Additive Manufacturing for SRU production in a maintenance environment

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Management Summary

Additive manufacturing (AM) has been used in industry for prototyping, but usage in production parts has been limited. With the ongoing research in AM the possibilities for the usage of AM-produced parts increase, and industries are looking for ways to implement AM in the best possible ways. The Company (TC) operates in the airline industry, where regulations on replacement parts are strict. Aircraft are designed decades ago using conventional manufacturing techniques (CM), and the regulations state that the same parts still need to be used when repairing and maintaining the aircraft. Changes from the original parts to an alternative part, whether produced using CM or AM, requires testing of the new part to ensure its strength and durability. In the case of AM production, this process needs to be more extensive because of the new characteristics of the production method.

In earlier research, usage of AM in load bearing parts and tooling has been tested. The results of these researches were that the investment costs for load bearing parts are too high to make up for the increased supply security and cost effectivity of AM production. TC wants to investigate if parts with less regulations have potential for AM production. Printing of these parts can then be used to expedite the repair processes. Within TC, small parts or Shop Replaceable Units (SRUs) are used in the repair of aircraft components parts or Line Replaceable Units (LRUs). These LRUs have the same airworthiness regulation as loadbearing parts, but the SRUs are less regulated and can be approved for production by TC.

TC wants to know if AM produced SRUs have a competitive advantage over CM produced SRUs in the supply chain. To test this hypothesis, the following research question has been formulated:

> **'Under which circumstances/criteria can AM be used to produce SRUs used in a maintenance environment and how do the possible solutions compare to conventional manufacturing'**

We split the research in two parts. The first part focusses on single SRU repairs, where each LRU is repaired by replacing one failing SRU. In the second part we extend this model to accommodate LRU repairs where two or more SRUs are replaced in one LRU repair.

LRU repairs with a single SRU

For both conventional and additive sourcing we use the same model where a fixed order quantity is placