolete spare parts for which tooling is missing at The Company Services (TCS). RT is a tool manufacturing methodology based on additive manufacturing (AM), and it will be referred to as AM-tool interchangeably with RT. This technology is the key driver of the research project SINTAS (Sustainability Impact of New Technologies on After Sales service supply chains), which dedicates itself to research the logistical after-sales impact of AM.

Background

In previous researches conducted at TCS, other students have assessed the possibility to print these obsolete parts directly using AM. Because of stringent certification issues in aerospace, these options were considered too expensive at this point in time. Because certification does only apply to the resulting part, Jansman (2017) recommended to research using AM for RT purposes. This could lower tooling costs, and as a result, spare part costs might decline too. This Master thesis project is a direct response to his recommendation for further research. Therefore, the following research question is formulated:

> *Under which circumstances can AM be used for spare parts production tools and how do the possible solutions compare to the conventional manufacturing solutions?*

Research setup

To answer our research question, we roughly divide the research into three parts. In the first part, we will assess the theoretical applications of RT and the practical problematic production processes TCS faces. When aligning these, we will focus on certain production processes for the cases studies. Secondly, we will build a mathematical model to quantify the expected costs over the remaining life cycle of the The Company fleet. This mathematical model will then serve as an input for last part. In the last part, we will assess two case studies. These case studies are used to derive a sourcing intuition for using RT in general.

Results

Injection molding, vacuum forming, sheet metal forming and die casting are problematic production processes. The key for RT in low-volume manufacturing is using a lower-grade tooling material, like plastic. This is possible for the first three processes. However, for die casting we need metal molds. This can possibly be avoided by switching manufacturing processes, but these are not used by TCS and neglected in the thesis. This leaves the following applications in Table 1.

Table 1 - Promising applications for RT

Production process	Practical problem	Interesting theoretical application
Vacuum forming	Yes	Yes
Injection molding	Yes	Yes
Sheet metal forming	Yes	Yes
Die casting	Yes	No
Investment casting	No	Yes (to replace die casting)
Sand casting	No	Yes (to replace die casting)

Instead, we used the stochastic dynamic programming model for an injection molding and a vacuum forming case. We find two cost factors to be significant in our analysis; holding costs and initial tooling expenses. After performing sensitivity analysis to the cases, we find the following general results for our sourcing intuition:

- If demand is low (<1), it depends on the part and tool costs whether AM-tools are favorable over CM-tools, due to the initial batch size of 10 parts if we are to use AM-tools for manufacturing. If part costs are very low, we would be better of buying a batch of parts using AM-tools, which are generally indicated to be a lot cheaper. If part costs are high, holding costs are dominant. This favors the option to source using CM-tools, since we do not have to overpurchase expensive parts in this case.
- If demand is less low (>1), this still applies. Holding costs are still a dominant factor if part costs are relatively high in comparison to the CM alternative. If part costs are low, the advice would be to buy a tool and stock parts. Dependent on the difference in tool purchasing costs, we might favor AM-tools over CM-tools, or the other way around.

Conclusions

We can conclude that RT might provide a cost-efficient tooling solution for obsolete spare parts. For metal casting, we have not obtained any circumstances in which RT is beneficial in the spectrum of the current production processes used by TCS. For parts produced using sheet metal forming, vacuum forming and injection molding, we see potential based the initial tooling expenses. However, if part costs are high, holding costs might overshadow the saving in initial tooling expenses. Therefore, TCS should firstly test with parts that have low part costs.

Recommendations

As stated, the RT-options regarded in the case studies look very promising. Therefore, TCS should start testing with tools made using AM for the promising production processes; injection molding, sheet metal forming and vacuum forming. Since AM service providers are experienced in using AM for RT purposes, it is best to collaborate with on those. To successfully do this, inventory should be digitalized. 3D printing bureaus need a CAD-model to make a design suitable as input for the printer. Currently, part designs are still drawn on paper and therefore, these are not suitable for processing.

In addition, we recommend TCS to perform research on their production methods for metal parts. Die casting is a manufacturing method set up for high volumes and therefore, manufacturing a new die casting mold for spare part production is very costly. Instead, a transition from die casting to sand casting or investment casting can be made. These manufacturing methods are suitable for lower quantities, because the tools are broken during the manufacturing process. Both manufacturing methods are widely supported in RT-literature.

PREFACE

Dear reader, in front of you lies my master thesis, entitled: “Using additive manufacturing for rapid tooling purposes in the aerospace industry.” This research has been conducted at The Company Services, an independent aerospace service provider providing maintenance and service logistics solutions. They are one of the companies participating in the SINTAS research project, in which this research has been performed. I want to thank The Company Services for letting me perform my master thesis within their company.

This thesis could not have been finished without supervision within The Company Services, for which I greatly thank all employees helped me during my research. Some of the employees I would like to thank particularly. Firstly, I would like to thank obsolescence engineers Martin Samsom, Chris de Gans and their team leader Vincent van Vliet for spending a lot of time with me in the identification phase of the practical problems and in assessing whether RT could provide a solution to the obsolescence problems encountered.

In addition to the obsolescence engineers, I would also like to thank Kars Bouwma. He gave me valuable insights in the current activities within The Company Services with the focus of additive manufacturing. Furthermore, he also aided in the indications regarding quality control. Robin Rijnbeek provided similar assistance, for which I thank him as well.

Finally, I would of course like to thank my daily supervisor, Kaveh Alizadeh. Although he is a very busy man, he always managed to free some time if I desperately needed assistance with a problem. Furthermore, he provided lots of thoughts and ideas for practical assessments of the problems.

Next to the aid received within The Company Services, I would also like to thank my supervisors within University of Twente, Matthieu van der Heijden and Nils Knofius. Both have been very critical in the process, which was very good for me. Every now and then, I needed a little push in the right direction. Furthermore, the constructive feedback has really helped a lot during the research. More than once have I travelled to Enschede with the idea that I would be burnt down to the ground, because I was unsatisfied with what I had delivered. This never happened and I always returned to Amstelveen with new energy to continue my research.

Finally, I would like to thank my mother and stepdad. In the final phase of my research, I had to leave my old room, saddling me up with the need to urgently find a new place to live. To ease the stress, my parents have taken me back into their house, taking away additional concerns.

Kind regards,

Olaf

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1 INTRODUCTION

This master thesis focuses on rapid tooling (RT) for obsolete spare parts at The Company Services. RT refers to the rapid production of parts that have the function to be a tool, as opposed to being a prototype or a functional part (Chua, Leong & Liu, 2015). The thesis is part of the research performed within the consortium project "Sustainability Impact of New Technology on After-sales service Supply chains" (SINTAS). This project focuses on the potential impact additive manufacturing (AM) technology can have within the after-sales service supply chain. For RT researched in this thesis, AM technology will be used as well. The Company Services has actively taken part within the SINTAS project and two other students already graduated by performing research within this project (Jansman, 2017; Sterkman, 2015). The company will be introduced in Section 1.1, obsolescence will be introduced in Section 1.2, AM will be introduced in Section 1.3 and more details on SINTAS will be given in Section 1.4. A review of the previous thesis outcomes will be given in Section 1.5.

1.1 COMPANY DESCRIPTION

The Company Technologies is one of the leading aircraft manufacturing and service providers and is a part of PARENT COMPANY Aerospace. The five key business units are The Company Aerostructures, The Company Landing Gear, The Company Elmo, The Company Techniek and The Company Services. This research will be performed for business unit The Company Services (TCS), the independent aerospace services provider of The Company Technologies accounting for over 200 million dollars in sales a year.

The customers of TCS consist of airlines, original equipment manufacturers (OEMs) and maintenance, repair and overhaul services (MROs). The ambition of the company is to be the most innovative aerospace service provider of affordable and reliable availability solutions. TCS aims at minimizing downtime by providing and repairing spare parts. In this research, we look at the operational The Company fleet, for which TCS strives to support it through 2030 and possibly beyond.

Furthermore, TCS is the Type Certificate holder of the The Company aircraft, meaning that TCS owns the designs for the The Company fleet. This also comes with the responsibility of overseeing design changes for parts and the accompanying 'Certificate of Airworthiness', ensuring safe flights. These will be obtained according to the European standards, set by the European Aviation Safety Agency. These design changes need to be certified when for example AM is integrated in the production of a spare part. In Chapter 4, we will look at this certification procedure.

1.1.1 The Company Aircraft bankruptcy and production tool scrapping

The Company Technologies is a remainder of former aerospace company The Company Aircraft, which has faced bankruptcy in 1996. The Company Aircraft, as a Type Certificate holder of the The Company fleet, was the legal owner of all production tools. Following the bankruptcy, the curator then obliged all suppliers to return the The Company production tools to The Company Aircraft. Furthermore, it meant The Company was no longer a production company, but an after-sales service logistics company. During that transition, decisions had to be made regarding tool scrapping. Tools needed in the end of the production line (like assembly tools and ground support equipment) became unnecessary and were therefore removed from The Company inventory. These were donated to Rekkof, a The Company Aircraft spin-off aiming to innovate the The Company fleet and launch a rebooted version. However, this does not cover the complete tool donation The Company did to Rekkof, as also a big part of the production tools was donated because they seemed unnecessary. The Rekkof project currently is not viable and a lot of their tools has been scrapped, making the donated production tools non-retrievable. However, those production tools might be necessary in case of obsolete spare part demand.

Next to donating a lot of production tools to Rekkof, not all of them have been successfully retrieved from the suppliers. Production tools that were located at the Shorts Brothers production facility became unusable. Short Brothers was bought by Bombardier in 1989, which was a competitor of The Company Aircraft. When they heard about the The Company bankruptcy, all production tools had been thrown into an open area, where the rain caused the production tools to rust. Since the spare part inventory could be successfully retrieved, no big deal was made of this issue.

Approximately 22000 tools are currently available in the ERP system, of which approximately 15000 are in physical inventory and approximately 500 are used. These tools might have been misplaced during the 30-year lasting life cycle of an aircraft. Next to the bankruptcy issues, once every few years a warehouse clean-up is done. During these clean-ups, production tools can be scrapped, based on current spare parts inventory, forecasts and technical feasibility to create a new production tool if it would be necessary. Approximately ten years ago, this was dealt with somewhat carelessly, resulting in too much tool scrapping. In addition, it could be that production tools are lost.

1.2 OBSOLESCENCE

In Section 1.1, we stated that this research will focus on the operational The Company fleet. For this fleet, TCS offers total support solutions. Therefore, it will fulfill all customer service requests for maintenance or spare parts. After the transition from The Company Aircraft to TCS, The Company arrived at the state of End of Production (EOP). After EOP, service is guaranteed to until the point of End of Service (EOS). The time in between is called the End of Life (EOL) period. During this period, TCS will provide total support to aircraft operators. This is visualized in Figure 1. EOS is currently determined to be in 2030, but for this thesis we will work with a remaining service period of 10 years.

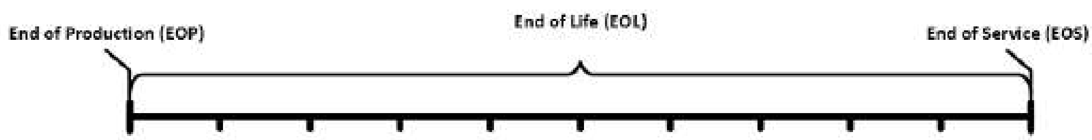

Figure 1 - End of Life period

During EOL, the size of the fleet usually declines. This has also happened to the The Company fleet, which has gradually been declining from the moment the The Company fleet was stopped in production. This results in a spare parts demand decline, which we will discuss in more detail in Chapter 7. Current demand rates for obsolete parts range between 0-10 parts a year, while we have a fleet size decline of approximately 5-10% per year. We assume the demand rates to decline at the same rate, although we have an intermittent demand pattern (we have years in between in which zero demand occurs). This also means we have an increase in obsolescence risk, both on the inventory and the supply side. Inventory obsolescence is encountered if inventory is kept while demand has dropped to zero. This means we have to scrap the stock and have obsolescence costs. Li, Dekker, Heij, & Hekimoglu (2016) define this as "*the non-availability of parts due to discontinued production.*" The increased risk for supply obsolescence originates from production stops by suppliers, because capacity can be allocated to more profitable products. One of the causes for such a production discontinuance is the non-availability of production tools to produce spare parts with. Within this thesis, we focus on supply obsolescence.

In Appendix B, we can see that we have had approximately 1100 obsolescence cases to be solved. 15% of these cases are the result of missing tooling, while 85% of the cases originates from production stops initiated by the supplier. In 33% of the missing tooling cases (thus 5% of the total obsolescence cases) the production tools are still necessary to fulfil the service obligations. which is 55 cases in the last ten years. For the other 10%, development of conventional manufacturing technologies means we can produce the spare part without the need of specialized tools. In general, obsolescence cases can be solved in multiple ways, for which TCS has established a seven-step-model, which is shown in Figure 2. The seven steps are given below and TCS always considers the options in the order given below.

Figure 2 - Possible obsolescence solutions.

Out of the cases in Figure 2, the first three (orange) options are the options that are mostly preferred. Performing a Last Time Buy (LTB) is usually the most preferred option. To be able to place an LTB, production tools should be in place or the supplier should have sufficient finished parts in stock. In addition, it should be known that there is a possibility to perform this LTB. This can be the case when a supplier notifies its TCS of product discontinuation or when TCS successfully is able to predict the discontinuation and anticipate on it. An LTB provides the possibility to buy sufficient parts for the original price which are fully certified. Therefore, this option is usually preferred. However, a lot of suppliers do not issue a warning of product discontinuation and at TCS, only 8% of the cases can be predicted due to a lack of historical demand data (Li et al., 2016). This causes a lot of missed opportunities to place an LTB.

If an LTB cannot be done or demand cannot be accurately predicted, the second-hand market is considered. The second-hand market is a spare part trade market between different players, like MROs, repair shops, dismantlers or airline operators. This happens through online trading platforms. According to Jansman (2017), this market is expected to grow because of the declining fleet and subsequently the higher supply availability of dismantled parts. TCS engineers state that if an airplane is phased out, which means it is taken out of service for good, they get the opportunity to indicate which dismantled parts they want to obtain from the aircraft. However, second-hand parts might have quality issues. Furthermore, not all parts can be dismantled and reused.

If second hand supply is not (sufficiently) available, possible options for resourcing are explored. In this case an alternative supplier is sought, which needs to be an approved manufacturing of the European Aviation Safety Authorization. However, resourcing is not always available for spare parts, or minimum order quantities/values apply to be able to let them manufacture the spare parts. A supplier might also apply fixed setup costs. Moreover, variable parts costs will be much higher because of the lack of economies of scale for the part (Inderfurth & Kleber, 2013). However, for parts with no/too low economies of scale, The Company engineers state resourcing results in lower costs. Due to a lack of experience with a new part, it will likely underestimate the work involved.

The other four options all repair or redesign parts with the same functionality, either in-house or outsourced. These options require a lot of up-front investments and are therefore not preferred. These options are described in more detail in Appendix B. The use of direct AM and RT are considered in the sixth stage: Redesign of the part. Although redesign of the part is not preferred, we can see in Appendix B that the option is often considered, because other options were not possible.

RT is an enabler to produce the obsolete part again, although it does not necessarily mean we should place an LTB. It could also be the case that the production is considered no longer discontinued and thus the parts can be obtained by issuing a purchase order like what would normally be the case.

1.3 Additive manufacturing

Additive manufacturing (AM) is a promising new production technique which is more commonly known as 3D printing under consumers. American Society for Testing and Materials defines AM in ASTM F2792-12a as ''a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies" (ASTM International, 2013). Due to the rapid development of AM technology, application is shifting from rapid prototyping use to full production purposes. A lot of potential advantages are still to be exploited.

Just a grasp of what literature provides as potential benefits for AM application are given by Khajavi, Partanen & Holmström (2014): feasibility of small batches, possibility for quick design changes, production function optimization, possibility of introducing more complex geometries (eliminate manufacturing restrictions), potential for simpler supply chains with less inventory, reduction of material waste and no need for tooling. Jansman (2017) already researched direct printing of spare parts at TCS and thus elimination of tooling needs. However, printing parts directly under current certification needs within the aerospace industry turned out not to be economically feasible at this point in time as will be explained in Section 1.5.

1.4 SINTAS

Because of the potential AM has for future after-sales service logistics, the research consortium SINTAS has been organized. University of Twente and Eindhoven University of Technology collaborate with several industry partners to research possible benefits. One of the companies within the project is TCS.

Within the SINTAS research project, three work packages (WPs) have been defined for PhD student research. WP1 focuses on new technology potential, requirements and the impact on component failure behavior and maintenance options. The focus of WP2 is on the impact of AM on the structure and dimensions of the service supply chain and the last package, WP3, researches the impact on spare part inventories at the various stages in the asset life cycle.

This research will contribute mostly to WP3, as one of the focuses will be to reduce spare part inventory costs by integrating AM into the spare parts supply chain. Furthermore, it will contribute to TCS's obsolescence management. Therefore, it could be a good contributor in providing the answer to question 2 of WP3, namely "For which type of parts may we expect the highest impact on sustainability in terms of obsolescence reduction?".

1.5 Previously performed research

As stated in the introduction, Sterkman (2015) and Jansman (2017) performed earlier research within TCS. Sterkman's research was a quick scan to provide TCS with information on promising AM applications. This resulted in four possible application areas. In the short term, AM might be a solution to the obsolescence problem or it might be a production alternative. The next step will be to use it for redesign purposes and consolidate the parts to reduce weight and save costs. In the long term, decentralization might be possible in the spare parts industry, and the spare parts might be printed on demand at the nearest location possible. In addition, some parts were selected for an analysis of alternative production with AM. This looked very promising and together with a recommendation to perform an analysis of AM applications for obsolescence problems formed a starting point for the thesis of Jansman (2017).

Jansman (2017) then made a model for obsolescence management. It turned out that even though Sterkman (2015) thought that certification would not be a problem, part certification is a very big up-front and at some points even recurring investment. Aviation authorities are currently very busy with industry aviation partners to make new standards to give innovation within the aerospace sector an opportunity, but solutions are not readily available. Current issues are mostly about reproducibility and structural safety. Based on these findings, Jansman (2017) did recommendations for further research, including investigation of producing production tools with AM instead of printing parts directly, as opposed the potential benefit mentioned by Khajavi et al. (2014) of not having any production tool in place. Certification will likely be less restrictive for rapid tools, since these will not end up within an aircraft and thus should conform to less safety regulations. Furthermore, production processes remain similar, thus final part certification should also be less restrictive.

2 Research proposal

This chapter covers the research approach and problems to be solved. From the problem statement discussed in Section 2.1, we identify a core problem to be solved. Therefore, we generate a main research question and accompanying research sub-questions in Section 2.2. Since we cannot treat the complete spectrum of AM-research, we will define the scope of the research in Section 2.3. Furthermore, the deliverables and project planning will be discussed in the subsequent sections.

2.1 Problem statement

As discussed in the previous chapter, TCS strives to support the The Company fleet until 2030 and possibly even beyond. However, the operational fleet is declining and consequently, the demand volume is decreasing as well. This makes obsolescence inevitable, because profitability reduces for suppliers and they will stop production of an unprofitable part. In addition, because of age related wear and tear, demand for certain parts which have been out of production for many years, may rise. As we have seen in Section 1.5, this has already lead to some research on improvement of the obsolescence management protocol with AM possibilities. Certification requirements make direct application of AM not economically feasible at this point in time. However, the future potential of AM technology has been confirmed if certification costs can be reduced (Jansman, 2017).

Based on these findings, TCS wants to continue exploration of AM usage. The conventional manufacturing techniques of The Company often require specialized production tools or molds (in case of castings, will be included in the general term 'production tool hereafter'), resulting in thousands of production tools. As we have seen in Subsection 1.1.1, these could be scrapped or lost for various reasons. However, it could be that demand for obsolete spare parts arises and not all production tools necessary are available for manufacturing the spare part.

The absence of such production tools, upon demand for a spare part, will result into supply disruption. In such cases, sometimes the required production tool needs to be manufactured. This could result into substantial setup costs, since these are also produced based on conventional methods. Jansman (2017) indicates that certification for the production tools is less restrictive than for direct spare part AM, so AM could perhaps be utilized to reduce non-recurring costs. Therefore, TCS would like to investigate the possibilities of AM to produce production tools for improving obsolescence management capabilities. The insight in these capabilities must then provide TCS with insights on the sourcing strategy for obsolete spare parts.

2.2 Research questions and problem approach

Based on the problem statement, we formulate the research question below:

> *Under which circumstances can AM be used for spare parts production tools and how do the possible solutions compare to the conventional manufacturing solutions?*

To solve this main question, seven sub-questions have been posed in the following subsections. Below the questions, question-specific approaches have been developed for obtaining the answers. The questions are interrelated and their relation should lead to answering the main question. These relationships have been modelled in a research model, which is given in Figure 3.

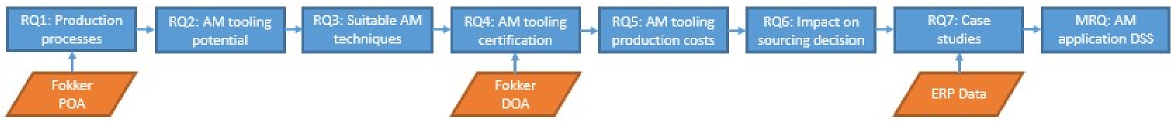

Figure 3 – Connection of research questions to answer main research question

2.2.1 Production processes

What are the conventional production processes within the capability of TCS and which of these can potentially be redesigned by printing the production tools instead of manufacturing these conventionally?

For obtaining spare parts, TCS uses several manufacturing technologies for different technical applications. These are documented in Production Organization Approval Schedule. However, not all of these methods have production tools which are feasible to be replaced by RT. Based on current production processes discussed with The Company engineers we will identify possible applications of RT.

2.2.2 Rapid tooling potential

What are the benefits and drawbacks of rapid tooling in comparison with direct AM and conventional production?

Before we can make final trade-offs on when to use rapid tooling (RT) for making an obsolete spare part, we need to compare the benefits and drawbacks of potential sourcing options. We make a pro/con list for three options: conventional manufacturing, direct AM of the spare part and RT. Based on the potential benefits and drawbacks of the manufacturing approaches, we identify application areas that might benefit from RT. A literature and expert review will be done to clarify the potential of the different manufacturing strategies. In addition, trade-offs are defined for determining this strategy. These might be interesting for the case studies to be performed later on.

2.2.3 Suitable AM techniques

Which additive manufacturing technologies can be applied for production tools and what are the boundary conditions for applying them?

To answer this question, we perform a literature study and in addition, evaluate online industry examples of 3D printer manufacturers. The focus is specific on potential production tool applications, since Jansman (2017) already evaluated possible techniques for final part production. Literature regarding possible applications is available and for example Holmström, Holweg, Khajavi and Partanen (2016) state that there is a widespread use for tool making with additive manufacturing. Schiller (2015) even states that "tooling is an unsung hero using AM techniques. Any aerospace company that is not paying attention to AM tooling opportunities is missing a tremendous advantage." Holmström et al. (2016) provide a broad overview of typical applications of AM technologies. Based on this overview we can explore the opportunities of the technologies.

2.2.4 Certification of parts produced with rapid tooling

What does the certification process of parts produced with rapid tooling look like and what are the associated costs?

Since airworthiness certification was the biggest bottleneck in potential application of 3D printed LRUs, we want to know what this process looks like for parts produced with rapid tools. The TCS engineering department can be very helpful in providing information on this process, since they have certification rights as a Type Certificate holder of the The Company fleet. Based on this process, we can estimate the costs associated with certifying the part produced using the rapid tool.

2.2.5 Production costs of rapid tooling

What are the costs of producing production tools with additive manufacturing?

After the certification process has been defined and costs have been estimated, we can put together a total cost model for RT. We will come up with an indication of the cost parameters by means of literature and online study. In addition, we will perform literature research on the expected cost developments of AM, to have a more accurate cost model for future use of AM.

2.2.6 Impact of rapid tooling

What is the impact of rapid tooling on the decision of spare parts acquisition of nearly obsolete spare parts?

To answer this question, we will use the cost indications found by answering question 2.2.5. We will use the updated model for the case studies in Subsection 2.2.7. After evaluation of these case studies, we can return to this question and answer both questions consequently.

2.2.7 Case studies

Can AM be used for production tools to save spare parts cost in case of (near) obsolescence?

Two case studies will be performed on spare parts facing obsolescence for which it could be possible to make production tools using AM. We propose a bottom-up approach in which an obsolescence engineer of TCS selects promising case studies based on experienced problems in the past or present. Using the model of Subsection 2.2.6 for the specific cases, this should result in a sourcing decision to obtain the necessary spare parts. These parts will be part of the TCS catalogue, since demand data and other specifications will be available in the ERP-system of TCS. Based on the case studies, we will draw conclusions on the possible cost-effectiveness of RT for the examined applications. In addition, we will perform sensitivity analysis on the trade-offs defined after answering the question in Subsection 2.2.2 that apply to the specific cases.

2.3 PROJECT SCOPE

The research will take place within The Company Services in Hoofddorp. As stated in the chapter's introduction, not every aspect of the research on AM can be considered in this research. Therefore, we focus on the currently existing applications and for example do not consider technologies like continuous liquid interface production, which is still under rapid development at this stage.

We will restrict ourselves to the manufacturing capabilities within The Company Services' capability list. This means we will not introduce production techniques with which TCS is unfamiliar, except for RT. Since we are dealing with obsolescence cases, this also means we focus on production tools that support end-of-life (EOL) situations.

Furthermore, a cause not mentioned in the problem statement in Section 2.1 is the support of possible customizations. Aircraft operators might have redesigned parts or made them in slightly other configurations. Because of the support service TCS wants to offer, tools that are not available have to be reverse engineered to be able to support customers. However, market for this is very small, cases are extremely rare and unpredictable and there is a lack of obligation to deliver service to these instances. Therefore, this tooling option is disregarded within the thesis.

Another thing we will not do is build a complete cost model for AM or extend the model Jansman (2017) has already been developing. We will determine our costs based on online and literature research and where possible, we will use his model where he has made indications for direct AM.

2.4 RESEARCH DELIVERABLES

All the research questions posed under Section 2.2, have accompanying research deliverables. These are listed below:

- Pro/con comparison of conventional manufacturing versus direct AM and RT (D1).
- An overview of production processes within the The Company POA with the potential to make AM a feasible alternative (D2).
- Overview of the certification implications for redesign of production tools using AM (D3).
- A decision model for spare parts acquisition of (nearly) obsolete parts (D4).
- Business cases to illustrate the cost effects of AM in comparison to conventional methods (D5).

2.5 THESIS OUTLINE

In the remainder of this thesis, we will firstly determine the production processes that suffer most from obsolescence and are possible to redesign in Chapter 3. We will also assess the theoretical applications and the possible technologies to use RT in the same chapter. This means we will answer question 2.2.1, 2.2.2 and 2.2.3 in Chapter 3. Chapter 4 will be used to review the necessary certification steps, based on in-house knowledge, answering question 2.2.4. Interesting cost factors for RT in our sourcing model will be elaborated on in Chapter 5. This should answer question 2.2.5. The costs defined in that model serve as an input for the decision model for sourcing obsolete spare parts in Chapter 6**Error! Reference source not found.**. This model will be an input for the case studies performed in Chapter 7, after which we will be able to answer questions 2.2.6 and 2.2.7 . From there, we will draw conclusions and give recommendations in Chapter 0.

3 RAPID TOOLING POTENTIAL

In this chapter, we will answer three of the research questions we posed in Section 2.2. The answer to those three questions combined allows us to focus on problematic production processes for TCS, which also are supported by RT theory. The questions we answer are: "*What are the conventional production processes within the capability of TCS and which of these can potentially be redesigned by printing the production tools instead of manufacturing these conventionally?"*, *"What are the benefits and drawbacks of rapid tooling in comparison with direct AM and conventional production?"* and *"Which additive manufacturing technologies can be applied for production tools and what are the boundary conditions for applying them?"*

In the sections below, we will firstly focus on the production processes used by TCS in Section 3.1, before we will assess the possible theoretical applications of RT in Section 3.2. In Section 3.3, we will discuss the benefits and drawbacks of using direct AM, RT and CM, which we will compare in Section 3.4. In accordance with TCS engineers, we identify the most interesting tooling applications in Section 3.5. The trade-offs in using RT instead of CM are discussing in Section 3.6 after which we conclude the chapter in Section 3.7.

3.1 PROBLEMATIC PRODUCTION PROCESSES FOR OBSOLESCENCE

In this section, we will go through the production capabilities of TCS. The production capabilities are documented in Production Organization Approval Schedule. The schedule itself is given in Appendix C. From this schedule, we can derive everything TCS is allowed to do within aerospace production. The schedule is, as we can expect, very extensive on type of manufacturing technologies and the technical applications that can be used. However, some are not interesting for this report. This could be because it is not possible to manufacture with AM (electronics), machinery is unavailable (trusses), obsolescence problems are unlikely to occur (drilled products) or due to a lack of tooling (metal bonding).

Even though some processes are not considered to be interesting for incorporating RT, a lot of production processes used are. In the subsequent subsections these will be discussed separately. We have determined these production processes in discussions with production and maintenance engineers which deal with solving obsolescence. We will discuss vacuum forming in Subsection 3.1.1, injection molding in Subsection 3.1.2, sheet metal forming in Subsection 3.1.3, die casting in 3.1.4 and other, less urgent cases in Subsection 3.1.5.

3.1.1 Vacuum forming

In the vacuum forming process, a plastic sheet is heated and when hot enough, a platform containing a mold is rammed against the sheet surface. This mold is also heated, but to a lower temperature than the plastic sheet. After ramming the plastic sheet, a vacuum sucks out all air between the plastic sheet and the mold to obtain the final shape. This process is illustrated in Figure 4. At TCS, current vacuum forming molds are made by machining or casting aluminum. If an order is placed for an obsolete vacuum formed part, this mold needs to be machined, which TCS engineers indicate to start with costs around €8,000, -, up to €20,000, - for complex geometries. Because the plastic sheets are so thin, we do not have an alternative production process to produce the part without tooling. Therefore, RT might be an option to cut initial tooling expenses.

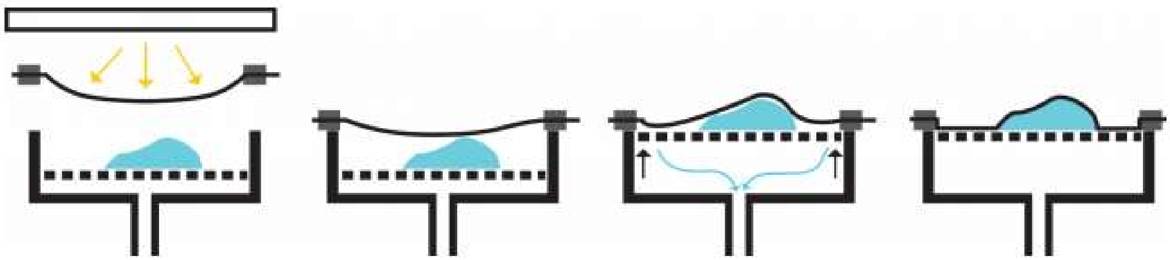

Figure 4 – Black plastic sheet formed over blue vacuum forming tool with simple geometry (Hartman & De la Rosa, 2014)

3.1.2 Injection molding

A production process used a lot back when TCS was still a production company is injection molding. Injection molding is a production process in which two mold halves are pressed against each other, and plastic is injected with high pressure to obtain a plastic part. Before the bankruptcy of The Company Aircraft, the process was set up for mass production and investments have been done in very durable metal tooling. At the time, tool cost started from 20,000 guilders, which would be €9,000, - in current currency. The TCS engineers indicate that current price for the same type of injection mold will be around €15,000, - due to the price developments that have occurred within 30 years. More complex and expensive molds can cost as much as €50,000, -.

In case of obsolescence and missing tooling, this is very costly. Parts produced with injection molding genuinely are cheap and for remaining demands of no more than 50 parts for the obsolete items, tooling costs are a considerable burden. TCS engineers confirm this issue and it is one of the most frequently occurring type of items for which tooling is missing in the obsolescence phase. If switching to RT means we can set up injection molding for low volumes, we might be able to avoid excessive tooling costs.

3.1.3 Sheet metal forming

A manufacturing application used commonly within the aerospace industry is sheet metal forming. Sheet metal is usually thin and therefore, parts are light. Sheet metal forming can be done by rubber pad pressing, hydroforming or deep drawing. For these applications, sheet metal (already cut beforehand) is placed on a solid block and put under pressure. These types of blocks can be made from any type of material, if they are massive and strong enough to hold the pressure. Conventionally, these press tools are made for medium to high volumes and they are made of machined aluminum or hardened wood. If these should be remade, TCS is practically over-engineering the press blocks for the remaining demand. This is the type of tooling missing the most during obsolescence. However, tools are less expensive than those of injection molding or vacuum forming. They are obtainable from approximately €1,000, - and for the most complex geometries to be formed, this could add up to €10,000, -.

3.1.4 Die casting

Die casting is the metal manufacturing equivalent of injection molding. At TCS, any metal part that does not have a homogeneous sheet thickness is made using die casting. Because the materials processed using die casting have a higher temperature than the plastics inserted in an injection mold, the tool material must be stronger as well. The general estimation is that the cost for a mold doubles if we use die casting instead of injection molding. This means the costs range from €30,000-€100,000, -. These high costs have lead TCS into research on direct metal printing, because tooling costs for spare parts can then possibly be avoided. As discussed in Jansman (2017), current certification costs are approximately €30,000, - for the first metal part produced with a lot of those costs recurring for consecutive parts. Therefore, it would be great if RT could provide a solution for low-volume obsolete metal parts.

3.1.5 Other production tools

TCS engineers also mentioned some other types of tools which could be missing for obsolete spare parts. However, these are not very interesting to be 3D printed, because of various reasons. For example, TCS uses sheet lamination tools to form composite parts, which are lightweight and still have high strength. The molds are conventionally machined from solid metal. These parts have very large dimensions and therefore are not considered to be interesting for RT.

Next to shape-defining manufacturing tools, other tooling might get lost as well. These are tools like assembly tools, jigs, trim tools, contour tools and welding molds. Since act as manufacturing assistance and are not pressurized, making these by means of AM is feasible. Usually, these tools come as an accompanying tool to produce a part and reduce errors in finishing a part. Although losing these tools can be somewhat annoying, new tools of this parts are relatively cheap and it is possible to neglect them and still end up with the part according to specifications. Therefore, tools that are used as manufacturing aid are left out of this research.

3.2 Theoretical RT applications

Now that we know more about the problematic production processes from the perspective of TCS, we will dig deeper into the applications discussed in theory. We will elaborate on the application types and the production processes supported.

Holmström et al. (2016) state that there is a widespread use for tool making with AM. They also provide short method descriptions, materials, typical applications and typical machine costs for different AM applications. Tool-making, casting pattern production and casting mold production are the tooling applications mentioned by Holmström et al. (2016). Gibson, Rosen & Stucker (2014) make a distinction between hard (long-run) tooling and soft (short-run) tooling. Hard tooling can be compared with conventional tooling in terms of usage cycles, whereas soft tooling can be used to achieve tools fast and for just one to a hundred parts. In addition, Chua et al. (2015) also distinguish direct and indirect tooling, leaving us with four categories to discuss in the subsequent subsections, as seen in Figure 5. These will not include tools that are not used for production of end products, like jigs and fixtures or molded pulp tools for packaging.

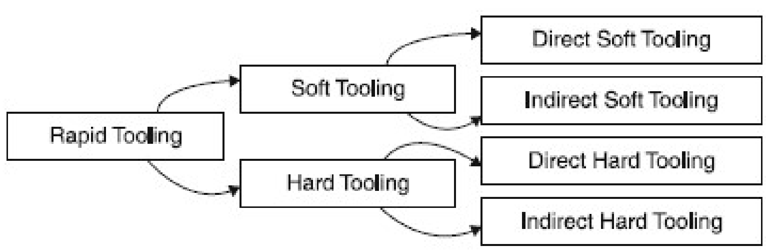

Figure 5 – Rapid tooling classification (Chua et al., 2015)

3.2.1 Direct soft tooling

Direct soft tooling is short-run tool application of RT in which the production tool is directly printed without any intermediate steps. The aim is to directly produce a tool in an optimal and efficient way, while still maintaining its intended function. An example of a direct soft tool is the direct production of sand casting molds, which are destroyed when the casted part is broken out of the casting mold. These molds have similar properties for accuracy and surface finishing in comparison with conventionally produced sand casting molds (Chua et al., 2015). However, using RT for direct sand printing has a major advantage over the conventional process. This would require a replica made of a material that is strong enough to pack the sand and is precisely machined to specifications by hand or CNC machining. This step can be avoided when printing a sand mold directly. In one of the videos posted in Maxey (2015), it can also be seen that several parts of a printed sand casting mold can be glued together to produce solid metal parts. Therefore, size limitations are unlikely to occur. Furthermore, because the casting mold is broken off, there are no manufacturability constraints and design freedom is equal to direct AM.

Snelling et al (2013) perform an experiment using the binder jetting technology. The conclusion is drawn that metal specimens can be produced with similar properties in comparison with conventional sand casting. Two major industry players are ExOne and Voxeljet (Maxey, 2015), which have fully focused on printing sand casting molds for manufacturing of complex metal parts. In Figure 6, we can see an example of a turbine blade.

Figure 6 – 3D printed sand casting core and casted result (Maxey, 2015)

A different direct soft tooling method possible to produce metal parts is the direct printing of ceramic investment casting shells using photopolymerization, a solidification method also used in SLA. Just as is the case with conventional investment casting, the ceramic mold is broken to obtain the casted metal parts. This method has been successfully used for super alloys like Inconel 718 and SC180 airfoil cast parts for aerospace applications (Chua et al., 2015). The authors see this development as a disruptive change for the investment casting industry. The company DDM Systems (n.d.) agrees on this and has dedicated itself to manufacturing their Large Area Maskless Photopolymerization (LAMP) machines for ceramic mold printing.

The disruptive characteristic of direct investment casting mold production is not a very weird thought. Just as is the case with printing sand casting molds, we can skip some steps in the process. In Figure 7, we can see nine process steps to conventionally produce investment casted parts. The first four steps, including the costly production of an injection mold for wax patterns, can be avoided when printing ceramic molds directly.

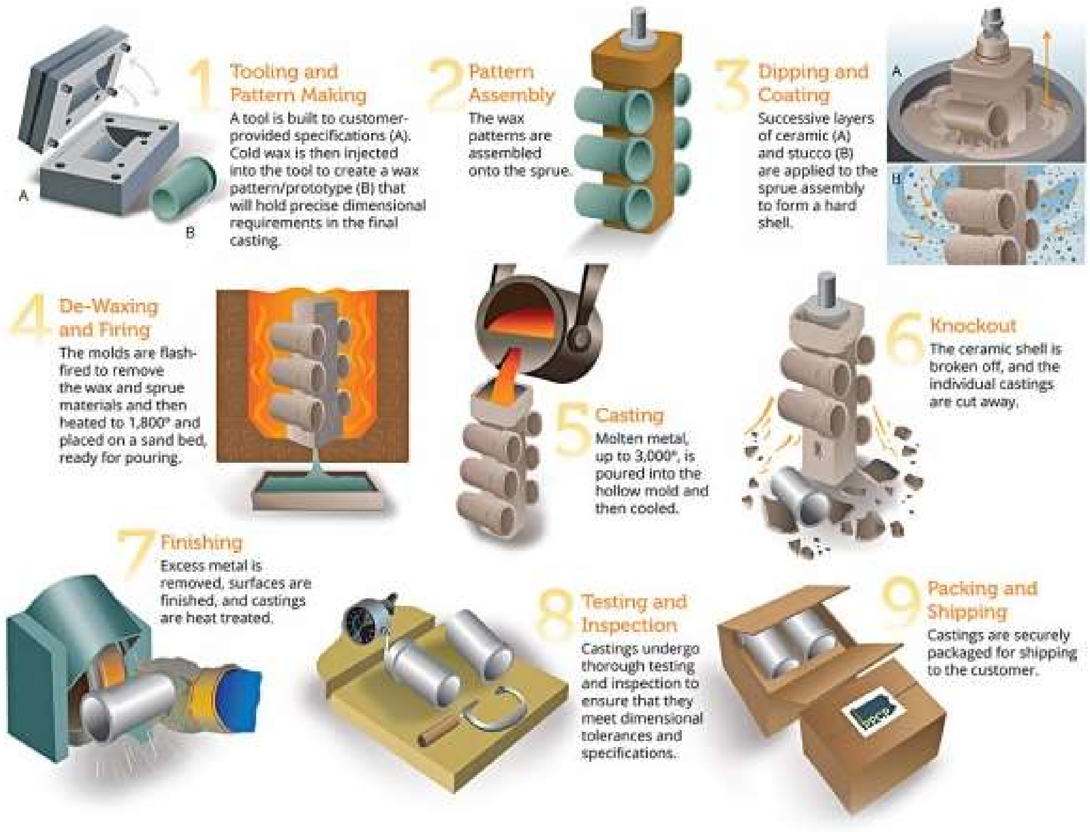

Figure 7 – Investment casting process (PPCP, n.d.)

Next to applications for metal parts direct soft tooling also has applications for plastic parts. Multiple possibilities arise for low-volume injection molding of plastic components with high accuracy. Chua et al. (2015) and Redwood (n.d.-a) mention printing resin molds using SLA. In the same article, Redwood also mentions the use of material jetting for resin molds, which is supported by Gibson et al. (2014) and Stratasys (n.d.-c). However, these tools have limited life and have a chance of occurring damage during the injection molding process, especially if the part geometry is complex (Chua et al., 2015). However, Chua et al. (2015) and Gibson et al. (2014) state that this breakdown will most likely happen after approximately 100 parts produced. Redwood (n.d.-a) and Stratasys (n.d.-c) indicate this possibility as well, but as material grades get higher, the number of uses can drop to 10 parts. If we want to produce up to 1000 parts, we can coat the resin mold with a composite shell (Chua et al., 2015).

An additional application which is mentioned by Stratasys (n.d.-a), is the direct tool production for sheet metal forming. They provide hydroforming/rubber pad pressing tools by printing using FDM. This can be used for several hundreds of parts to be formed. D3 Technologies (2016) mentions a similar application by using SLA, where the die mold did not show any signs of wear after a hundred formed parts. An example of such an application can be found in Figure 8.

Figure 8 – FDM hydroforming tool (Stratasys, n.d.-a)

Gibson et al. (2014) shortly mention vacuum forming tools as an AM possibility. Usually forces and pressures are not very high, so polymeric materials are commonly used for this kind of tool to produce a shell-like product from a flat sheet. D3 Technologies (2016) show a case study harvesting the SLA technology for this purpose, whereas Stratasys (n.d.-a) shows the use of FDM for tool manufacturing.

The last application we found is fiber layup tooling for composite manufacturing, which are for example marketed by Stratasys (2016). It is possible to design these layup tools in such a way that the tools become trapped. Materials are available that withstand the pressure needed to produce the composite parts in an autoclave and can be washed away in a detergent solution (Gibson et al., 2014; Stratasys, 2016). An example of this is found in Figure 9. Although this RT-application looks very interesting, this part complexity is not found in conventional manufacturing due to manufacturability constraints. Therefore, it seems to be more beneficial in the product development phase.

Figure 9 – Sacrificial composite tooling: Left – tool, middle – tool with part, right – resulting part.

Summarizing what is discussed above, we find Table 2:

Table 2 – Theoretical direct soft tooling processes

Manufacturing process	Tool material	Part material	#Uses/tool	Technologies
Sand casting	Silica sand	Metal	1	Binder jetting
Investment casting	Ceramic	Metal	1	LAMP
Injection molding	Resin/coated resin	Plastic	10-1000	Material jetting, SLA
Sheet metal forming	Polymer, resin	Metal	Hundreds	FDM, SLA
Vacuum forming	Polymer	Plastic	Hundreds	FDM, SLA
Composite tooling	Ceramic, urethane	Composite	1	FDM

3.2.2 Indirect soft tooling

Indirect soft tooling is similar in amount of uses in comparison to direct soft tooling, with the difference that the 3D printed object is used as a master pattern/prototype to produce a production tool rather than to use it directly. Lots of AM processes can be used for production of such master patterns, of which SLA is most popular and widely used due to the high level of accuracy and surface finishing (Chua et al., 2015). The resulted molds have limited mechanical properties and can be used for a single cast, or small batch production. For low volume production, this can be advantageous.

An example of such an indirect soft tool is a master pattern for injection molding. The process to create the injection mold is shown in Figure 10. This can be used for a limited number of parts, but is produced fast. The best options for producing the master pattern for this injection mold are SLS and FDM. Indirect soft tooling also has an application in silicon molding, which is the most flexible and popular rapid tooling process for vacuum casting. Part produced can also be easily removed from the mold cavity and silicon molds can be used for plastic, urethane and ceramic, making it a very handy application. An illustration of this phenomenon is shown in Figure 11.

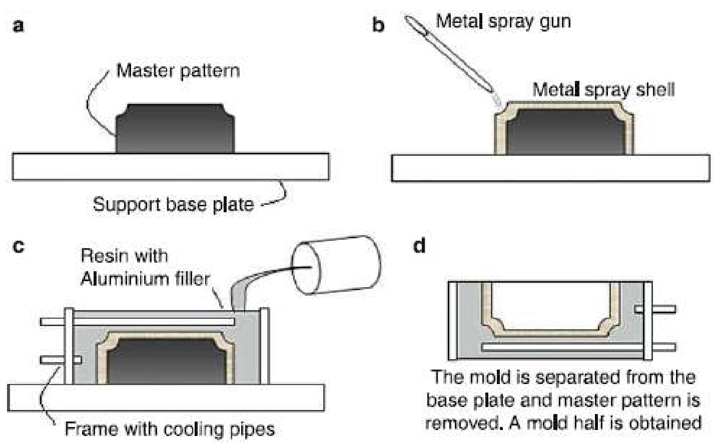

Figure 10 – Indirect soft injection mold production (Chua et al., 2015)

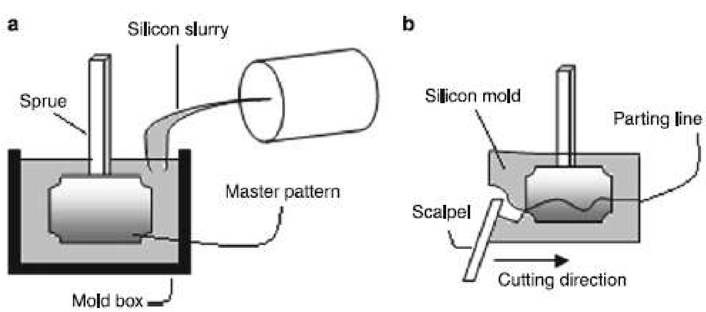

Figure 11 – Creation of a silicon mold with a 3D printed master pattern (Chua et al., 2015)

In addition to the possibility of direct soft tooling for investment casting, indirect soft tooling can also be used. For this application, not the ceramic mold is printed, but the foam, wax or paper master pattern is printed. The most important property of the material is that it is easy to burn or melt away from the ceramic mold after it is produced from the master pattern (Chua et al, 2015). To illustrate, an example of the indirect investment casting process is given for a very simple geometry in Figure 12. If we refer to Figure 7, we only skip the first process step, as opposed to four steps when producing direct soft tooling, which is a newer application for RT in investment casting. The indirect soft tooling method was one of the enablers of AM development for the field of aerospace and automotive, since it did not rely on metal printing, but could still make parts of conventional product quality (Gibson et al., 2014). Patterns for this application can be made using FDM, material jetting and SLA (Holmström et al., 2016; Stratasys, n.d.-b). The repeatability of these master patterns is very high, especially for SLA.

Chua et al. (2015) also mention this type of pattern production as direct, because there is an extra layer of indirectness which can be added in the process. For very low volumes, it might be most beneficial if the master pattern is printed using for example FDM and the ceramic mold is formed around it. For volumes starting from approximately 40 parts, it might also be a possibility to make a short-run injection mold. With this mold, it is then possible to form a small amount of wax patterns from which ceramic molds can be made to cast metal parts in. If the silicon injection mold breaks down, the FDM master pattern can be reused to make another one.

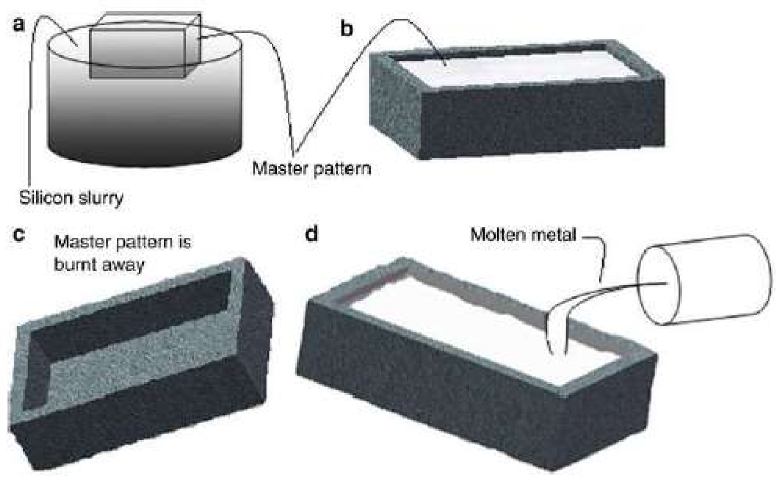

Figure 12 – Indirect investment casting process (Chua et al., 2015)

Summarizing the applications discussed, we obtain Table 3.

Table 3 – Indirect soft tooling approaches

Manufacturing process	Tool material	Part material	Pattern material	Technologies
Injection molding	Aluminum resin	Plastic	Polymer, resin	SLS, FDM, SLA
Vacuum casting	Silicone	Urethane, plastic, ceramic	Polymer, resin	SLS, FDM, SLA
Investment casting	Ceramic	Metal	Foam, wax, paper	FDM, SLA, material jetting

3.2.3 Direct hard tooling

As stated in the introduction of the section, hard tooling is tooling with possibilities for mass manufacturing. Based on this characteristic, it does not seem very beneficial for the spare parts supply chain, especially not for items facing obsolescence. Direct hard tools we can think of here are die casting molds and series injection molds. The key reason to start using direct hard tooling is to reduce cycle times in operation. The design freedom of AM allows integrating conforming cooling channels, which are designed for optimizing operations (Gibson et al., 2014). Although it might be interesting for other applications, direct hard tools are not interesting for this thesis.

3.2.4 Indirect hard tooling

Indirect hard tooling implies producing something intermediate before obtaining the final mold. For example, a liquid metal or steel powder is cast in a binder system and then needs binder removal. The part is then sintered in a furnace and further infiltrated with a secondary material. Because of the huge amount of post-processing, this is regarded as indirect hard tooling. However, just like direct hard tooling this application is more beneficial for mass production and this is not interesting for TCS.

3.3 Advantages and drawbacks

Now that we have addressed the practical tooling problem cases and possible theoretical applications, we can elaborate on the benefits and drawbacks of using RT in comparison with CM and AM. It should be noted that the benefits and drawbacks of all categories are generalized. The distinction is in the fact that we consider AM to be additive processes, CM to be subtractive processes and RT to be a hybrid version in which AM is used for tooling and the parts are made conventionally. For AM in general (direct or for using RT), we will further explain technology dependent benefits and drawbacks in Appendix D: AM technologies that can be applied for RT. This will only include the AM technologies that have potential for application in RT, others can be seen in for example 3D Printing Industry (n.d.) and Wullms (2014).

Firstly, we will discuss direct AM in Subsection 3.3.1, after which we will discuss CM in Subsection 3.3.2 and finally RT in Subsection 3.3.3. These will serve as an input for Section 3.4, in which we will compare the separate options on tooling and part level.

3.3.1 Direct AM

Direct AM applications share the characteristics that they are based on 3D computer-aided design (CAD) product data and that they are manufactured layer by layer (Lindemann, Jahnke, Moi & Koch, 2012). Therefore, the technologies share quite some mutual benefits, which widely discussed in literature. Furthermore, triggers are discussed for the adoption of AM within an organization.

Wagner & Walton (2016) present results from a discussion in focus groups about AM within the aerospace industry, the industry where TCS also operates in. For aerospace companies, the potential fuel savings arising from topology optimized parts with reduced weight is the biggest adoption factor. A nice bonus is the reduction in environmental footprint and some cost reductions, which are mainly obtained by the flight operators (Sterkman, 2015; Wagner & Walton, 2016). An addition to this environmental footprint reduction is in material efficiency, which in aerospace is calculated as the buy-to-fly ratio. This indicates how many raw materials were needed to produce a part. When using AM this can be close to 1, where this usually is 5-20 (Sterkman, 2015; Portolés et al., 2016; Wagner & Walton, 2016).

Another adoption of AM is increased by redesign possibilities that reduce the number of components and may increase reliability (Sterkman, 2015; Knofius, Van der Heijden & Zijm, 2016). The fast design iterations possible allow for multiple design evaluations to pick the best design (Lindemann et al., 2012; Sterkman, 2015). The technologies are not influenced my manufacturing capabilities, so designs can be extremely complex as well. An aerospace success example is given by Airbus (2014), who integrate two pipes and assembly into one piece with an original assembly of ten welded parts. This can be seen in Figure 13.

Figure 13 - integrated fuel pipe example (Airbus, 2014)

Moreover, a 30% cost reduction and a toolless situation were obtained. The latter of which, accompanied by the reduction of amount of parts, reduces business and warehousing complexity and thus costs. Warehousing complexity can be further reduced if the possibilities arise to print on demand instead of using forecasts (Khajavi et al., 2014; Knofius et al., 2016; Wagner & Walton, 2016). This can also significantly reduce lead times (Sterkman, 2015).

Sterkman (2015) also mentions low set-up costs for small batches, which is also stated in a later paper by Holmström et al. (2016), which state batching could become entirely redundant. Using AM, the price is potentially independent of the batch size, possible enabling mass customization, which is an interesting feature if custom spare parts were to be printed.

We can see that a lot of enablers and potential advantages are present in the points raised above, but there are also some drawbacks of using AM directly. The technology has not completely matured yet, making material and machine costs very high (Schiller, 2015; Sterkman, 2015). Savastano, Amendola, Fabrizio & Massaroni (2016) state this will decrease quite rapidly from this point in time, since critical patents already have been expired or are on the edge of expiration. Technology developments and competition are given a boost for the future. This should also tackle some of the challenges discussed in the focus groups of Wagner & Walton (2016), like the building speed of current technologies.

Management of the digital properties is also quite a challenge. The limiting software discussed by Lindemann et al. (2012) seem to have been overcome (Schiller, 2015). However, management of intellectual property still seems to be an issue (Schiller, 2015; Holmström et al., 2016). In addition, component redesign, size limitations, extensive post-processing needs and non-reparability of AM components are discussed as unaddressed challenges (Sterkman, 2015; Holmström et al., 2016).

This leaves the last drawback, which the extensive need for certification, which made all business cases discussed by Jansman (2017) infeasible. Other researchers highlight the same problem, which occurs due to uncertainty in structural safety (Schiller, 2015; Wagner & Walton, 2016; Gorelik, 2017).

3.3.2 Conventional manufacturing

Most of the benefits and challenges of CM are covered by the fact that the AM counterparts still have disadvantages. From the disadvantages of direct AM, we can for example deduct that CM makes for excellent surface finishing, durable parts, tools that last a lot longer and fast production in large volumes. Another major advantage is that CM methods adopted by TCS are fully certified, which means no additional costs will occur for using the technology.

In the same way, we can make up the disadvantages of CM in comparison to the AM applications. One of the negatives of conventional manufacturing is that the technologies are inflexible and adaptation to other processes takes quite some time. Furthermore, complex geometries are very hard and costly to make because of restrictions conventional manufacturing technologies imply. And as Sterkman (2015) has stated, it is designed for mass production. Producing new hard tools for low volume application implies that the tool is very expensive per part and in case of obsolescence, low volumes are very likely. If tool manufacturing time is also considered, production of a spare part also takes considerably longer in comparison to AM.

3.3.3 Rapid tooling

Since RT makes use of AM technology, quite some of the benefits mentioned for AM also apply to RT. In addition, leading researchers in logistic AM research mention AM can be used to improve tool-based manufacturing (Holmström et al., 2016). The advantage in lead time offered by direct AM is reduced, because an intermediate step arises. Tooling lead times can be greatly reduced in comparison to CM, but it will keep the same conventional production process and part lead times thus do not decline when using the same processes.

Furthermore, the complexity in geometries might still exist, but it depends on the application. As we have discussed in Section 3.2, there exist direct soft tooling applications that destroy the tool during manufacturing (Maxey, 2015; Stratasys, 2016). However, when applying RT for indirect soft tooling or non-breaking direct soft tooling, you will keep the manufacturability constraints of CM. Other benefits that still exist with smaller impact are the reduction of the environmental footprint, possibilities for rapid design iterations and the improved buy-to-fly ratio. The benefits arise during tool production, not part production.

Lyons (2014) states that AM lends itself perfectly for complex parts. Therefore, it is very well-suited for the manufacturing of production tools, which is a complex one-off fabrication. This could leverage the potential of AM technology, while producing products that are at the mechanical property level of an original part in a much shorter amount of time. Gibson et al. (2014) mention the opportunity to use AM for creating casting patterns for parts that require materials or material properties currently not available within the AM spectrum faster than conventional alternatives. Another possibility is on AM for longer run tooling where AM may be able to simplify the process chain and it may make for a more cost-effective manner than direct printing. As a last argument for using rapid tooling, they give that it might be the quickest and most effective way of creating tooling to specifications. This is particularly relevant in applications where short lead-times are important. D3 technologies (2016) agrees and states that this also is accompanied by considerable cost reductions, although costs can be higher than direct AM for extremely low demand.

Schiller (2015) also underlines the usage of AM for tooling purposes, especially if a metal tool can be replaced by a plastic one. These are lighter and more ergonomic to work with. Additionally, he agrees with Jansman’s (2017) statement of tooling not requiring certification for usage, unlike flight components. Verifying the tool is functional for the use is still necessary, but the level of testing and analysis is not as stringent as for certification of flight components.

As can be seen in the subsections above, Schiller (2015) is positive of RT, but he also mentions some disadvantages in using it. Tools are not as robust in the long term and wear and tear will take their toll earlier on compared to conventional alternatives. Furthermore, post-processing is often necessary to obtain tight tolerances, especially when combining plastic with metal. However, this challenge reduces as more experience is gained with the technology.

3.4 Comparison and opportunities

In this section, we will compare the manufacturing types discussed in Section 3.3 based on their advantages and drawbacks. These will be separated in tooling and parts, to indicate where the technologies are preferable over the other ones. In Subsection 3.4.1, we will compare the tooling characteristics and we will proceed with the part characteristics in Subsection 0.

3.4.1 Tooling summary

Based on the separate advantages and drawbacks, we can compare RT against the alternative options of AM and CM. In the table below, we summarize the options on tooling level. It should be noted that direct AM has as benefit that we can get rid of production tools. However, some comparison still applies. Therefore, we do include it in Table 4. Below the table we will give some explanatory comments.

Table 4 – Comparison of properties of AM, RT and CM for tooling

AM	RT	CM
Setup lead time in form of certification process	Short lead time	Long lead time
Not applicable	Tools can have more complex geometries, if broken during manufacturing	Manufacturability restricted
Not applicable	Limited materials	Not restricted by materials
Not applicable	Size limitations can occur because of building box size	We know we can make the tool we need, so size is no issue
Not applicable	Functioning of the tool should be determined by testing	Fully tested
Not applicable	Potential weight saving of tool	Tool remains the same
Not applicable	Reduction of environmental footprint	No reduction of environmental footprint
No tool needed in stock	Possibly stock tool, if it is not broken upon use	Need to stock the tool
High certification costs	Low costs	High costs
Not applicable	Much post-processing	Little to no post-processing
Not applicable	Fast design iterations possible	No design iterations
No tool life	Short/No tool life	Long tool life

As we can see, the setup factor to manufacture parts using AM is the certification process. According to Jansman (2017), this takes approximately 200 engineering hours. This would be equal to five weeks of setup lead time to start using AM within TCS, costing €20,000, - for setting AM up. If we compare RT and CM, it becomes clear that CM would be easier to reuse than AM and certainly preferable if we would have high demand left. The only drawbacks in comparison to RT are the costs, the lead time, tool weight and the manufacturability restriction. However, since we are not going to alter part design, the latter factor is not an issue. The costs and lead times might be, because theory suggests that using RT instead of CM for low-demand cases can save up to 80% in terms of costs and 90% in terms of lead time some cases (Stratasys, n.d.-c; Redwood, n.d.-a). Because of the stringent certification requirements, it might even be the most cost-effective approach for one-off spare parts. The reduced tool weight is regarded as a cost saving factor for holding the tool if it is to be handled by warehouse employees.

3.4.2 Part summary

Just as we did in the previous section, we will also summarize the pros and cons of RT against CM. Since this table is about the resulting part, we can compare direct AM to both RT and CM as well. Furthermore, some of the general properties are not very relevant or applicable for the aerospace industry. Reduced product quality can for example not be an issue, because of the stringent certification requirements. However, additional post-processing to fulfil these requirements could be an issue and therefore we include it as such. Based on the text in Section 3.3, we obtain Table 5. Below the table we will give some explanatory comments.

Table 5 – Comparison of properties of AM, RT and CM for parts

AM	RT	CM
Very short LT (days)	Long LT (weeks, equal to CM)	Long LT (weeks, equal to RT)
Complex geometries possible	Application dependent, possibly complex if tooling is broken	Manufacturability restricted
Limited materials	Same material as original design	Same material as original design
Limited size	Part size will be equal to original design	Part size will be equal to original design
Expensive certification process	To be determined in Chapter 4	Fully certified
Potential weight saving	No potential weight savings	No potential weight savings
Great reduction of environmental footprint	No reduction of environmental footprint	No reduction of environmental footprint
Possible reduction in number of components (better reliability)	No reduction in number of components	No reduction in number of components
Stock reduction, potentially no stock	High stock if LTB applies, otherwise low stock	High stock if LTB applies, otherwise low stock
Slow build speed	Possibly lower build speed than CM	High build speed
Mass customization	No mass customization	No mass customization
High material costs	Low material costs	Low material costs
Much post-processing	Little post-processing	Little post-processing
Fast design iterations	No design iterations	No design iterations
Production on demand	No production on demand	No production on demand
High part costs	Low part costs (higher than CM, due to quality checks)	Low part costs
Wall thickness could be an issue	Wall thickness is not an issue	Wall thickness is not an issue

Product complexity is one of the benefits arising from AM. For parts made with RT, there is a possibility to obtain complex geometries if tooling is broken away. On the other hand, when printing injection molds for example, the part still must be released from the mold, so its shape is restricted based on the production technique. In addition, the logistic freedom obtained when using direct AM is superior to both RT and CM. We can produce on demand and therefore, inventory is unnecessary. If we need to place an LTB, this freedom would be quite a relief. If certification were not an issue, this would clearly be the most beneficial option out of the three.

The only type of parts for which this does not seem valid, are parts with very thin walls. Direct AM is restricted by minimum layer resolutions, whereas this is not the case for tool-based production. Therefore, some types of manufacturing, like vacuum forming and sheet metal forming, are better off with CM or RT. To maintain lightweight structures in an aircraft, these production types are very common and these tooling types form a problem for obsolescence, as discussed in Section 3.1. The difference between CM and RT is mainly made in the tooling costs. However, some additional quality checks might be necessary for the parts produced with RT due to a lack of experience manufacturing these. Furthermore, the build speed might be a bit slower for RT. Volpato & Solis (2016) for example state that when using Digital ABS as mold material, the plastic insulation causes the cooling process to be slower. Nevertheless, parts of similar quality can be obtained. The slower cycle times might however add a little bit to the part costs, but since this is a matter of adding a minute of waiting time, we will neglect this.

3.5 MOST PROMISING APPLICATIONS FOR RT

In Section 3.1, we discussed all applications for which TCS engineers which are problematic in case of obsolescence. We also discussed what criteria should be used in assessing whether to prefer a certain application for our case studies, because they seem promising. The criteria are as follows:

1. The conventional costs of tooling
2. The possibility to replace a tool by using a cheaper material
3. The number of obsolescence cases arising
4. The possibility to work around tooling by altering a similar part
5. The possibility to replace a tool which can conform to the drawing specifications
6. The expected future demand

The conventional costs of tooling are the key driver in deciding which type of production processes are interesting to include in a case study. As discussed in Section 3.1, the costs are highest for die casting. However, die casting molds cannot be replaced by cheaper materials, as noted in Subsection 3.2.3. The possibility to use RT is there, but the gains are in operational efficiency, rather than tool costs. It seems to be more suitable to switch to a different metal manufacturing process, like sand casting or investment casting. However, in the scope we stated to only consider current production processes that TCS uses. If we would want to produce using sand or investment casting, we formally change the type of production process and this means we go into the certification phase, just like we would with direct use of AM. This is what we tried to avoid by applying AM for tooling instead of parts. Therefore, we will neglect this option in the thesis.

Injection molds, press tools and vacuum forming tools are much more interesting options. Injection molds are the most expensive of the three and while looking for potential case studies, there were two injection molded parts that had lost tooling, as opposed to vacuum forming and sheet metal forming, which had one potential cast. The general idea is that when AM keeps developing, parts that used to be produced using injection molding can be successfully replaced by printing a part directly. Therefore, in the long term general estimation is that direct AM would be the better option. For the short term, however, certification is too expensive for direct AM and RT might provide a good solution. In addition, demand for injection molded parts is the highest of the three processes. Therefore, one of the case studies will be on an injection molded part. This case study will be introduced in Chapter 7.

The interest in vacuum forming tools and sheet metal forming tools is also cost driven, but as stated before, these production methods cannot be replaced by direct AM. Tools will always be necessary to support the product. Since vacuum forming tooling is more expensive and every part has a specific design, we will choose the obsolescence case for vacuum forming over the sheet metal forming tool. For the current sheet forming obsolescence case, it is possible to work around it by altering another pat which has some drilled holes in it, but has the same functionality. Based on the discussions within this chapter, we construct Table 6 to indicate which production processes seems to be benefitting most from RT possibilities.

Table 6 - Promising applications for RT

Production process	Practical problem	Interesting theoretical application
Vacuum forming	Yes	Yes
Injection molding	Yes	Yes
Sheet metal forming	Yes	Yes
Die casting	Yes	No
Investment casting	No	Yes (to replace die casting)
Sand casting	No	Yes (to replace die casting)

3.6 Tooling trade-offs

Now that we have chosen the most interesting applications for RT, we should make trade-offs on how and when we will use this tooling. In our decision model, which we will elaborate on in Chapter 5.2. we will incorporate three decisions on how to use them.

The first trade-off we will make is based on the production process to use over time. Do we use CM, RT or perhaps both? It would be unnecessary to use both options at the same time, because we will have double tooling costs if we do so. However, holding tools in inventory costs us storage space and money. If a tool gets lost or accidentally scrapped, do we make the same tooling decision in a later period?

We might also scrap tooling on purpose if we think the remaining inventory is sufficient to fill the future demand. Therefore, the second trade-off we make in the model will be to keep the tool in inventory or to scrap it. If we scrap a tool and inventory has not been sufficient, we go back to trade-off 1 and we will decide again which production type to use. Since over time the costs of RT are likely to decrease, we might switch to RT if necessary in the last years of the life cycle.

This means we also have a trade-off to make on the production quantity. Do we wait for backorders to arrive, or do we stock inventory? And if we stock inventory, how high will this inventory be and what are the batch sizes we produce?

Finally, we should make an initial decision trade-off on the AM-technology we will use in case of RT. As we have seen in Section 3.2, multiple AM-processes are suitable for manufacturing tools. It is important to note that we do not included the use of direct AM in the trade-off comparison, nor do we model the possibility to obtain parts using second-hand supply. These have both been included by Jansman (2017) and a comparison between the options researched in this thesis and his could possibly be done afterwards.

3.7 Conclusions

In this chapter, we have tried to answer the first and second research questions posed in Section 2.2: *"What are the conventional production processes within the capability of TCS and which of these can potentially be redesigned by printing the production tools instead of manufacturing these conventionally?", "What are the benefits and drawbacks of rapid tooling in comparison with direct AM and conventional production?*" and *"Which additive manufacturing technologies can be applied for production tools and what are the boundary conditions for applying them?"*.

We have identified four production processes that are considered highly problematic for TCS if tooling is missing. These are injection molding, vacuum forming, die casting and sheet metal forming. From a theoretical perspective, these options are supported as well and we can use FDM, SLS, SLA and material jetting for the various tools.

However, using RT for die casting is beneficial in reducing cycle times and not in reducing tooling expenses for small series. Replacing die casting with another manufacturing strategy for metal parts might be much more beneficial, as these are not set up for mass production. The most interesting applications to replace die casting seem to be sand casting and investment casting. This is emphasized by the fact that there are 3D printer manufacturers, which specifically develop their machinery to be used for RT applications. However, this would require certification of new production methods and therefore, we will neglect them for this thesis. We do recommend to further research this possibility in the future.

4 CERTIFICATION AND PART APPROVAL

The biggest bottleneck within the thesis of Jansman (2017) was the certification and as seen in Subsection 3.3.3, certification costs are probably lower for parts produced using RT. Therefore, we will have a look at the certification implication when using RT and we will compare it with the certification efforts for direct AM. These efforts should then be translated to fixed and variable costs of certifying a part produced using RT. In Section 4.1, we will briefly discuss the process steps that belong to the certification process and we translate this to the typical RT-case in Section 4.2. The cost implications will be discussed in Section 4.3. We will conclude the chapter in Section 4.4.

4.1 CERTIFICATION PROCESS

Since TCS is the Type Certificate holder of the The Company fleet and it has been granted the Design Organization Approval by the European Aviation Safety Agency, it has the right and possibility to alter its designs. When a design is changed or a part is redesigned, the part must be certified. Because TCS has the status of design organization, in-house knowledge on the certification process is available.

As a design organization, TCS can classify design changes to be minor or major. To determine this, a checklist is walked through and all separate steps must indicate a minor change for the design change to be classified as minor. If one of the steps indicates a major change, design changes should pass through the European Aviation Safety Agency before being definitive. The checklist is shown in Appendix E. In general, if part design alters in such a way that it might affect structural safety, we have a major design change. Otherwise, we consider design changes to be minor.

4.2 PART APPROVAL WHEN USING RT

For part approval when making use of RT, we look at the typical RT-case for TCS. As stated in Section 1.2, the cases in which production tools are missing are quite limited in number, with 55 cases in the last 11 years. In addition, TCS first wants to experiment with this type of application for parts that are non-critical and non-structure. This means that the parts do not have a high failure severity and they do not belong to the aircraft structure. If there are going to be any certification costs, these will be minor.

Several engineers of TCS have shared their expertise on this issue. These are from the design and the production organization. The certification issues encountered by Jansman (2017) are a part of the design organization, as we have seen in Section 4.1. However, we need to change the design to perform any certification steps. Therefore, keeping part design the same would mean there is no certification involved at all, which would drastically reduce the up-front investment of production tools in comparison to using direct AM. In the case of Jansman (2017), part certification was €20,000. – per part, with €15,000. – of recurring costs. This will not be necessary for the tools in case the part size, material and other part specifications documented remain unchanged.

Instead, the consensus is that we perform extra effort during the production step. When producing items with a new production tool, we must perform a first article inspection (FAI). During the FAI, we make a sample of new parts to be produced and verify the tool produces parts according to design specification. Usually, we would take a sample out of a batch to ensure the production tool is producing proper parts. Because of a lack of experience in using RT, we will now test every single part of the sample batch on form fit and function. Therefore, we will add a quality inspection factor to the sourcing model in Chapter 6. This will be a quality check per batch, meaning that the costs are equal for every batch size.

One of the engineers, who also had years of experience in the automotive industry, compared this situation to the one of an automotive supplier he used to work for. When introducing new products, samples were tested and in case of inconsistencies, the mold was slightly adjusted to make it perform within the design specifications. Such iterations require a lot of testing to optimize mold performance. This is beneficial when millions of parts are produced with it, but not for a small number of spare parts. At TCS, there are multiple cases of estimated demands below ten parts during the remaining lifetime. For this extremely low demand situation, he stated it would be more cost effective to produce a sample for FAI and keep the samples which conform to specification in stock. The amount of inventory to keep is then to be determined.

In addition to what is discussed above, we had another session with two materials and processes engineers. They do not share this opinion, because the technology is quite unknown and therefore it should be tested. This should be done in consultation with the supplier of the part, since they should use the mold. An idea is to perform tests with RTs in the PARENT COMPANY (parent company) R&D-lab, but then it would become a long-term project.

Because there is a lack of in-house knowledge, we also consulted a 3D printing service provider, Seido-Solution. These have experience in using RT and state no structural issues will arise in comparison to the conventional manufacturing method. They have also offered to collaborate in testing, because their experience could be helpful and if testing is successful, TCS could become one of their customers. Given the parts regarded in the case studies, we think testing will not be very costly and we will include a setup cost for using RT. We repeat this for every new RT made, because of lack of knowledge of the process.

4.3 Cost implications

Instead of having major up-front investment costs, we will have a small setup cost if we use a new mold and additionally, we perform quality checks per batch produced. It could also be the case that the parts do not comply exactly. Then we would have to discuss the parts with engineers with specific knowledge on the critical measures of the parts. For the non-critical and non-structure parts, the obstacle would then become if a part will or will not become a hindrance for other parts within the system. If this is not the case, the parts might still be used, otherwise, they need to be scrapped. Presenting the targeted case studies, the engineers agreed that the non-critical non-loaded parts presented can be off by multiple millimeters, we expect no rejections for parts. The extra quality checks are estimated to be €100. –, representing one engineering hour. If parts become more complex, the costs might become higher.

4.4 Conclusions

In this chapter, we have sought the answer to the fourth research question posed: “*What does the certification process of parts produced with rapid tooling look like and what are the associated costs?”* In Section 4.1, we briefly introduced the certification process and indicated when it is applied, since it was the biggest bottleneck in adopting AM in an earlier phase. For parts produced using RT, certification is not an issue if process parameters remain unchanged. However, additional control mechanisms apply. We include a quality check per batch of parts produced with an RT, and we have a small testing setup cost each time we produce a new RT.

5 AM COST INDICATIONS

In this chapter, we make cost indications for production tools made with AM, answering the question posed in Subsection 2.2.5: *"What are the costs of producing production tools with additive manufacturing?"*. Therefore, we will perform literature research on cost estimations in Section 5.1, which will apply for obtaining the RTs. In Section 5.2 we will introduce an expected cost development factor, after which we will conclude the chapter in Section 5.3.

5.1 ONLINE COST INDICATIONS

Since we will be assessing a thermoforming case and an injection molding case, literature research will be performed on the costs of producing these tools with several of the discussed possibilities in Chapter 3. We will firstly address vacuum forming in Subsection 5.1.1, after which we will continue with injection molding in Subsection 5.1.2.

5.1.1 Vacuum forming cost indications

For vacuum forming, Redwood (n.d.-b) makes a comparison between different mold production opportunities. Factors that are considered interesting for determining the type of production method for the tool are given are given below in Table 7.

Table 7 - Thermoforming mold properties (Redwood, n.d.-b)

Technology	FDM	SLA	Material Jetting	CNC
Materials	Polycarbonate, ULTEM, ABS, PPSF/PPSU	High temperature resins	Simulated ABS, VeroWhitePlus	Aluminum
Level of detail	Low	High	Very high	Very high
Surface finish	Poor, can be improved by post processing	Very good	Excellent	Excellent
Porous	Yes	No	No	No
Lead times	Very short	Short	Short	Long
Cost	$	$$	$$$$	$$$$$
Sheet thickness	Thin and thick	Thin (<1.5mm)	Thin (<1.5mm)	Thin and thick
Best suited for	Low cost prototyping, simple geometries	Prototyping and production	Prototyping and production	Production

From the comparison in Table 7, we can see that FDM provides the cheapest option. In addition, porosity necessary to draw the vacuum is inherent to the production process of FDM, meaning no additional machining is required for vent holes. Therefore, we will focus on the FDM technology for our vacuum forming molds. If we compare it to the CNC costs, we indicate the tool to be five times as cheap as the CNC-machined tool. Since TCS engineers state these will cost us approximately €10,000.-, we indicate the FDM-tool to cost us approximately €2,000. - Due to post processing and the fact that we are outsourcing our tool production, these costs might become higher. Therefore, we will vary the cost to a higher level in our sensitivity analysis. Based on Stratasys (2016), we indicate that this outsourcing markup factor lies between 300% and 400%.

In addition, Stratasys (2017) also provides some information on FDM printing for thermoforming, of which vacuum forming is a specific type. One cost comparison is given, in which a cost reduction of 91% is obtained. This is a cost reduction given for the case when the manufacturer owns a 3D printer. We thus assume that this cost reduction will be anywhere in between 64-73% when the production is outsourced.

5.1.2 Injection mold cost indications

For the RT-injection mold application, three main characteristics need to be present in the mold material to make it suitable for usage as a direct soft tool (Redwood, n.d.-a):

1. *High Temperature resistance:* The mold material must be able to withstand the molten material while still producing accurate parts. An engineer of Seido-Solutions states that for example Digital ABS is used frequently as mold material using a 3D printed mold. This has a glass transition temperature of 84, which is a lot lower than the materials being injected into the mold. This is because the materials act as thermal insulator.
2. *High stiffness/toughness:* This is a property necessary for maintaining mold accuracy after multiple injections. It is especially required to keep its shape when removing parts from the molds repetitively.
3. *High level of detail:* This is needed to ensure parts are highly detailed as well.

Because of these characteristics, SLA and PolyJet are the preferred technologies for producing injection molds. More specific Redwood (n.d.-a), Digital ABS and Formlabs High Temp resin are mentioned for being used a lot in this application. The Formlabs High Temp resin application could be restricted because of the small dimensions of the Formlabs printer available. In addition, we cannot service parts printed by a Formlabs printer, but we should buy one. Therefore, RT-injection molds will be made on a PolyJet printer, made from Digital ABS.

We make a tooling costs comparison based on Stratasys case studies and indications of The Company engineers. As discussed in Subsection 3.1.2, TCS engineers estimate the costs of an injection mold is anywhere between €15000 and €50000 for very complex parts. Our case study part is relatively simple, so we estimate it to be at the absolute bottom of this range. Stratasys (n.d.-c) indicates cost savings of 50%-70%, although Table 8 indicates even higher cost reductions for molds made with Digital ABS. We will vary between the ranges given for cost reductions, up to 90%.

Table 8 - Stratasys Digital ABS injection mold costs

CM costs	AM costs	Cost reduction
\$52,725	\$1,318	97.5%
\$20,000	\$2,000	90%
\$4,000-\$5,000	\$800-\$1,000	80%
\$13,000	\$1,500	88.5%
\$15,000	\$1,500	90%

5.2 COST DEVELOPMENT FACTOR

In one of the other researches within the SINTAS-project, Reimert (2017) carried out an analysis on using direct AM for manufacturing spare parts. He developed a function based on the learning curve model of Sullivan, Wicks & Koelling (2015) to make an estimation of cost development for AM-processes. Since the technology is new and the market is growing, costs for AM are expected to decline in the future. As is the case with the military parts in his case studies, tooling also must meet high requirements to function. Therefore, we use the formula he developed for his direct part as an indication of the cost decline over time for AM. As is the case in Reimert (2017), we will develop this over a per-period basis, rather than a per-output-unit basis.

Since we are using a learning curve formula, we will also use this development factor for the inspection markup of parts produced. Under the wings of the European Aviation Safety Association, lots of research on AM is ongoing. In addition, TCS is also collaborating with the PARENT COMPANY Aerospace (TCS's mother company) AM research center in Filton, which gives TCS more experience as well. Therefore, we assume this learning curve model will also hold for the additional inspections, which we also find supported by Schiller (2015).

The function we introduce for our AM-tools is given by $c_{TOOL}(t,1) = c_{TOOL}(1,1) * t^n$. $c_{TOOL}(t,x)$ will be used in the sourcing model in Chapter 6 and is defined as *"The cost of a tool of type x (1: RT, 2: CM) in period t"*. n denotes the learning curve exponent, which is calculated by $n = \frac{\log(1-c_{AM})}{\log(2)}$. We will take his base level of $c_{AM} = 25.8\%$ and we vary this in our sensitivity analysis. To see how this cost function behaves, we plot the cost development of AM-tools over time against costs of CM-tools in Figure 14.

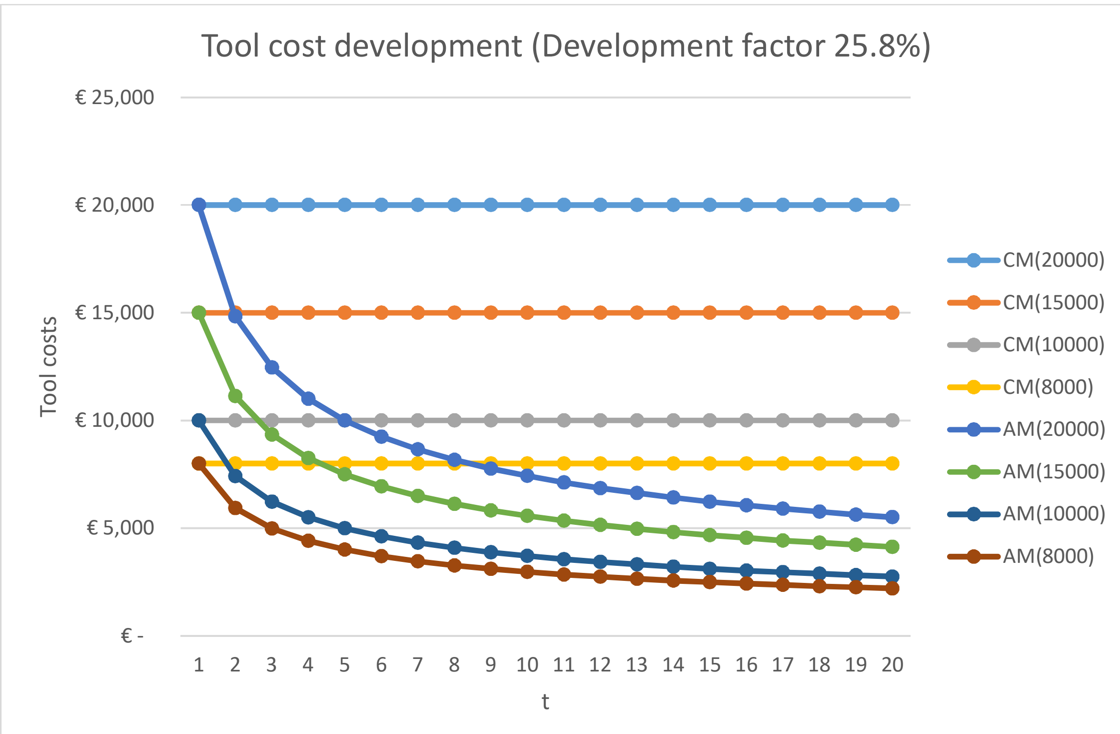

Figure 14 - Tool cost development over time, with c_{AM}=25.8% and initial costs as given between brackets.

5.3 Conclusions

In this chapter, we have tried to answer, *"What are the costs of producing production tools with additive manufacturing?"* As we can conclude from Section 5.1, a lot of potential is available for reducing tooling costs by using RT, up to 80% for thermoforming tooling and up to 97.5% for injection molds. Moreover, we expect future AM costs to decline, meaning this becomes even more in the future. Based on the results, we can conclude that severe opportunities exist for cost reductions if implementation and certification costs are not as severe as in the direct AM case. Since we have discussed this already in Chapter 4, we conclude those opportunities do exist.

6 MODEL SETUP FOR SOURCING DECISION

In this chapter, we construct a decision model for sourcing obsolete spare parts. Using the model, we obtain the minimum expected total costs over the remaining life cycle of the part and the policy to acquire this minimum cost level. The model we develop will be a generic model, because cost factors vary among the parts and for the case studies, we need to be able to perform some sensitivity analysis. With the model developed, we can assess the impact of RT on sourcing decisions and answer the question if RT might be suitable for lowering costs for obsolete spare parts.

Firstly, we will address the model assumptions in Section 6.1. After noting these, we will describe the development of the model and the decisions it should facilitate in Section 6.2. In Section 6.3, we will list and discuss the input parameters and used variables, after which we will formulate the model in Section 6.4. We will conclude the chapter in Section 6.5.

6.1 MODEL ASSUMPTIONS

Before we can start model construction, we need to elaborate on the assumptions we make. This will affect model building, so the assumptions should be clear before the start. One of the things we must model is that we are dealing with parts that will be put in the The Company fleet, which will be phased out. Therefore, our service model must be finite at some point. Currently, the expected year for the The Company fleet to reach EOS is set to 2030, which means twelve years are remaining for service. Based on this information, we formulate the first assumption:

1. We assume a fixed remaining service period, in which the EOS-period will be given by T.

In addition to the fleet behavior, it is also important we consider the part failure behavior. Since this research is conducted in a phase in which The Company is still experimenting with AM, we do not use any critical parts. This means the parts do not carry any significant load and failures (and thus demand for the part) are related to incidents. Since these occurrences are random discrete events, we can use a Poisson process to model this phenomenon. We will not alter the installed base size if a part fails, because failure rates are low and the fleet size is relatively large, making one failing part insignificant for the arrival process. Therefore, we assume a failure in the fleet will not affect the demand arrival process. Furthermore, the manufacturing process for the part is assumed irrelevant for the failure behavior of the part, because a part must be qualified as safe to go into the air with a The Company aircraft. We will use the same material for the part, so safety for non-loaded parts is not an issue. We thus have the following set of additional assumptions:

2. Failure rates of parts produced are independent on the manufacturing method.
3. The installed base size, and thus the demand arrival, is not affected by any part failure.
4. The demand arrival process is modeled as a Poisson process.

As stated, we use non-critical, non-loaded parts. These parts therefore will not cause downtime of an aircraft. Nevertheless, unavailability of the part will not be good for customer satisfaction. In addition, the parts regarded in this case study might serve as a protection for other parts and those parts might get damaged once the demanded part is unavailable. Therefore, we do model a penalty cost for backorders. In general, TCS models a penalty of 180% of the part costs per backorder to push for higher service levels. However, we will differentiate on the part lead time a backorder faces to distinguish the different sourcing types. Thus, the longer it takes to fulfil the demand, the higher the penalty gets. We thus deduce a daily penalty cost. We define the part lead time as the time it takes for a part to be delivered to TCS if a tool is already on hand at the supplier. If we translate the penalty of 180% of the part costs into a daily penalty, we obtain a penalty of $\frac{1.8 * part\ cost}{part\ lead\ time}\ per\ day$. This means that backorders that occur without tooling in place will in have a higher penalty cost than if tooling would be in place. We thus assume:

5. We model a penalty for backorders based on a percentage of the part its cost and the expected lead times encountered.

We should note that the lead times given will be modeled as deterministic variables. The part lead times are quoted in the ERP-system of TCS and we will regard those as a given fact. These are assumed identical for the RT and CM-case, meaning that a possible lead time difference will be due to different tooling lead times.

There are also some modeling differences between RT and CM. The CM-processes are known and therefore we will not include additional quality checks for parts produced using CM. This is different for parts produced using RT, which require an additional quality check per batch produced, at cost q_{AM}. This is independent of the batch size. Additionally, if we need a new RT, we will always produce ten parts with it to test the tool. We assume that we can use all ten parts to sell to our customers. We thus have the following assumptions:

6. Part lead times assumed deterministic for both production types.
7. Parts produced with AM-tools need additional quality checks per batch (q_{AM}), independent of the batch size.
8. If we produce using a newly manufactured AM-tool, we will always produce ten parts for testing, which we can all use to sell to our customers.

Just as is the case for part lead times, we will regard the tooling lead times as deterministic variables, although they might vary. For the CM-tools, the lead time range will be indicated by internal engineers. AM-tools will be provided with a lead time range indication by AM-professionals of Seido-Solutions. For the AM-tools, we will include an additional lead time of a week for development of a CAD-model. This range of lead times indicated will be included in the sensitivity analysis to analyze the influence of tooling lead times on the total costs.

Next to the lead time, the tooling costs will be regarded as deterministic variables, since a request for quotation will always be sent before the decision is made to use a certain sourcing strategy for sourcing. The costs for the CM-tools are quoted by the TCS engineers and for a cost indication of the AM-tools we use quotations derived in Section 5.1. However, these costs might be somewhat inaccurate and therefore sensitivity analysis is performed on the tooling costs for both sourcing options. In addition, sensitivity analysis will be performed for the cost development of the AM-tools. AM technology is still being developed and therefore manufacturing costs are expected to decline. The tooling itself is specialized for the parts to study and therefore, we will fully address these tooling costs to the parts we produce.

The last tooling factor to discuss is the availability behavior of the several tooling options. One of the problems we addressed in Section 1.2 is that tooling might be lost or (accidentally) scrapped without notifying personnel outside of the warehouse. The indication is that after ten years, 15% of the times tools are not retrieved and alternative sourcing is needed. Therefore, we add a parameter (P_{surv}) to our model to include the assumption of tools being lost or scrapped. Since we will evaluate the model using a full year as a period, $P_{SURV} = 1.61\%$.

Usually CM-tools are designed for mass manufacturing, so we assume these will not break due to operation. However, this assumption probably does not hold for AM-tools, since these (when we transform to plastic tools) will be set up for small batches and have a limited life. According to the materials and processes department and professionals of Seido-Solutions, this life is not influenced by deterioration over time, but it is more likely to break because of operator errors for the production processes used within TCS. Therefore, we will assume that there is a probability for an AM-tool to break down for each part produced. This will be noted by P_{AM}, which will be a constant parameter in which we do not take factors like wear into account.

Nevertheless, we will assume for the sake of modeling that we can always produce what we expect to produce in a period, including the backorders that are produced expedited. In theory, this could mean that we underestimate the lead time and cost a backorder faces. For CM, this will not be an issue, because a tool does not break down. For AM-tools, this is very unlikely to be an issue. For an initial batch we have an MOQ of 10 for and if we still have a tool available, we have must check the complete batch at costs independent of the batch size. This favors larger orders when using AM-tools, strongly reducing the probability of a backorder due to expedited production within a period. A tool could also break down before finalizing the batch. This would mean we obtain less parts and subsequently face an additional decision on making a new tool and continuing production, or leaving it the way it is. We neglect this, because we will always outsource production and we will pay a fixed price to obtain a part. In addition, tool capacities of RT generally are not low enough to break in the initial batch (e.a. Redwood, n.d.-a; Stratasys, 2017 and D3 Technologies, 2016).

For tooling, we thus have the following assumptions:

9. Tool lead times are assumed deterministic and the possible costs effects will be sketched in the sensitivity analysis.
10. The CM-tool costs are assumed constant over time, whereas the costs of AM-tools will develop over time. Again, we will perform sensitivity analysis on these costs. We do the same for cost development of those tools.
11. Tooling is dedicated to the specific parts and therefore, we will fully address the tooling costs to the parts in the case studies.
12. Tools of both types might be lost or scrapped in the warehouse. AM-tools might also break down due to operation, but do not deteriorate while stocked in the warehouse. The failure rate per part is constant.
13. For modeling simplicity, we aggregate failure behavior of the AM-tools by determining failure probabilities related to the expected total production in a period.

For the modelling logic, we also make some assumptions. Since we have a discrete time process, it is best make periodic decisions and therefore divide the costs into periodic costs to be incurred in period t of length L. We also have a discrete quantity process, meaning only full parts can be demanded. Under the first set of assumptions, we stated that at some point we will encounter EOS. If we still have parts or tools on stock, we will dispose parts at EOS, but these will have no value left and no costs will be accounted for. The same goes for tooling.

We will account for holding costs in the beginning of the periods, both for parts and tools. We will not make a distinction in holding costs for parts produced, because they have the same value for TCS. The tools for the parts regarded in the case study will rarely be used. We will also not distinguish on holding costs, since tools will use the same shelf space. In addition, differentiating between these might trigger tool scrapping, which TCS would never do if a tool is produced recently. Thus:

14. At EOS, we dispose all remaining inventory for free.
15. Holding costs for part and tools will be calculated at the beginning of the period, based on current inventory
16. We do not differentiate on tool and part holding costs.

Finally, we need to make some sourcing rules for the model. In general, it would be costly to keep multiple tools in stock, therefore, we can only have one. We can thus only use one type of sourcing in a period. What we can do, is dispose a tool and switch production method if we need to produce at a later point in time. This can also be in the same period, for the case in which we do not choose to produce. If we run out of stock in a period and face a backorder, we could choose a different type of tool. However, we cannot dispose a functioning tool in a period in which we decide to produce. This would give us unnecessary additional costs. The last assumptions thus are given by:

17. We can only use one sourcing type per period.
18. We can dispose tooling and use another type of tooling later in time.
19. We cannot dispose tooling if we decide to produce.

6.2 Description of model development

As already stated under the assumptions, we are dealing with a discrete time process. We thus take decisions in every period t. The decisions are made on sourcing type, tool scrapping and regular production quantities. The goal of the model is to minimize the costs over the remaining life cycle. After EOS, we dispose all inventory, in period $T+1$. We thus minimize over period $t=1$ to $t=T+1$. Because we have a discrete process with sequential decisions, we can use dynamic programming to solve the problem. Since our demand pattern is stochastic of nature (we have Poisson demand) and we consider tool breakdown probabilities, we are dealing with a stochastic optimization problem. Therefore, we will construct a model based on stochastic dynamic programming (SDP) in which we will periodically make the three decisions as described above.

6.3 Variables and parameters

6.3.1 Input parameters

Under the input parameters, we list the general input in Table 9. Some input parameters only apply to parts produced using an AM-tool. These are given in Table 10.

Table 9 - General input for stochastic dynamic programming model

Parameter	Explanation
p	Penalty factor for backorders per part lead time (in % of part cost)
h_p	Holding cost rate of a part per period (in % of part cost, without inspection)
T	End of service period
L	Period length (in days)
LT_{MAN}	Lead time of a (batch of) part(s) (in days)
$LT_{TOOL}(x)$	Lead time of a tool of type x ($LT_{TOOL}(x) < L$)
h_T	Holding cost rate of a tool (in % of tool cost)
$c_{MAN}(x)$	Cost of a part of type x (in €)
c_{PEN}	Penalty cost of a part ($c_{MAN} * p$)
P_{SURV}	Probability of any tool to be retrieved from the warehouse in the next period

Table 10 – Input parameters for AM-Tools

Parameter	Explanation
c_{AM}	Cost development factor of AM technology (% of cost reduction per period)
q_{AM}	Costs to check a batch of parts produced with an AM-tool
P_{AM}	Survival probability of a tool when it produces a part

6.3.2 Model variables

Next to the input parameters, we also have some variables which will be entered in our SDP. These factors are in general time dependent and will form the base of expected cost and expected demand calculations. We can find them in Table 11 below.

Table 11 – Model variables

Variable	Explanation
$\lambda(t)$	Demand rate in period t
$p_t(d)$	The probability of having demand d in period t
$c_{TOOL}(t, x)$	Cost of a tool of type x in period t (in €)
$E[P(t, s, i)]$	Expected backorders due to expedited production in period t if s parts are in stock and i parts are ordered in the beginning of period t.
$P_{MAN}(s, t)$	Probability of expedited production in period t if s parts are in stock at the beginning of the period. Otherwise said: $P(d(t) \geq s + 1) = \sum_{n=s+1}^{\infty} \frac{\lambda(t)^n e^{-\lambda(t)}}{n!}$
$P_{S,AM}(t, s, i)$	The probability for an AM-tool to break down in period t given stock level s and order level i

6.4 MODEL FORMULATION

For a stochastic dynamic programming problem, we need to determine what our phases look like, in which states we can be and which decisions we can take. With these, we formulate a value function, of which the cost factors and their determination will be further explained after the value function formulation.

Phase

The phase is always the start of period t. We evaluate for period $t = 1, \dots, T + 1$.

States

We have two state parameters, which are the stock level and the tooling condition at the beginning of period t. These parameters are noted by u for the tooling condition and s for the stock level. Combined, this the state in period t will be expressed as $[u, s]$. Parameter u can have three different values:

0. We have no tool on hand
1. An AM-tool is on hand
2. A CM-tool is on hand

The value of s is the stock level at the beginning of the period. We could choose this stock level as high as we want in theory, but this would not make any sense and result in a considerable burden. Therefore, we need to determine an upper bound for the value of s. Because prices might increase in the future, we want to include the option of a relatively large purchase order in an early period. Therefore, we round the expected remaining demand over the expected remaining life time up to the nearest integer value. If this value is lower than 10, $UB = 10$. We include this, because we need to tolerate the decision to produce an initial batch of 10 parts. The maximum is $UB = 15$. This is the case because we do not want to overload our VBA-program, since the number of computations increases exponentially if an additional stock level is allowed. In addition, if demand would be relatively high for our case studies, we still include the possibility for AM-tools to break down. In the current model, we can always produce what we want, meaning that we could theoretically decide to perform an LTB with the certainty of an AM-tool not breaking down.

Decisions

The possible decision set consists of all separate decisions we can make in a period. As stated before, we decide on sourcing type, tool discarding and regular production quantity.

1. We source using an AM-tool ($x = 1$) or CM ($x = 2$)
2. We discard the tool we have ($y = 1$) or do nothing ($y = 2$)
3. We regularly produce i parts to go in inventory

With these possible options, we formulate possible decisions to take as $D(u, s)$. These consist of a subset of the options $\{x, y, i\}$ for $u = 0,1,2$, $s = 0,1,2, \dots, UB$, where $x = 1,2$; $y = 1,2$ and $i = (0, UB)$. For all $D(u, s)$, we give the possible decision set below:

$$D(0, s) = \{x = 1,2; y = 2; i = quantity\}$$

$$D(1, s) = \{x = 1; y = 1,2; i = quantity;\ if\ y = 1, i = 0\}$$

$$D(2, s) = \{x = 2; y = 1,2; i = quantity;\ if\ y = 1, i = 0\}$$

Value function

The decisions we can take under the previous step affect the value function, which is the function that minimizes the expected cost during period t, given that we started at state $[u, s]$. We note this by $c_t([u, s]; [x, y, i])$. These costs will be summed over all t, multiplied by state transition probabilities. This is the probability of decision $[x, y, i]$ in state $[u, s]$ resulting in state $[w, r]$ for period $t + 1$, where w is the resulting tooling state in $t + 1$ and $r = \max\{0, s + i - D\}$ denotes the starting inventory of period $t + 1$. We note the state probabilities as $p_t([w, r]|[u, s]|[x, y, i])$. Next to these decisions, we dispose our remaining inventory at $T + 1$. This gives us the following function:

$$V_t(u, s) = \min_{x,y,i \in D(u,s)} \{c_t([u, s]|[x, y, i]) + \sum_{(w;r)} p_t([w, r]|[u, s] \wedge [x, y, i]) * V_{t+1}(w, r)\}$$

With the last states given in the form of

$$V_{T+1}(u, s) = \begin{cases} hc(s), & if\ u = 0 \\ hc(s) + hctool(u), & if\ u \neq 0 \end{cases}$$

For $t = 1$, our case studies will have the initial state $[u, s] = [0,0]$, for which the value function will be given by $V_1(0,0)$.

Cost expressions

To aid decision making, we determine cost expressions for the factors given below. In general, the cost factors are dependent on the decisions we take in a period given the initial state.

Variable sourcing costs per option

The variable sourcing costs per option are different for all options. One thing that the options have in common is the fact that the inventory will always be an integer number of parts and the production decisions are made at the beginning of a period. We will choose the periods as such, that whatever sourcing decision we take, we will receive the parts within the same period. In that case, we can use the parts produced for fulfilling demand in the same period. The sourcing quantity to fulfil demand then becomes dependent on (1) the demand in a period, (2) the initial period inventory and (3) the number of parts produced regularly in the period. We can also have expedited production to fill a negative gap between (1) and (2) + (3). This will be the expected number of backorders based on an inventory shortage.

This expected number of backorders is essential for our calculation, since we count penalty costs if demand cannot be fulfilled from stock and we want to determine if we should have a sufficiently high stock level to fulfil demand. We will calculate the expected number of backorders based on Sherbrooke (2004).

Under model variables, we introduced $E[P(t,s,i)]$ as the expected backorders due to expedited production in period t if s parts are in stock and i parts are ordered. We need the period specification because of the declining demand as we approach EOS. This expectation can be regarded as the number of backorders that are the result of stocking decisions made within the period. This can be expressed as:

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

However, this is an enumeration that would result in a lot of computations. Instead, we can rewrite the function to a subtraction of two sums to infinity, which yields the same result:

$$\begin{aligned} E[P(t,s,i)] &= \sum_{n=s+i+1}^{\infty} \big(n-(s+i)\big) * \frac{\lambda(t)^n e^{-\lambda(t)}}{n!} \\ &= \lambda(t) \sum_{n=s+i}^{\infty} \frac{\lambda(t)^n e^{-\lambda(t)}}{n!} - (s+i) \sum_{n=s+i+1}^{\infty} \frac{\lambda(t)^n e^{-\lambda(t)}}{n!} \end{aligned}$$

The variable sourcing costs then rely on which tools are developed. Given this formula, we have the following sourcing costs:

$$(E[P(t,s,i)] + i) * c_{MAN}(x)$$

If $x = 1 \; and \; u = 0$, the sourcing costs will always be $10 * c_{MAN}(x)$, due to the initial batch size. Otherwise, we account the part manufacturing costs as expected.

Penalty costs under different scenarios

The penalty costs under different scenarios are determined by the expected number of backorders times penalty costs. The lead times of different options will vary and therefore, the expected penalty costs will vary as well. These are dependent on the state and the decisions taken period t. The scenarios are sketched below:

1. We have a tool in stock and we do not place a regular order for inventory replenishment

2. We haven't got a tool in stock and we do not place a regular order for inventory replenishment.
3. We have a tool in stock and we place a regular order for inventory replenishment
4. We haven't got a tool in stock and we place a regular order for inventory replenishment

It should be noted that all penalty costs below are indicated based on the expected backorders based on expedited production, $E[P(t,s,i)]$. For scenario 1, this is accurate for the number of backorders expected. This is because we will not have demand during lead time. In the other cases, we will encounter demand during lead time. For these cases we should have modeled a separate arrival process, with an arrival rate of $\mu(LT) = \frac{LT}{L} * \lambda(t)$, in which the lead time can consist of LT_{MAN}, $LT_{TOOL}(x)$ or both. Combining this with the current stock level s, the expected number of backorders during lead time can be calculated. Nevertheless, given the demand characteristics of the obsolete spare parts, we do not remodel these penalty costs due to demand during lead time. These are rather insignificant. What is given in the scenarios below, is how the penalty costs are modeled in VBA.

Scenario 1: We have a tool in stock and we do not order anything to put in inventory

The only penalty time we encounter when facing a backorder in case we have tooling available is the lead time of the part. Since we do not produce anything regularly, this will always be the full lead time of the part. The expected penalty for this scenario is solely dependent on s and t and will consist of expedited production. For the penalty costs, we obtain Equation 1:

$$E[P(t,s,i)] * LT_{MAN} * c_{PEN}, \qquad if\ u = 1\ or\ 2;\ y = 2\ and\ i = 0 \qquad [1]$$

Scenario 2: We haven't got a tool in stock and we do not order anything to put in inventory

For this scenario, we have additional penalties in comparison with Equation 1 discussed under scenario 1. The penalty under Equation 1 will also be applicable in case we have a backorder in scenario 2. Because we do not have regular production, a backorder will always have the full part manufacturing lead time and this is captured in Equation 1.

In addition to that, any backorders under this scenario might encounter some form of tooling lead time. The additional lead time for the first backorder to arrive under this scenario will always be equal to the full lead time of the manufacturing tool. The probability of this occurrence is equal to $P_{MAN}(s,t)$, which we have defined before as the probability demand exceeds the current stock level. Therefore, the expected additional penalty for the first backorder under this scenario is given by:

$$P_{MAN}(s,t) * LT_{TOOL}(x) * c_{PEN}$$

It could also be the case that demand occurs during the production of a tool. The backorders that arrive during tool production will not encounter a full tooling lead time, as opposed to the first backorder. This means that we must derive an expression that indicates the fraction of the lead time a backorder will encounter on average. One of the properties of a Poisson process is that when it is conditioned on the number of arrivals in a fixed period, these will on average be uniformly distributed over the interval. Because all orders during the tool production are considered backorders, we have on average half a lead time for each backorder that occurs during tool production.

In addition, we need to place this in perspective of the total period length. For the expected backorder calculation, we virtually put an extra part in stock (which is the part that is currently being backordered) and thus calculate backorders for $E[P(t,s+1,0)]$. This gives an expected backorder amount of:

$$E[P(t,s+1,0)] * \frac{LT_{TOOL}(x)}{L}$$

This gives associated penalty costs during tooling lead time of:

$$E[P(t,s+1,0)] * \frac{LT_{TOOL}(x)}{L} * \frac{1}{2} LT_{TOOL}(x) * c_{PEN} = E[P(t,s+1,0)] * \frac{LT_{TOOL}(x)^2}{2L} * c_{PEN}$$

Combining all factors, we obtain the following expressions for the penalty costs under this scenario:

$$(E[P(t,s,i)] * LT_{MAN} + P_{MAN}(s,t) * LT_{TOOL}(x) + E[P(t,s+1,0)] * \frac{LT_{TOOL}(x)^2}{2L}) * c_{PEN},$$
$$if\ u = 0\ and\ i = 0$$

Scenario 3: We have a tool in stock and we order to put in inventory

Just as in the other scenarios, we have a possible penalty for expedited production backorders. The expected backorder costs arising from expedited production are given by the same formula as in scenario 1, only now with $i > 0$. We give this as Equation 2, as it will also return at scenario 4:

$$E[P(t,s,i)] * LT_{MAN} * c_{PEN}, \qquad if\ u = 1\ or\ 2;\ y = 2\ and\ i > 0 \qquad [2]$$

We also might encounter a similar phenomenon as we did under scenario 2, which is demand during lead time. We have a tool in stock, so this will not occur during tool production. Instead, we might have demand during lead time of the regularly produced parts. These demands will initially be filled with the stock that is currently on hand (s). If we run out of that stock, backorders will occur. These can also possibly be filled with the parts that are currently in the regular production run (i). As we stated under scenario 2, the arrivals within a fixed period (the part lead time in this case) are on average uniformly distributed over the interval. If $s \neq 0$, the average encountered lead time for backorders that are filled with parts from i will not necessarily have half the part lead time as the lead time.

To show this, we have made an illustration below. If we define the period between $NULL$ and LT_{MAN} as Z, then A, B, C and D are all equal to $\frac{1}{4}Z$. This generalization holds for all homogeneous Poisson arrival processes.

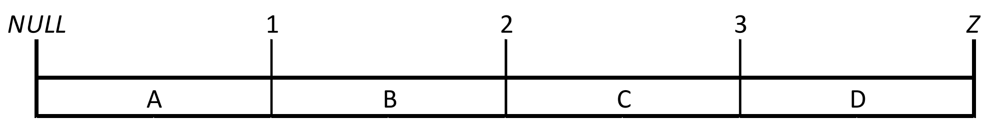

Figure 15 – Example arrival point distribution over a fixed interval

Let us define $d(Z)$ as the number of arrivals in period Z as specified above. If $s = 0$ and $i \geq d(Z) = 3$, arrival 1 will have $\frac{3}{4}L$ left, arrival 2 will have $\frac{1}{2}L$ left and arrival 3 will have $\frac{1}{4}L$ left until replenishments i arrive. Thus, when we have zero stock, the average lead time fraction encountered by the replenishments will be equal to:

$$\frac{\frac{3}{4} + \frac{1}{2} + \frac{1}{4}}{3} Z = \frac{1}{2} Z$$

This lead time fraction resembles the situation we have under scenario 2, in which every arrival in L will face on average half a tooling lead time. However, it could also be that we have a part on stock, or perhaps even more, while $s + i \geq d(Z)$ and $s < d(Z)$. If $s = 1$, we have on average already passed period A. This means that we have $\frac{3}{4} * \frac{1}{2} Z = \frac{3}{8} Z$ left as the expected lead time for arrivals 2 and 3. If $s = 2$, we have also passed period B. This leaves us with an expectation of $\frac{1}{2} * \frac{1}{2} Z = \frac{1}{4} Z$ for arrival

3. We want to capture these fractions into an expected fraction of the lead time that a backorder faces in a separate formula. We describe a pattern in Appendix H, which results in our lead time fraction variable $LTFrac(s,i,d)$. This also considers the fact that demand might be higher than $s+i$. The resulting fractions are equal to:

$$LTFrac(s,i,d) = \begin{cases} \dfrac{d(Z)+1-s}{2(d(Z)+1)}, & if\ s+i \geq d(Z)\ and\ s < d(Z) \\ \dfrac{\sum_{n=1}^{i} d(Z)+1-(s+n)}{i(d(Z)+1)}, & if\ s+i < d(Z) \end{cases}$$

This also holds for the case where $s=0$, since $LTFrac$ will always be equal to $\frac{1}{2}$ in this case. Based on these lead time fractions for all demand scenarios, we need to determine an expected lead time for all backorders that arrive during lead time. We capture this in variable $LT_{BO}(t,s,i)$. Because we have stochastic demand that decreases over time, this is dependent on t, as well as the stock level and the regular production quantity. We calculate $LT_{BO}(t,s,i)$ by enumeration over all $p_d(t)$. Thus, we obtain the following formula for $LT_{BO}(t,s,i)$:

$$LT_{BO}(t,s,i) = \frac{\sum_{d=1}^{UB} p_d(t) * LTFrac(s,i,d)}{\sum_{d=1}^{UB} p_d(t)}$$

For the backorders during lead time that can be filled from replenishments i, we need to derive a cost expression. These expected backorders are given by $E[P(t,s,0)] - E[P(t,s,i)]$. Considering the replenishment period, the expected backorder costs are given by:

$$(E[P(t,s,0)] - E[P(t,s,i)]) * \frac{LT_{MAN}^2}{L} * LT_{BO}(t,s,i) * c_{PEN}, \qquad if\ x = 1\ or\ 2$$

Combined with the other backorder cost factors, this gives us the following penalty costs expression for scenario 3 in Equation 3:

$$\left(E[P(t,s,i)] * LT_{MAN} + (E[P(t,s,0)] - E[P(t,s,i)]) * \frac{LT_{MAN}^2}{L} * LT_{BO}(t,s,i) \right) * c_{PEN},$$
$$if\ x = u = 1\ or\ x = u = 2, y = 2\ and\ i > 0 \qquad [3]$$

Scenario 4: We have no tool in stock and we order to put in inventory

For this scenario, our period is split in three separate sections, as given below in Figure 16:

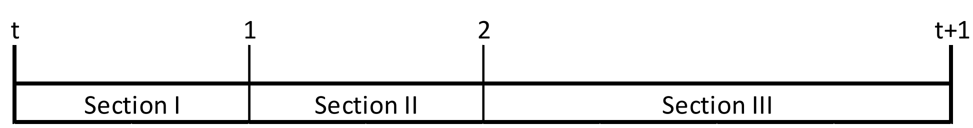

Figure 16 – Period sections of scenario 4

1. Section I is the replenishment period of the tool.
2. Section II is the replenishment period of the part.
3. Section III is the section of the period in which all replenishments should have arrived.

Since we will decide at t and decisions will not be altered until $t+1$, we will make one interval of Section I and Section II combined and derive an expression for the expected backorders in the combined period. However, there also is a possibility to have demand during tool manufacturing lead time that cannot be filled with the replenishments i. We further explain this in Appendix H, but it is derived in a similar way as $LT_{BO}(t,s,i)$, which has been shown earlier in the report. The resulting factor is specific for scenario 4 and is given by $LT_{BO}\ (t,s,i)$. If we add this factor and the tooling lead times to Equation 3, we obtain the following penalty cost equation:

$$\left(\begin{array}{c} E[P(t,s,i)] * (LT_{MAN} + LT_{BO}\ (t,s,i) * \dfrac{LT_{TOOL}(x)^2}{L}) + (E[P(t,s,0)] - E[P(t,s,i)]) \\ * \dfrac{\left(LT_{MAN} + LT_{TOOL}(x)\right)^2}{L} * LT_{BO}(t,s,i) \end{array}\right) * c_{PEN}\ ,$$
$$if\ u = 0, y = 2\ and\ i > 0\ or\ u \neq 0, y = 1\ and\ i > 0$$

Tooling costs

Tooling costs are only incurred in case tooling is needed to produce parts to fulfil demand. There are two possibilities of having to buy tooling, under the condition of deciding to buy a tool or when current inventory does not suffice and a tool should be produced to fulfill the backorders. In the first case, we will have the cost of tooling with probability 1. In the other case, we only must produce a tool with the probability given below:

$$P_{MAN}(s,t) = \sum_{n=s+1}^{\infty} \frac{\lambda(t)^n e^{-\lambda(t)}}{n!}$$

We note that another probability might arise in theory: A tool could break down while it is in service and not all parts have been produced as planned. In this case, an additional decision should be taken on keeping the number of parts we have successfully made already or continuing production as planned. As discussed under the assumptions, we will neglect this and we assume that an available production tool can always fulfil the production in certain period. If a tool breaks down, we start the next period without the tool. This leaves us with the following costs:

- $c_{TOOL}(t,x) * P_{MAN}(s,t),\ if\ u = 0\ and\ i = 0\ or\ u \neq 0, y = 1\ and\ i = 0$
- $c_{TOOL}(t,x),\ if\ u = 0\ and\ i > 0$
- 0, otherwise

Holding costs parts

The holding costs for parts are determined at the beginning of period t and are determined based on s. We thus have:

$$hc(s) = c_{MAN}(x) * h_p$$

Holding costs tools

The holding costs for tools are determined at the beginning of period t and are determined based on u. We have:

$$hctool(u) = \begin{cases} 0, & if\ u = 0 \\ h_T * c_{TOOL}(1,2), & if u \neq 0 \end{cases}$$

Final cost expression for value function

The final cost expression is a combination of all different cost expressions under different states and decisions. We summarize this as follows:

$$c_t([u,s];[x,y,i])$$
$$= \{all\ expressions\ mentioned\ above\ for\ state\ space\ [u,s]\ and\ decisions\ (x,y,i)\}$$

State transition probabilities

The state transitions are built upon the decisions taken in all periods t, demand d, stock level s, tooling state u, the decisions we make and the possibilities to lose or break down tools. The decisions itself will not be much of a variable, since we can choose these. However, resulting tooling state w and resulting stock level r are still stochastic variables because of the demand and tool breakdown/losing probabilities.

Both of those factors have been incorporated in the periodic costs in an earlier stage. We split the transition probabilities into two, making a probability expression for the remaining stock level and a probability expression for the resulting tooling state.

Remaining stock level probability

For the remaining stock level, we are dependent on the demand d, the initial stock level s and regular production level i. Introducing parameter r as the remaining stock level, we introduce probability $P_{t,REM}(r|s \wedge i)$ as the remaining stock level probability. We have four options for this variable. The remaining stock can never be higher than $s + i$, we can have stock remaining, we could run out of stock in a period and we can remain stockless. We list the possibilities below:

- $P_{t,REM}(r|s \wedge i) = 0,\ if\ r > s + i$
- $P_{t,REM}(r = s + i - d|s \wedge i) = \frac{\lambda(t)^d}{d!} e^{-\lambda(t)},\ if\ d \leq s + i - 1$
- $P_{t,REM}(r = 0|s \wedge i) = 1 - \sum_{d=0}^{s+i-1} \frac{\lambda(t)^d}{d!} e^{-\lambda(t)},\ if\ d \geq s + i$
- $P_{t,REM}(r = 0|s = 0 \wedge i = 0) = 1$

Tool state probability

For the tooling state probability, we are dependent on all decisions we take. We can differentiate nine different scenarios for resulting tool state probabilities, which we will denote by $P_{t,TOOL}(w|[u,s] \wedge [x,y,i])$. The first option is that there is no possibility to go to a tool state, which are the infeasible combinations of decisions ($P_{t,TOOL}(w|[u,s] \wedge [x,y,i]) = 0$):

- $y = 1\ and\ i > 0$ (we cannot scrap a tool if we decide to produce)
- $y = 1\ and\ u = 0$ (we cannot scrap a tool we do not have)
- $x = 1\ or\ w = 1, u = 2\ and\ y = 2$ (we cannot source using AM-tools if we decide to keep our CM-tool)
- $x = 2\ or\ w = 2, u = 1\ and\ y = 2$ (we cannot source using CM-tools if we decide to keep our AM-tool)
- $x = 2\ and\ w = 1$ (we cannot have an AM-tool because of choosing CM in the period before)
- $x = 1\ and\ w = 2$ (we cannot have a CM-tool because of choosing AM in the period before)
- $u = 0, x = 1\ and\ 0 < i < 10$ (when using an AM-tool, we cannot choose to produce less than the minimum initial batch of 10 parts, unless we decide not to produce).

The feasible probabilities are given by the following combinations:

1. $P_{t,TOOL}(w = 2|[u = 2,s] \wedge [x, y = 2, i]) = P_{SURV}$
2. $P_{t,TOOL}(w = 0|[u = 2,s] \wedge [x, y = 2, i]) = 1 - P_{SURV}$
3. $P_{t,TOOL}(w = 1|[u = 1,s] \wedge [x, y = 2, i]) = P_{SURV} * P_{S,AM}(t,s,i)$
4. $P_{t,TOOL}(w = 0|[u = 1,s] \wedge [x, y = 2, i]) = 1 - P_{SURV} * P_{S,AM}(t,s,i)$
5. $P_{t,TOOL}(w = 0|[u = 0,s] \wedge [x = 1, y, i]) = P_{t,TOOL}(w = 0|[u = 1,s] \wedge [x = 1, y = 1, i]) = P_{t,TOOL}(w = 0|[u = 2,s] \wedge [x = 1, y = 1, i]) = 1 - P_{MAN}(s,t) * P_{SURV} * P_{AM}^{10}$
6. $P_{t,TOOL}(w = 1|[u = 0,s] \wedge [x = 1, y, i]) = P_{t,TOOL}(w = 1|[u = 1,s] \wedge [x = 1, y = 1, i]) = P_{t,TOOL}(w = 1|[u = 2,s] \wedge [x = 1, y = 1, i]) = P_{MAN}(s,t) * P_{SURV} * P_{AM}^{10}$

7. $P_{t,TOOL}(w = 0|[u = 0, s] \wedge [x = 2, y, i]) = P_{t,TOOL}(w = 0|[u = 1, s] \wedge [x = 2, y = 1, i]) = P_{t,TOOL}(w = 0|[u = 2, s] \wedge [x = 2, y = 1, i]) = 1 - P_{MAN}(s, t) * P_{SURV}$
8. $P_{t,TOOL}(w = 2|[u = 0, s] \wedge [x = 2, y, i]) = P_{t,TOOL}(w = 2|[u = 1, s] \wedge [x = 2, y = 1, i]) = P_{t,TOOL}(w = 2|[u = 2, s] \wedge [x = 2, y = 1, i]) = P_{MAN}(s, t) * P_{SURV}$

In the fifth and sixth combination, we should note the P_{AM}^{10} indication the minimum initial batch size in case of a new AM-tool.

Combined transition probabilities

As stated in the introduction, the combined transition probabilities are determined based on the remaining stock level probability and the tool state probability. To obtain the actual numbers, we will enumerate over the possible decision set, starting states, resulting states and periods. For all options, we will compute:

$$p_t([w, r]|[u, s] \wedge [x, y, i]) = P_{t,REM}(r|s \wedge i) * P_{t,TOOL}(w|[u, s] \wedge [x, y, i])$$

6.5 Conclusions

In this chapter, we have developed a stochastic dynamic programming model for sourcing obsolete spare parts. In this model, we have modeled production costs, backorder costs, holding costs and tooling costs as stochastic output of demand and tool survival probabilities. With this model, we can perform our case studies and assess whether RT might have an impact on sourcing these spare parts and if so, how much we can potentially lower the costs. We will do this in Chapter 7.

7 CASE STUDIES

In case studies, we will analyze the results of the model we constructed in Chapter 6. The model is built to minimize the costs of certain parts over the remaining life cycle of the The Company fleet. We want to analyze under which circumstances it might become beneficial to switch to manufacturing parts using AM-tools, instead of the current conventional manufacturing techniques. If the model indicates we should switch to using AM-tools at some point in time, costs over the remaining life cycle will drop.

One of the goals of this research is to indicate the potential cost savings when we incorporate the sourcing possibility of using AM-tools for manufacturing the parts. Therefore, we will evaluate scenarios in which we only use CM with scenarios in which we also allow sourcing using AM-tools. We will calculate the expected cost savings as a percentage of the saved costs compared to the scenario where we only use CM.

Since we face EOS, the fleet size is declining. This fleet size is forecasted until 2021, we deduce a further reduction of the fleet size over the remaining life. The forecasting department indicated that the relatively linear trend currently forecasted is quite likely to continue. Therefore, we expect the fleet to develop as shown in Figure 17. The last year included in the graph is 2030, as this is the last year TCS considers.

(Confidential)

Figure 17 - Fleet development over time

Furthermore, there are some parameters which hold in general for our case studies:

- The daily penalty for a part is calculated by $\frac{180\% * part\ cost}{part\ lead\ time}\ per\ day$.
- The period length is set to a year.
- The holding cost factor for a part is 20% per year.
- The holding cost factor for a manufacturing tool is 1% per year.
- Disposal costs are neglectable.
- The probability a tool is not lost or scrapped, is equal to 98.39%
- Our parts are relatively simple, so we will use a batch inspection cost of €100 when using AM-tools.
- The additional setup/testing costs for a new AM-tool are set to €1,000. –
- We model part costs constant over time.
- We evaluate the situations, for which we do not have any stock or tool available.

7.1 CASE STUDY 1: VACUUM FORMED FLOOR COVER

The first case study will be about a vacuum formed floor cover, for which we can find more information in Appendix F. It is illustrated in Figure 18. This floor cover case study arises from a recently emerged obsolescence case, in which the tool was scrapped after being kept on stock for 20 years because of a forklift incident. Conventionally, this mold is machined out of a solid block of aluminum. As discussed under Section 5.1, FDM would be the most suitable production process for using RT. Stratasys' service-bureau Seido-Solutions gives us the advice to print the mold in ULTEM9085 in case we want to form a polycarbonate sheet, which is the original material. In the subsection below we will further elaborate on the part and its properties.

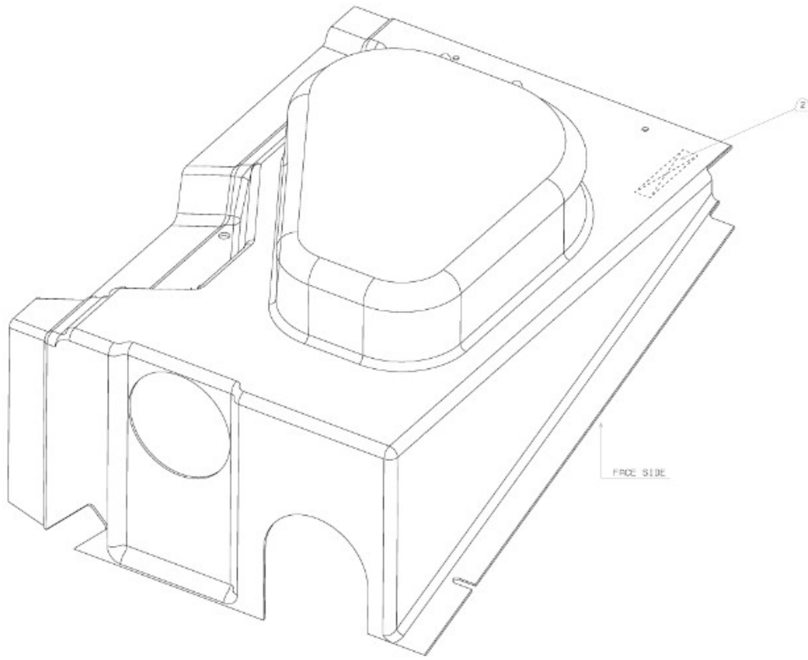

Figure 18 - Vacuum formed floor cover

7.1.1 Part properties and model input

Below, we give the model parameters as included for the first case study. The floor cover is a part with very low demand, with only three parts demanded over the last twelve years as we can see in Table 12. Since we model demand as a Poisson variable, we will start with an expected yearly demand of ¼ part. The floor cover is included in the FX and the FZ, of which we forecast the fleet to develop according to the parameters given in Table 13.

Table 12 - Floor covers demanded over the last twelve years.

Year	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
D86…	0	0	0	0	0	0	0	0	0	2	0	1

Table 13 - Fleet forecast for FX and FZ

(Confidential)

Next to the demand arrival process, there are some other uncertain parameters to consider in the model. These are the tooling lead times and costs, the cost development factor, the number of remaining periods and the failure probability of AM-tools. The ranges have found in indications are given below:

- Conventional lead time of the mold is estimated to be within the range of 4-6 weeks.
- Lead time of the RT estimated to be in the range of 4-7 days (Redwood, n.d.-b). Additionally, we take a week for setting up the tool, leaving a possibility of 11-14 days of RT lead time.
- TCS engineers indicate the conventional aluminum mold to cost between €8,000-€10,000.
- The costs for producing the RT are very uncertain. As described in Subsection 5.1.1, we only found two cost indications for FDM vacuum forming tools. We can find are the ratio of \$:\$\$\$\$\$, which we indicate to mean an FDM-tool would be five times as cheap as a conventional tool (Redwood, n.d.-b). In addition, we found a case with a cost reduction of

91%. Due to an outsourcing markup factor of 300%-400% indicated by Stratasys (2017), this cost reduction for the tool would decrease to 64%-73%. If we also apply this markup to the comparison of Redwood (n.d.-b), we would have a maximum cost for the RT of 80% of the conventional tool. Combining these indications, we obtain a cost range of €2,700-€8,000.

- The cost development factor is indicated to be 25.8%, based on Reimert (2017).
- We will evaluate for $T = 10$, but it is possibly necessary to evaluate until $T = 12$.
- We derive the tool failure probability from a test performed in Stratasys (2017), which used the same tool material for forming a sheet. This tool broke after 23 parts produced. Since we use a cumulative survival probability for AM-tools depending on parts produced ($P_{AM}^{\#parts\ produced}$), we estimate the survival probability per part to be $P_{AM} = 97\%$. $P_{AM}^{23} = 49.6\%$ in this case.

If we take the averages of these indications, we obtain general input parameters in Table 14 and the parameters specific to the lead times and costs of the different sourcing types in Table 15:

Table 14 - General input parameters for vacuum formed floor cover.

Factor	Value
Demand rate	0.25
Period length (days)	365
#Periods remaining	10
Holding cost factor part	0.2
Holding cost factor tool	0.01
Penalty cost factor	180%
Penalty cost/day	€ 19.68
AM development factor	25.8%
Disposal cost part	€ -
Disposal cost tool	€ -
Upper bound for stock	10
Batch inspection costs	€ 100
RT Tool survival prob	97%
Tool keeping prob	98.39%

Table 15 - Input parameters for RT and CM

Approach\Factors	Rapid tooling (RT)	Conventional manufacturing (CM)
Tool cost	€ 5,350.00	€ 9,000.00
Setup cost tool	€ 1,000.00	€ -
Tool Lead time	13	35
Tool holding cost	€ 90.00	€ 90.00
Part cost	€ 874.82	€ 874.82
Part lead time	80	80
Part holding costs	€ 174.96	€ 174.96

7.1.2 Sourcing evaluation

If we use the averaged input parameters, we obtain Figure 19. The initial decision with the least cost is to use CM and to not order any parts regularly. Instead, we wait for a backorder to arrive and we will then only fill the backorder.

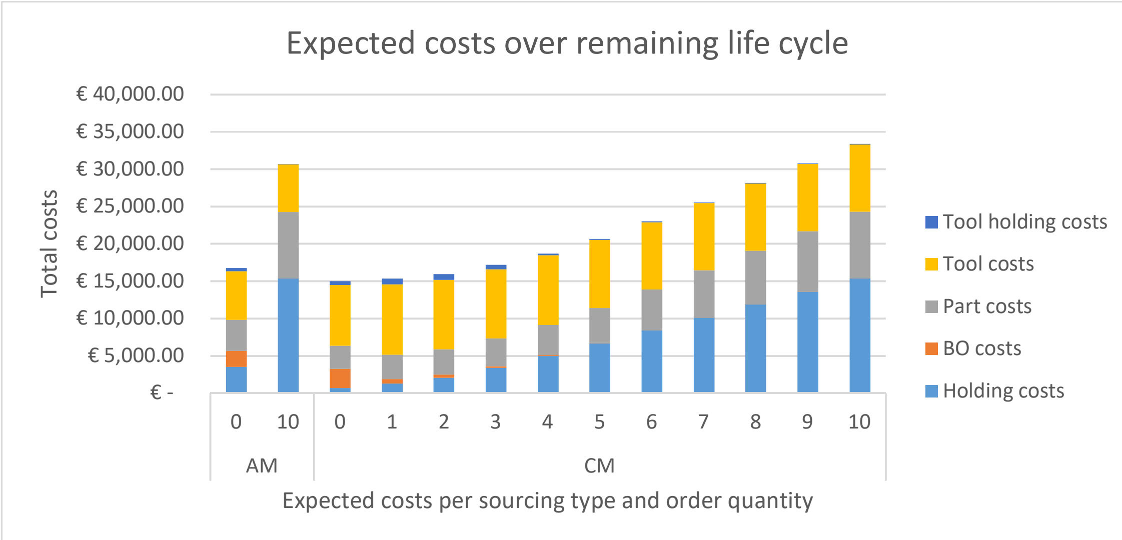

Figure 19 - Possible initial decision costs in state (0,0) based on the average input parameters.

If we compare the costs of the cheapest option per sourcing type, we get Table 16. The option of using AM-tools is 11.5% more expensive than using CM. As we can see, the backorder costs slightly drop and expected tool costs are lower as well. However, this cost advantage is annihilated due to higher expected part costs and moreover, the rise of part holding costs. This is comprehensible, since we must always buy a minimum batch of 10 part if we are using a new AM-tool. The difference becomes even larger if we use AM only. Our model evaluates periodically, and if we can avoid the purchase of an AM-tool in period $t = 1$, we will switch to sourcing using a CM-tool in a later period. The costs of using AM only are expected to be € 18,252.80, which is 21.5% more expensive compared to sourcing using CM-tools only.

Table 16 - Cost comparison of cheapest AM- and cheapest CM-decision.

Production type	Order quantity	Expected HC	Expected BO cost	Expected part costs	Expected tool costs	Expected tool HC	Expected remaining costs
AM	0	€ 3,541.11	€ 2,130.59	€ 4,138.87	€ 6,549.54	€ 385.74	€ 16,745.86
CM	0	€ 655.35	€ 2,589.33	€ 3,124.41	€ 8,135.82	€ 516.63	€ 15,021.54

Table 16 provides an overview for the least costly theoretical case, in which we can still react to an arriving backorder. Nevertheless, our case studies originate from the fact that there has been a backorder already. If we consider this and exclude the possibility to not place an order in the first period, we obtain a different cost comparison. If we look back to Figure 19, we can see that the cost difference for our AM- and CM-options now becomes larger. Our only AM-option would become to buy a batch of 10 parts, at a value of € 32,539.16 for the remaining life cycle, while we can buy just 1 part using a CM-tool, at the of € 17,622.71. Thus, sourcing using AM-tools is almost double as expensive. This increase is mostly due to the excessive holding costs of the resulting parts. Intuitively, there are three causes of the high costs when sourcing using AM-tools. The relatively high part costs are quite an influence in combination with the low demand rate. Because demand is low, parts are kept on stock longer. This causes the high holding costs. If part costs are low, these holding costs are not much of an influence. Another reason for the stock level to be this high, is minimum initial batch size, which is not favorable in low demand situations.

7.1.3 Sensitivity analysis

In our sensitivity analysis, we will vary the parameters regarded as uncertain in Subsection 7.1.1. Based on the results in Subsection 7.1.2, we would initially choose for CM in this case. However, situations might arise in which it is beneficial to use AM-tools. We will not regard all uncertain parameters for this sensitivity analysis. Since we will never opt for an AM-tool in a later period than the first period, the influence of the cost development will be neglectable. We will perform sensitivity analysis on the demand and the number of periods

Period sensitivity

In Subsection 7.1.2, we used 10 remaining periods. At maximum, TCS considers 12 periods. If we evaluate this, we do not see lots of differences in Figure 20. In cost percentages, the differences are between 11.48%-11.94%. We see the same insensitivity if we oblige ourselves to ordering at least one part in the first period, although the cost differences become a lot higher in favor of CM.

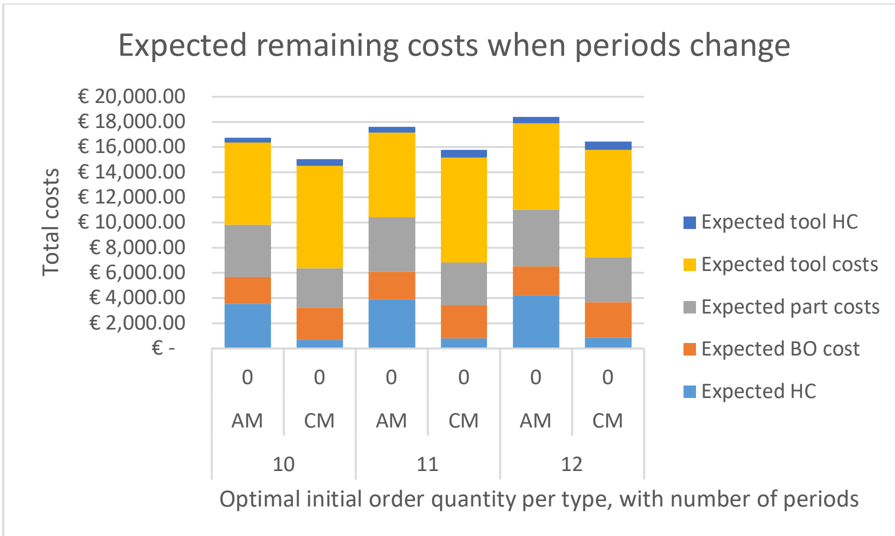

Figure 20 - Cost sensitivity to periods remaining

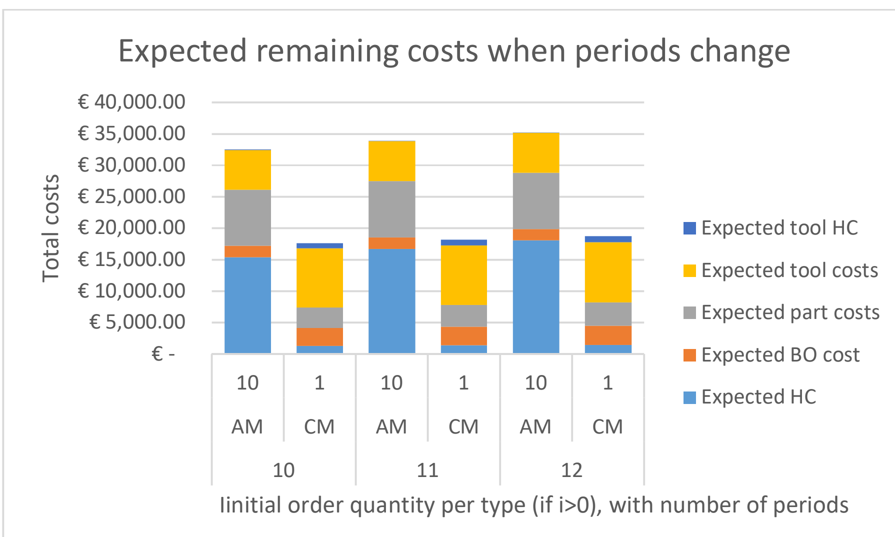

Figure 21 - Expected remaining costs if we must order in the first period.

Demand sensitivity

For the demand sensitivity, we alter the expected demand level somewhat to see how cost differences develop if we would have similar parts as given in the case study, but with different demand characteristics. If we increase demand marginally, we do not observe a lot of difference for the case in which we can still choose to react to a backorder, with a cost difference in favor of using CM-tools between 11.13%-13.61%.

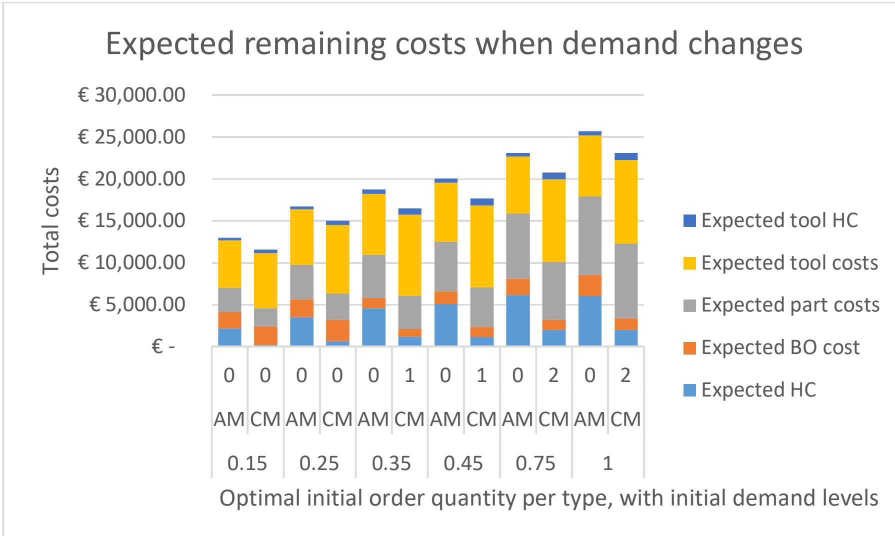

Figure 22 - Expected remaining costs if demand changes.

If we must order in the first period, we make a different observation. As we would expect, the higher demand level reduces the holding costs for when we use AM-tools. We observe that the gap resulting from the holding costs reduces, after which the cost difference stabilizes when we have an initial demand of 1.5. In these cases, we already put initial inventory in stock if we use CM. However, opting for AM-tools in the first period is never considered to be beneficial in comparison to CM alternatives.

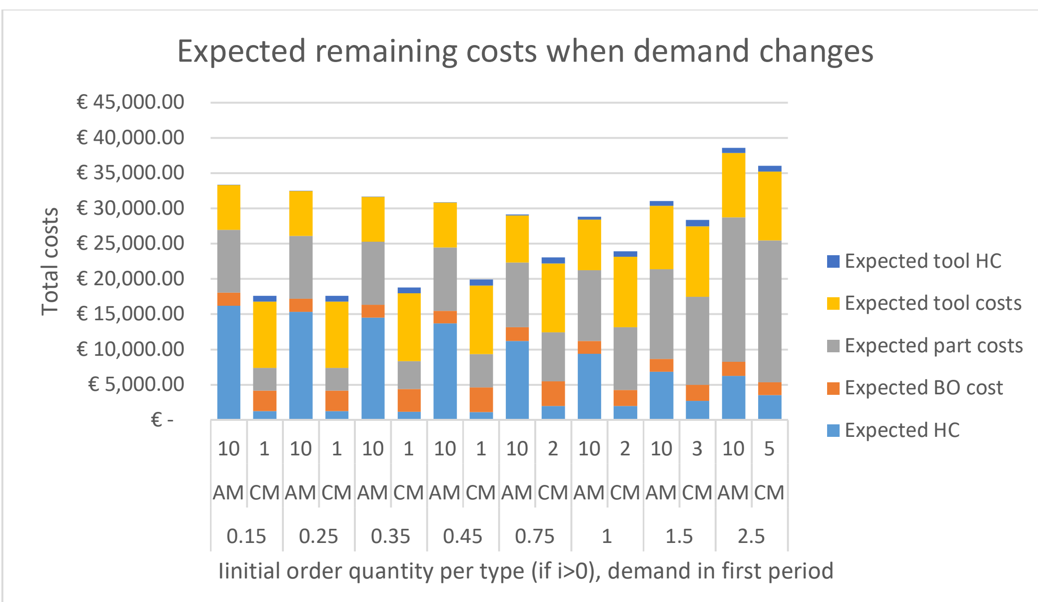

Figure 23 - Expected remaining costs under changing demand conditions

7.2 CASE STUDY 2: INJECTION MOLDED KNOB

Our second case study will be performed on a knob, which conventionally is injection molded. For more information on the part, we redirect the reader to Appendix G. For an impression of the part, we have included Figure 24. In comparison to the part studied in 7.1, this part is much cheaper and it has a higher demand level.

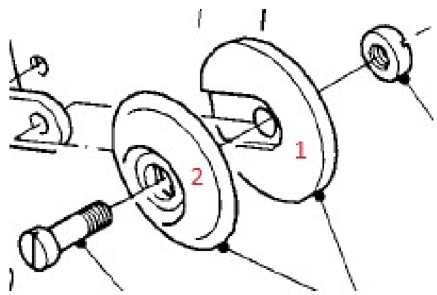

Figure 24 - Knob consisting of the half knobs melted together

7.2.1 Part properties and model input

Below, we give the model parameters as included for the second case study. In Table 17, we can see the historic demand pattern of the part. Although it is very lumpy, we still choose to model it as a Poisson variable, with a demand rate of 4 parts per year, based on 40 parts demanded over the last ten years. In the earlier cases, suppliers have been buying a little more due to an MOQ of 5 parts applied by TCS. It is more accurate to model the demand as a compound Poisson variable, in which the arrival rate and the number of parts demanded per arrival are treated as independent variables. This could cause an increase in backorder costs compared to the current model, as we might face multiple backorders arriving at the same time. The knob is included in all aircraft, of which we forecast the fleet to develop according to the parameters given in Table 18.

Table 17 - Demand pattern of injection molded knob.

Year	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Part F0N..	20	10	0	20	0	0	10	8	0	0	2	0

Table 18 - Fleet development over time

(Confidential)

Next to the demand arrival process, there are some other uncertain parameters to consider in the model. These are the tooling lead times and costs, the cost development factor, the number of remaining periods and the failure probability of AM-tools. The ranges have found in indications are given below:

- Conventional lead time of the mold is estimated to be within the range of 5-8 weeks.
- Lead time of the RT a week (Redwood, n.d.-a). Additionally, we take a week for setting up the tool, leaving two weeks of RT lead time.
- TCS engineers indicate the conventional aluminum mold to cost approximately €15,000. –
- As is the case for the floor cover regarded in the first case study, costs for producing the RT are very uncertain. In Subsection 5.1.2, we found an average cost reduction of 90%. Due to an outsourcing markup factor of 300%-400% indicated by Stratasys (2017), this cost reduction for the tool would decrease to 60%-70%. In comparison to our conventional mold, this would leave us with a tool cost in the range of €4,500-6,000-.

- We derive the tool failure probability from a tool failure test in Stratasys (n.d.-c). If we use the material that is currently also being used for our part, the tool will likely break down after approximately 10 parts. We will give a failure probability of $P_{AM} = 0.9$, yielding a failure probability of 34.9% after 10 parts produced. Additionally, we reduce the upper bound to 10, to avoid producing more than theoretically possible, without the possibility of tooling breaking down.

If we combine the averages above with the given data from TCS, we have the following model input:

Table 19 - General input parameters for knob

Factor	Value
Demand rate	4
Period length (days)	365
#Periods remaining	10
Holding cost factor part	0.2
Holding cost factor tool	0.01
Penalty cost factor	180%
Penalty cost/day	€ 0.66
AM development factor	25.8%
Disposal cost part	€ -
Disposal cost tool	€ -
Upper bound for stock	10
Batch inspection costs	€ 100
RT Tool survival prob	90%
Tool keeping prob	98.39%

Table 20 - Part data input for knob

Approach\Factors	Rapid tooling (RT)	Conventional manufacturing (CM)
Tool cost	€ 5,250.00	€ 15,000.00
Setup cost tool	€ 1,000.00	€ -
Tool Lead time	14	45
Tool holding cost	€ 150.00	€ 150.00
Part cost	€ 29.15	€ 29.15
Part lead time	80	80
Part holding costs	€ 5.83	€ 5.83

7.2.2 Sourcing evaluation

If we evaluate the model for the given input parameters given in Subsection 7.2.2, we obtain Figure 25. As opposed to the other case study, we see little difference in the decision costs over the remaining life cycle. In addition, we see that holding costs are not much of a cost factor. The main difference here is in the tooling costs. There is a difference of approximately €2,800. – in the tool costs (€12,700. – vs. €15,500). The general cost difference between both options is €3,500, in favor of using AM-tools (€15,700- vs €19,200). This is a cost reduction of 22.3%.

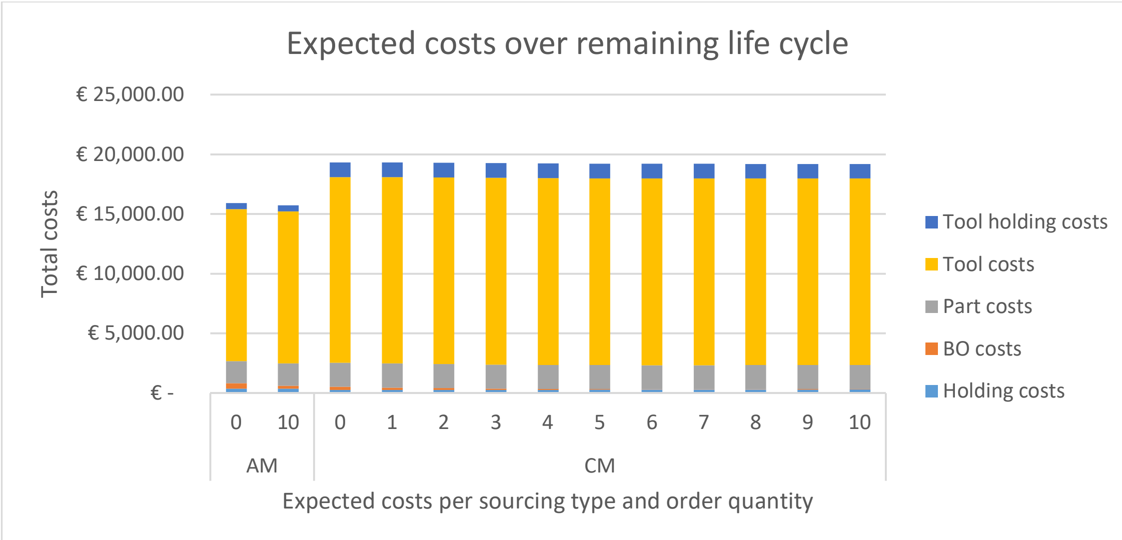

Figure 25 - Expected remaining costs given the input parameters of Subsection 7.2.1.

It is also noteworthy that we have €12,700 in tooling expenses for the AM-case, meaning we should buy approximately 2.5 AM-tools to produce all parts. Even if this is the case, we still have quite a cost saving compared to using CM-tools only. If demand reduces, the cost savings become even higher. This means less AM-tools are needed to produce the resulting parts, therefore reducing the overall tooling costs. If we would use CM-only, we would still need the same number of tools to produce the parts. This is illustrated in Figure 26. In addition, the gap in costs if we have to produce at least one part in the first period, increases greatly, to approximately 100%.

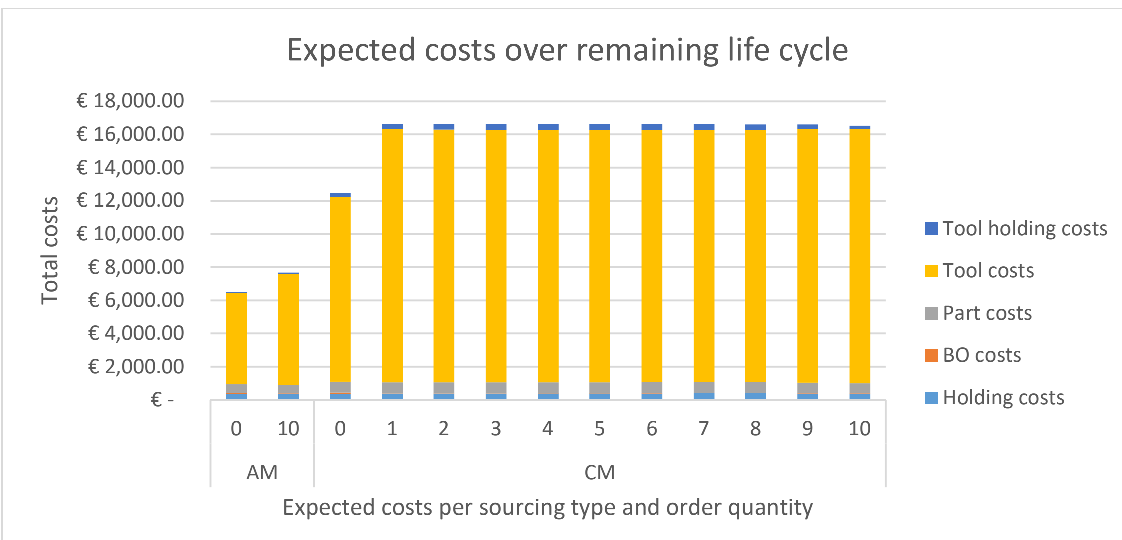

Figure 26 - Remaining costs if demand is 1 instead of 4

7.3 Sourcing intuition

Based on the case studies performed, we can deduce a sourcing intuition for using AM-tools in manufacturing. Both cases perform very differently, based on the demand characteristics and the part costs. The demand characteristics in this case are of much importance, due to the initial batch size of 10 parts if we need to produce using AM-tools. In the first case study, we have seen that relatively high part costs in comparison to the tool costs (10%) leave us with relatively excessive holding costs. Therefore, we think that if part costs are that high relative to the tool costs, one should avoid investing in AM-tools. However, if part costs are low and tool costs are high, it is probably worth the investment in AM-tools, because the holding costs will be low, and initial tooling expenses will be a bigger cost driver.

7.4 Conclusions

In this chapter, we have performed two case studies. Based on the case study results, we believe that it would be wise to first start testing with cheap parts, with high mold costs. If part costs become too high, we risk excessive holding costs for parts on stock, if we need to purchase too much due to the initial batch size. In this case, it is most likely beneficial to use CM for sourcing, instead of trying to use AM-tools for manufacturing.

8 CONCLUSIONS AND RECOMMENDATIONS

8.1 CONCLUSIONS

In this thesis, we have tried answering the research question *"Under which circumstances can AM be used for spare parts production tools and how do the possible solutions compare to the conventional manufacturing solutions?"*

Firstly, we have investigated the problematic production processes for TCS. These were injection molding, sheet metal forming, vacuum forming and die casting. Because die casting needs a metal mold, which is expensive to manufacture using RT, this option was not further investigated. The other options seem to be much more interesting from a theoretical perspective.

To assess if RT could be cost-efficient, we have built a stochastic dynamic programming model, in which we made yearly periodic decisions. Using this model, we have performed two case studies, one on injection molding and one on vacuum forming. The answer to the research question resulting from the case studies is as follows: RT might be a cost-effective solution, in case of low part costs and low demand. If part costs become relatively high, we should consider sourcing using CM, due to excessive holding costs for parts you make in the initial batch.

8.2 RECOMMENDATIONS

It has become quite clear that the current suppliers of TCS are dedicated to their conventional processes. Therefore, it would be wise to invest in putting some suppliers on the approved supplier list. The best case would be if that supplier can produce molds and produce the parts with the molds as well. This would minimize the number of additional suppliers in the system (TCS tries to reduce its supplier base), but give TCS more innovative opportunities.

In addition, we have discussed some potentially interesting applications for RT which we have not researched in more detail, because TCS currently does not use the production process. Nevertheless, soft tool printing (direct or indirect) could provide some very interesting applications, also for metal parts. TCS is very active in ongoing research for direct metal AM and the belief is strong that this provides big future opportunities. Almost all metal parts with a bit of a complex shape are die casted and once a die casting mold is lost, huge costs are incurred for manufacturing a new one if necessary. Investment casting and sand casting are manufacturing methods supported by RT. For investment casting, ceramic molds (which are broken upon use) or wax prototypes could be printed. For sand casting, sand molds (which are broken upon use) or prototypes can be printed. Both manufacturing processes are set up for much lower volumes than die casting and if certification for direct metal AM is still an issue in the coming years, these RT-approaches might be beneficial. Therefore, we recommend researching the introduction of new manufacturing techniques which use RT for manufacturing metal parts.

We also recommend integrating our work with the work already done by Jansman (2017) at TCS. The model of Jansman (2017) uses current cost estimations for the comparison, while a cost development factor is lacking. This could be beneficial for parts with low demand or high investment costs, as direct AM might become the most beneficial sourcing option over time.

Some noteworthy as well is that TCS does not keep track of their tooling for low-demand items well. For their ABACUS-program, this is all organized fine. However, for near-obsolete parts tooling is not properly tracked.

If tooling is missing and TCS want to make a transition to using AM. TCS should also update their part drawings and convert these into CAD-files. TCS parts have drawing specifications, which originate from the time TCS was still and aircraft manufacturer. The suppliers converted these drawings into 3D models to be able to manufacture these components. Inhouse, not much knowledge and skills are available to translate the old paper drawings into 3D models. If TCS wants to be reactive and flexible by using AM technology, the drawing archive should be digitalized and updated to formats like STEP-files.

8.3 RESEARCH LIMITATIONS

In our research, we have discussed the potential application of RT for obtaining spare parts and compared this to the CM alternatives. Initially, the plan was to also compare this to direct AM. Adding this as a third sourcing possibility could have had impact on the costs in the last years of the life cycle, given the fact that we have modelled a cost development factor.

In addition, a limitation exists in the practicability of this theoretical model. This does not account for minimum order quantities (MOQs). MOQs can have a severe impact on sourcing decisions, as it means we might have to purchase an excessive stock or find alternatives for sourcing. The knob of our second case study has an MOQ of 50 parts, which is higher than the expected number of parts demanded over the remaining life cycle. We have neglected this, and have only included a minimum batch size when using a newly manufactured AM-tool. It should be researched if these MOQs will still apply when changing supplier, but in general, we think that costs are possibly underestimated here.

Another limitation of this research is the modeling of the demand pattern. Since the demand for the case study parts is triggered by incidents, a Poisson process seems to be a decent way to model the demand pattern. Nevertheless, demand is usually intermittent and since TCS does not replace the parts themselves, order sizes might be higher than 1 (Dekker, Pinçe, Zuidwijk & Jalil, 2013). We treated each arriving demand separately, but this is not the case in reality. Therefore, we suggest integrating the demand prediction models made by external researchers. These might provide a more accurate forecast.

The last limitation we want to highlight is the failure behavior of tooling. Because of our periodic decisions, we have modeled the failure behavior of RTs based on expected production within a period. Therefore, we could in theory be certain that we produce enough for a last time buy, without the tooling breaking down. This would reduce our decision model to an initial stocking decision, in which the production process with the cheapest tool will always be the cheapest sourcing option. Due to the failure behavior of tooling, this might not be the case.

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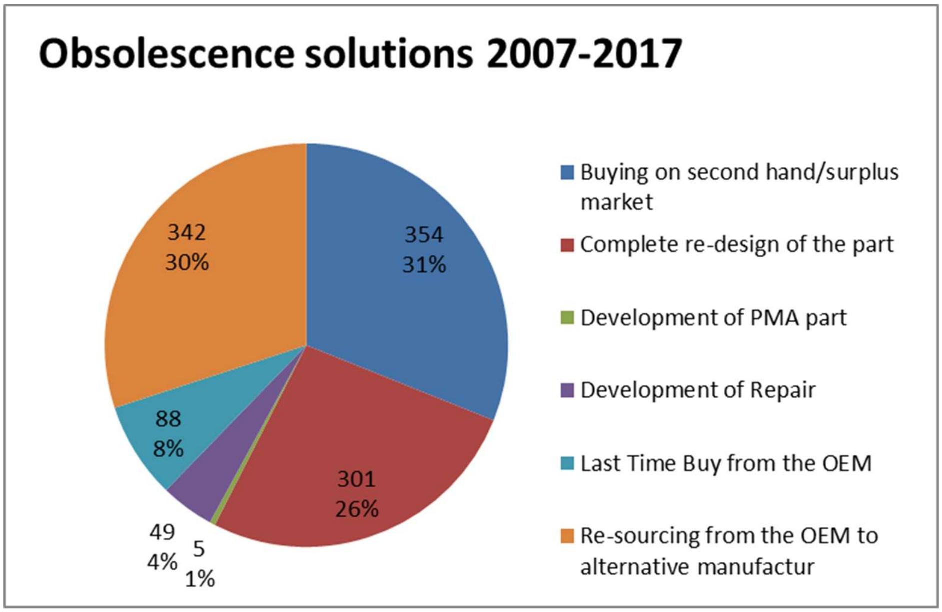
APPENDICES

APPENDIX A: LEARNING OBJECTIVES

A project like this has a lot of learning potential and therefore, we define some learning goals for this project. Firstly, this project gives me a big opportunity to increase my knowledge of the aviation industry, an industry with which I am not familiar yet. Secondly, I want to learn more about supply chain innovation. Lots of the courses I have followed are somewhat conservative and are based on older (generally accepted) methods. Innovation courses were given as electives, but due to my choice for maintenance courses there were no innovation courses in my course package. This is a nice opportunity to learn more about the potential impact an innovation like additive manufacturing can have on the supply chain industry in general. Thirdly, a learning goal is to learn more about the application of VBA. As far as my knowledge goes, VBA is programming language very often used within companies. I have learnt to apply some other languages, but VBA was not one of them (I still had Matlab during my bachelor). The DSS I want to make for The Company needs to be simply applicable by engineers and therefore, VBA will be used. It is a nice challenge to learn this during the project. And finally, a learning objective will be to put theory into practice and make theoretical findings practical for business application.

APPENDIX B: OBSOLESCENCE CASES

Below, the amount of obsolescence cases for TCS from 2007-2017 are given. In addition, the seven steps considered are elaborated upon.



1. The last time buy (LTB) is an order from the final production run of the original equipment manufacturer (OEM). At the end of the service time, TCS has the risk of having either too many, or to few parts, which will result in additional costs.
2. The second-hand market is the market of parts from unused inventories, or from scrapped aircraft. Parts from the second-hand market are considered slightly inferior to new parts, because of quality issues. Because the number of scrapped aircraft is increasing, this market is expected to grow.
3. Resourcing is finding a different manufacturer that can produce the same product. The price of resourced parts will be higher than the price of parts from regular manufacturing.
4. A Part Manufacturer Approval (PMA) is an approval to produce a part, even though TCS is not the OEM. This option is more expensive, because it needs reverse engineering of the part, and legal work to get the PMA.
5. Development of a repair means that a procedure is developed to repair the part. Because of quality issues, repair is not considered the preferred option for every item.
6. Redesigning a part means that the part is produced with different materials or procedures. This option requires additional engineering costs, and extra costs due to aviation certification.
7. Redesigning the system means that a complete system of an obsolete part is redesigned. Again, the costs of this solution are higher due to additional engineering and certification costs.

From the pie chart, we can see that redesign of the system has not happened in the given period. In addition, development of PMA has also been used just once every four years. Other options are used a little more often, with approximately equal amount of times for the choice or buying on the second-hand market, redesign of the part and resourcing from the OEM to an alternative supplier. Furthermore, from the amount of times an LTB is used, we can conclude that obsolescence is in general managed quite reactively. However, active management would be more cost effective. Li et al. (2016) try to predict these cases, but the implemented model is not very effective for most of the parts becoming obsolete. In Sterkman (2015), it was stated that a prediction can just be done for a very small subset of parts, below 10%. This is because we need historic demand to make these predictions.

Appendix C: Production Organization Approval Schedule

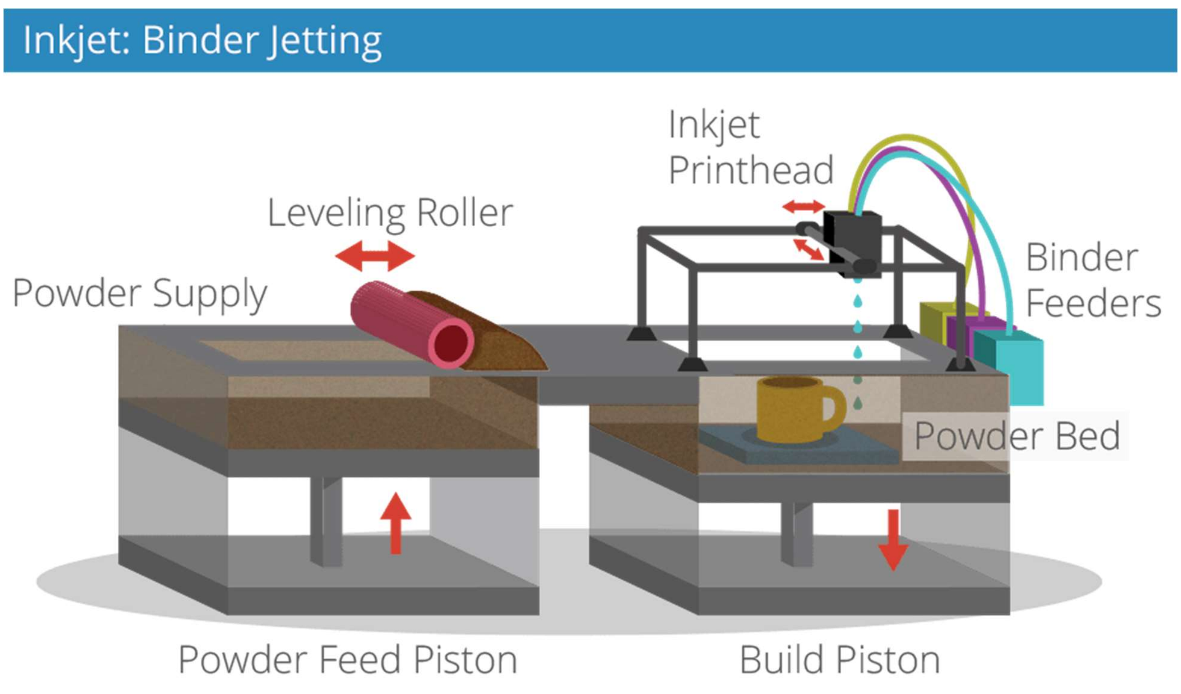
Left out due to confidentiality.

Appendix D: AM technologies that can be applied for RT

As discussed throughout the paper, some technologies are applicable for RT applications within this thesis and some are not. In general, the metal printing applications can be applied for rapid tooling, but these are tools that fall under the hard tooling category. This would be interesting for high demand situations which do not occur for the obsolete parts this thesis is focused on. Therefore, other printing methods are discussed below. The brief explanations and the figures are derived from 3D Printing Industry (n.d.), except for the large area maskless photopolymerization example, which is not displayed there. The explanation of that technology is derived from DDM Systems (n.d.).

Binder Jetting

Binder jetting is an inkjet-like technique. In binder jetting, a binder is jetted and selectively sprayed on a powder bed of the part material to fuse it a layer at a time to print the desired part. After each layer, the building platform is dropped a little bit and a roller distributes a new layer of the material to be sprayed by the binder. This then fuses the new layer on top. The powder acts as support material, so we do not need support structures to be printed in addition to the final part. Furthermore, the amount of material that this printing process is widely varied. Ceramics and even food can be printed using the binder jetting technology. Furthermore, a lot of colors can be used and added. A problem occurring when using this process is the durability of the parts. Parts printed with the binder jetting process are not very strong. Therefore, it is for example used in the process of printing sand casting molds, which are broken after using them once.



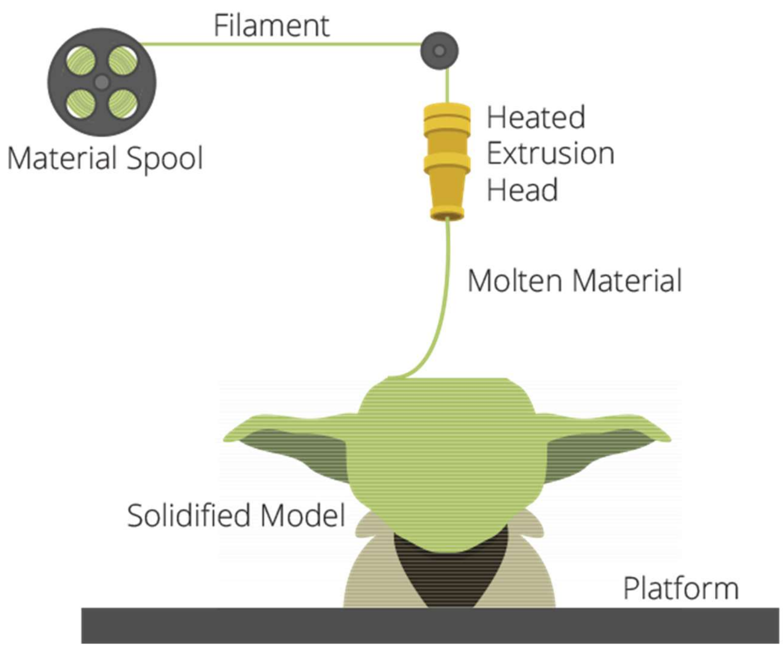
Fused Deposition Modeling (FDM)

FDM is a trademark name initially patented by Stratasys. Thermoplastic material is extruded out of a heated nozzle and the molten material is added layer by layer, as we can see below. This is the most common AM process in the field. FDM is the most commonly used name, but since it is a traded name, companies using similar processes usually refer to it is Freeform Fabrication (FFF).

The process deposits material using a heated extruder and the plastic filament extruded is dropped one layer at a time, bonding to the layer deposited below while hardening. Stratasys has developed a lot of industrial grade materials for use with the FDM process. Other market competitors must do with less materials, but PLA and ABS are quite common materials to use when using FDM.

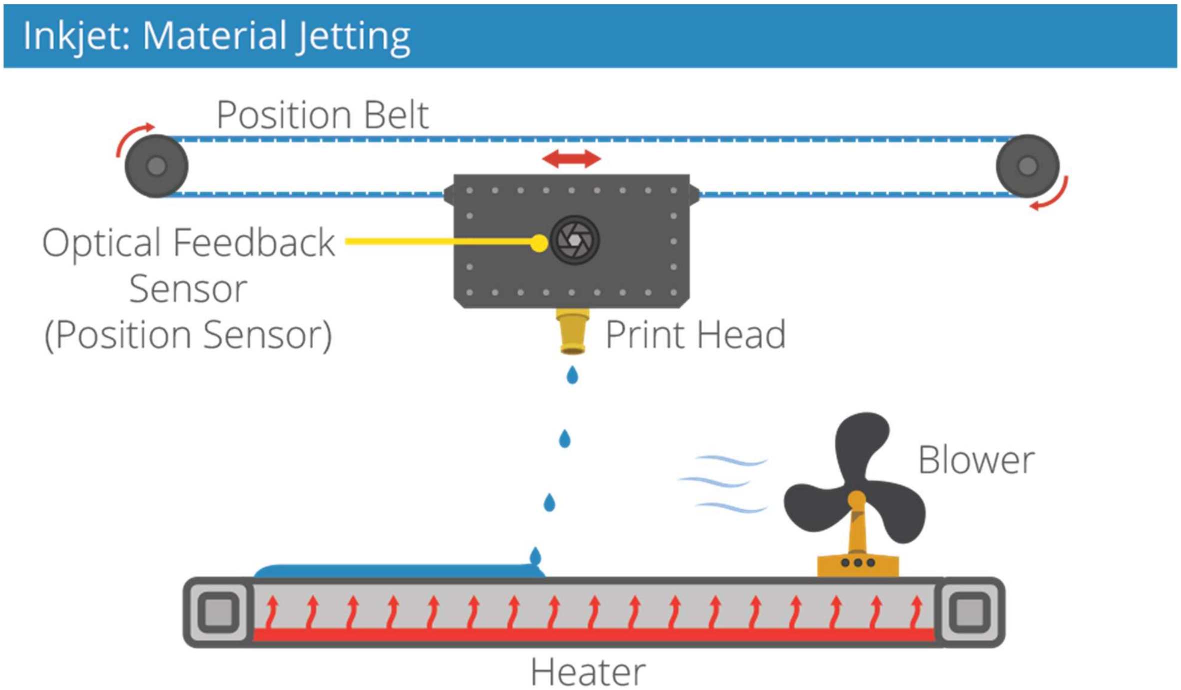
When using FDM, support structures should be printed with it as well. Overhanging geometries (like the ears if the Yoda being printed in the figure) would need a support structure to be printed with the final part to make sure the part gets its desired shape. This means that a second material is printed from a dual extrusion head in conjunction with the material needed for the part. This support material can then be broken off or washed away after printing.

This support material printing is quite a disadvantage, just as some other post-processing steps that might be necessary to obtain a final part. Furthermore, FDM is fairly slow for some part geometries and the adhesion of the layers can become a problem sometimes. Post-processing with acetone should resolve this issue. Advantages of this process are the accuracy and its reliability. Furthermore, it is relatively office/studio-friendly.



Material Jetting

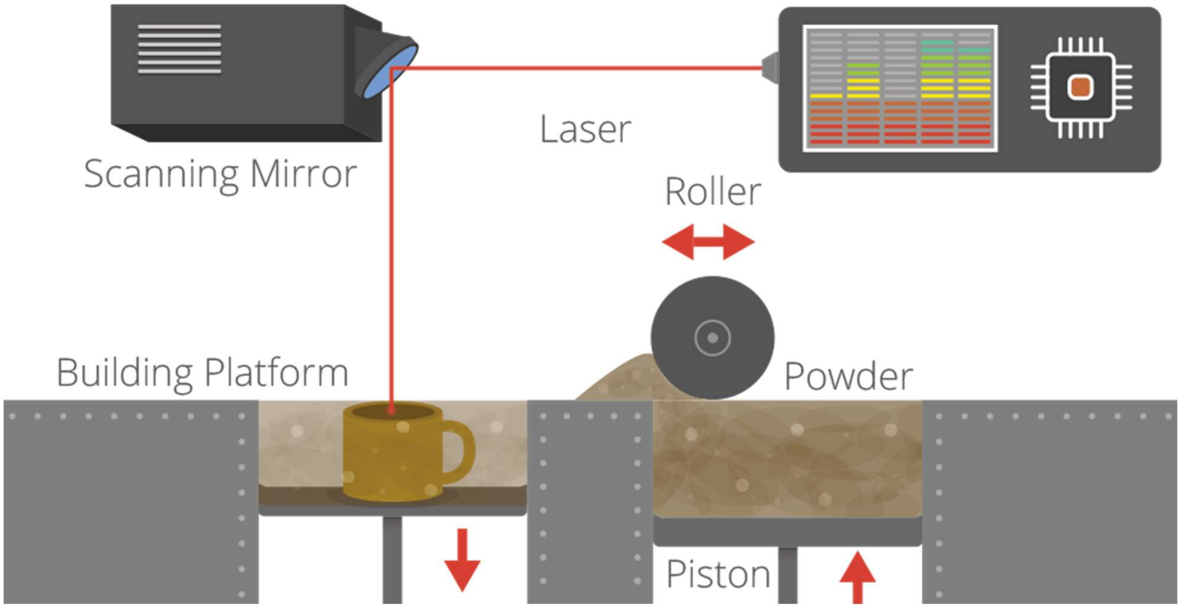
The material jetting process is a process in which the actual build materials are jetted through multiple heads simultaneously, with other print heads simultaneously dropping support materials. The materials are usually photopolymers, which are cured using UV light, one layer at a time. Material jetting is capable of depositing multiple materials simultaneously, meaning we can make parts consisting out of multiple materials with different characteristics and properties. Furthermore, the printing method is very accurate and surfaces are very smooth.



Selective Laser Sintering (SLS)

SLS is an AM technology that uses a powder bed for printing an object. A laser is projected on this powder bed to selectively sinter some of the tightly compacted metal powder particles. The laser moves along the X-Y axes and after sintering of a layer, the building platform slightly drops. Then a roller rolls a new layer of powder over the building platform, which is sintered on top the currently built structure, connecting the layers.

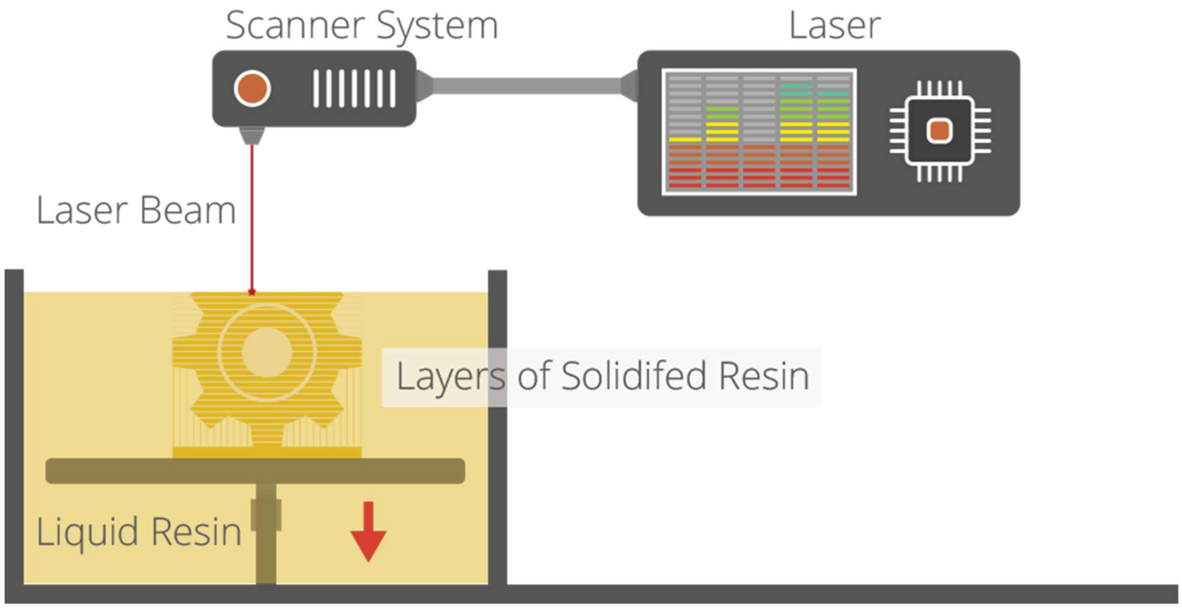
The build chamber of the machine is completely sealed, because of the precise temperature at which the process must be executed, specific to the melting point of the material to be sintered. The powder bed is removed as a whole and afterwards the excess powder is removed to leave the printed structures. During the process, this excess powder material acts as a support structure. Therefore, very complex structures are easily to obtain. A negative is the excessive cooling time needed because of the high temperatures at which the sintering process takes place. Historically, the porosity of the part also has been an issue. Developments have been made to obtain fully dense parts, but a lot of parts still need infiltration with another material to improve the mechanical properties. Metal and plastics can be produced using this process. Parts are generally quite strong, but surface finish and accuracy is lacking.



Stereolithography (SLA)

Below we can see the setup for a simple SLA case. It is the first AM-process that has been commercialized, by 3D Systems. It is a process that is controlled by a laser that beams on layers of liquid photopolymer resins. These react with the laser, curing it to become a solid on the places where the laser hits the resin. This is a very accurate process. As we can see in the figure below, the object to be printed rests on a platform that is moving down within a vat. This platform starts at the top, with one layer of resin on it. After this is cured, the platform moves down a layer, so that the next layer of liquid resin can be cured on top of the already cured structure on the platform. The beam itself can only move along the X-Y axes across the surface, but in conjunction with the platform, it can create objects in three dimensions.

SLA is a process in which support structures have to be printed for some objects, especially if they have overhangs or undercuts. These need manual removal after the printing process has finished. Other post-processing operations necessary after using SLA are cleaning and further curing in an oven. These operations are considered to be a disadvantage for using SLA, as is the material brittleness that develops over time. Advantages are the accuracy and surface finish of the resulting structures when using this process.



Large Area Maskless Photopolymerization

Large area maskless photopolymerization processes photocurable ceramic suspensions by illumination. It is a fairly recently developed technology by Georgia Institute of Technology. A UV light source selectively illuminates pixels on a ceramic suspension, which causes local polymerization. It can be used to build complex ceramic parts directly from CAD data and is specifically designed to be a disruptive technology in the area of investment casting.

According to its own site, the large area maskless photopolymerization system achieves the exacting tolerances and shape requirements inside and out for high precision application and integral-cored molds (DDM Systems, n.d.). After post-processing with binder burnout and high-temperature firing, the ceramic articles are ready for their intended application, investment casting. No additional hard tooling or handiwork is required to do so.

Appendix E: Certification procedure

Left out due to confidentiality.

Figure 27 – Certification classification

APPENDIX F: FLOOR COVER

The floor cover of the case study is given below to give an indication of what the part looks like. This is place in the appendix, because it will be left out of the public report.

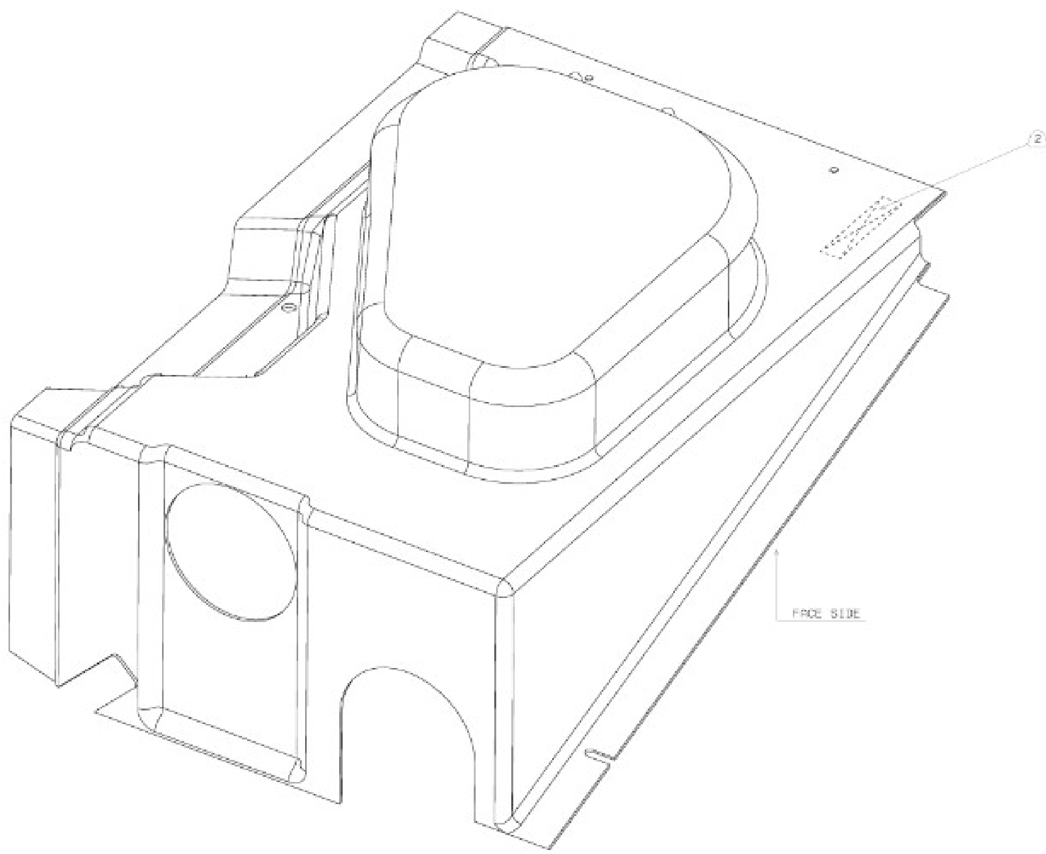


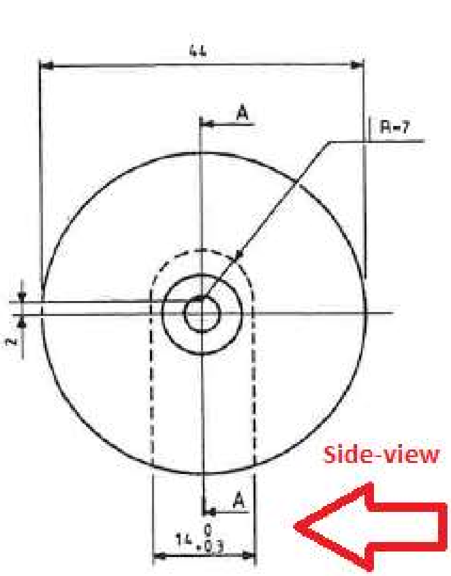
Figure 28 - Vacuum formed floor cover

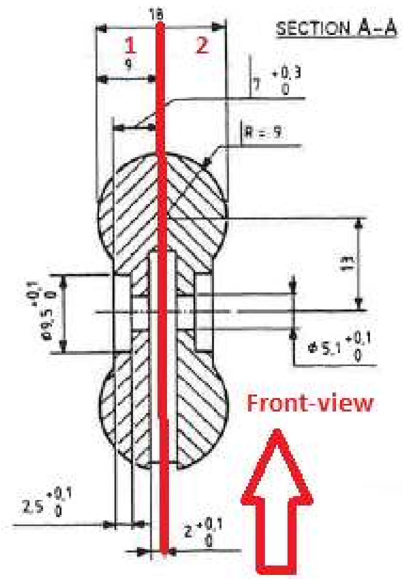
Some of the part specifications are given below:

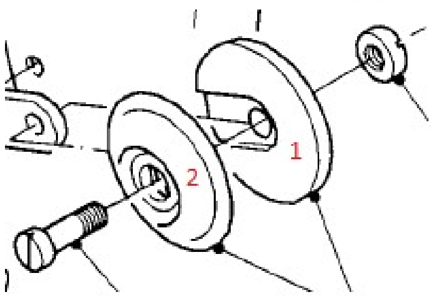
- The part is made of a 3-millimeter-thick polycarbonate sheet.
- The tolerances are $\pm 0.5\ mm$.
- This part is not considered to be a structure part. The floor cover is part of an air-conditioning covering system and it is not possible for any personnel or passenger to put load on the part. Parts can fail, because of leakage in other systems (air conditioning or air bleed systems) causing damage and plastic deformation of the part.
- The technical documentation allows thermoforming (and thus also vacuum forming) molds to be made from plastic.
- To obtain the part, two manufacturing tools are necessary. Since trim operation can be done without tool, we neglect the tool.
- One aircraft has one of these parts built in.

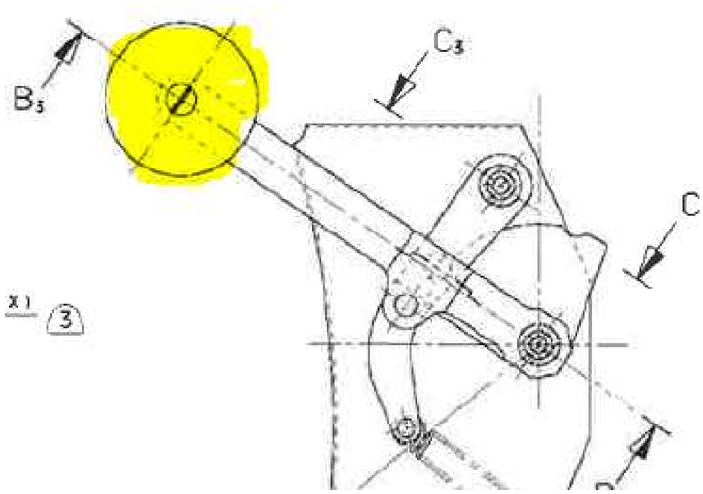
APPENDIX G: KNOB FOR CASE STUDY

The knob of the second case study is given below to give an indication of what the part looks like. This is place in the appendix, because it will be left out of the public report. Multiple views are included to give an impression of how the part looks. It is a knob of a handlebar, built out of two parts.









Some of the part properties are given below:

- To obtain the part, three manufacturing tools are necessary. The part manufacturer keeps a tool list in which the manufacturing tools for all parts they make are listed. In this list, the part numbers of the manufacturing tools are missing.
- The part is built out of two symmetrical halves, which means we need to use the injection mold twice to obtain one part.
- The part is made of polyamide 6 (PA-6), better known as nylon.
- One aircraft has one of these parts built in.

APPENDIX H: AVERAGE ENCOUNTERED LEAD TIME FOR BACKORDERS

In this appendix, we elaborate further on the possible penalty scenario for backorders and the lead times the backorders will encounter on expectation during production of tooling, parts or a combination of both.

As stated in the main report, we can determine the encountered lead time fraction by conditioning the Poisson arrival process on the number of arrivals in a fixed interval. If we do so, the arrivals are on expectation uniformly distributed on the interval. We can see this schematically in Figure 29. We have four interarrival timeframes and three interarrivals. If we define Z to be the length of period t, then A, B, C and D are all equal to $\frac{1}{4}Z$. This generalization holds for all homogeneous Poisson arrival processes.

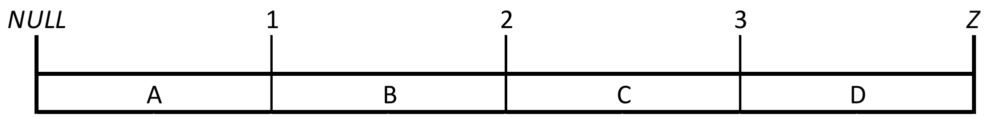


Figure 29 – Poisson arrival point distribution

For scenario 1, this will not apply. We do not order everything and have a manufacturing tool in stock. Therefore, every backorder will be filled with expedited production and they will face full part lead time. For the other scenario's we need to determine a lead time fraction for the backorders during lead time. The possibilities for demand during lead time are as follows:

- Scenario 2: During the lead time of the manufacturing tool
- Scenario 3: During the lead time of the part(s)
- Scenario 4: During the lead time of the manufacturing tool and the part(s)

The expected backorders during lead time are dependent on the stock level s, the number of regularly ordered replenishments i, the demand d, the period t and the lead times for the tools and parts. If $s \geq d$, no backorders will occur during lead time. In any other case, we have an expected lead time fraction, as we have already introduced in Section 6.4.

The fractions for the different s, i and d are given by:

$$LTFrac(s,i,d) = \begin{cases} \dfrac{d(Z)+1-s}{2(d(Z)+1)}, & if\ s+i \geq d(Z)\ and\ s < d(Z) \\ \dfrac{\sum_{n=1}^{i} d(Z)+1-(s+n)}{i(d(Z)+1)}, & if\ s+i < d(Z) \end{cases}$$

We have derived the upper statement of $LTFrac(s,i,d)$ by entering the number of parts on stock and demanded into an Excel-sheet. We conditioned on i to be sufficiently large to fulfil all demands during lead time. What happens then is already shortly introduced in Section 6.4. We illustrate it again by referring to Figure 29. If $s = 0$, the expected uniform distribution of the arrivals means we expect the lead time fraction of those arrivals to be equal to $\frac{1}{2}Z$. If $s = 1$, we have on average already passed period A. This means that we have $\frac{3}{4} * \frac{1}{2}Z = \frac{3}{8}Z$ left as the expected lead time for the backorders. If $s = 2$, we have also passed period B. This leaves us with an expectation of $\frac{1}{2} * \frac{1}{2}L = \frac{1}{4}L$. The same principle goes for any number of interarrivals, with the interarrival periods being equal to $\frac{1}{\#arrivals+1}Z$. If we condition on this, we can generate Table 21.

Table 21 - Fraction of lead time encountered by backorders, given the stock level

d\s	0	1	2	3	4
1	2/4	-	-	-	-
2	3/6	2/6	-	-	-
3	4/8	3/8	2/8	-	-
4	5/10	4/10	3/10	2/10	-
5	6/12	5/12	4/12	3/12	2/12
6	7/14	6/14	5/14	4/14	3/14

In this table, we can see that the denominator is always given by $denominator = 2(d(Z) + 1)$. The numerator is given by $numerator = d(Z) + 1 - s$ in all cases, which leaves us with the formula given below:

$$LTFrac(s, i, d) = \frac{d(Z) + 1 - s}{2(d(Z) + 1)}$$

This formula is logical, given the Poisson property of uniformly distributed arrival points within an interval we described earlier. If we have d demand arrivals in period Z, we will always have $d + 1$ interarrival periods between $NULL$ and Z. If the stock level is zero, $LTFrac(s, i, d)$ will always be equal to a half, since the denominator is always twice as big as the numerator. Under marginal increase of s (stock addition of 1), $LTFrac$ will always result in half the fraction of the time fraction left in which backorders might occur.

If we condition on $s + i < d(Z)$, we get a somewhat different equation. The last number of $d - (s + i)$ arrivals will be filled by expedited production backorders. We have found that the backorders that can be filled with the replenishments will follow:

$$LTFrac(s, i, d) = \frac{\sum_{n=1}^{i} d(Z) + 1 - (s + n)}{i(d(Z) + 1)}$$

This statement conditions on the number of remaining periods after the arrival has come. We illustrate this in Figure 30, in which we condition on four arrivals.

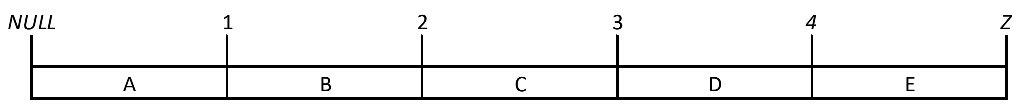


Figure 30 - Arrivals over a fixed interval Z

If we have no stock on hand and have ordered two parts regularly, the first arrival will have $\frac{4}{5}Z$ left and the second arrival will have $\frac{3}{5}Z$ left. The remaining arrivals will come from expedited production and have full part lead time. Therefore, the average lead time for the backorders that can be filled with the regular order are equal to $\frac{\frac{4}{5}+\frac{3}{5}}{2}Z = 0.7Z$, this is equal to:

$$LTFrac(0,2,4) = \frac{4 + 3}{2(4 + 1)} = 0.7$$

If we would have had a part in stock, the first arrival can be scrapped from the equation, which leaves

$$LTFrac(1,1,4) = \frac{3}{1(4 + 1)} = \frac{3}{5} = 0.6$$

If we would have ordered an extra part in comparison with the first illustration, we would have obtained $\frac{\frac{4}{5}+\frac{3}{5}+\frac{2}{5}}{3}Z = 0.6Z$, which is equal to:

$$LTFrac(0,3,4) = \frac{4+3+2}{3(4+1)} = 0.6$$

What we practically do is integrate the denominator of the upper sum into the denominator of the complete term by multiplying both. If we then return to the expected lead time fraction for backorders during demand in a period, we obtain

$$LT_{BO}(t,s,i) = \frac{\sum_{d=1}^{UB} p_d(t) * LTFrac(s,i,d)}{\sum_{d=1}^{UB} p_d(t)}$$

However, this does not address the full lead time fraction possibility under scenario 4. It could be the case that demand arrives during tool production and all demand to cover i has already arrived, in this case, the expedited production backorders also encounter a part of the tooling lead time. Therefore, we additionally include $LTFrac_4(s,i,d)$. For an illustration, we return to our example of $LTFrac(0,2,4)$, the third and fourth arrival, which would have $\frac{\frac{2}{5}+\frac{1}{5}}{2}Z = 0.3Z$. As we can see, this is equal to $1 - LTFrac(0,2,4)$, thus we define $LTFrac_4(s,i,d) = 1 - LTFrac(s,i,d)$. For an expectation value, we derive:

$$LT_{BO4}(t,s,i) = \frac{\sum_{d=s+i+1}^{UB} p_d(t) * LTFrac4(s,i,d)}{\sum_{d=s+i+1}^{UB} p_d(t)}$$

This will mean that we enumerate over specific numbers of backorders occurring under certain stock levels and the given arrival rate.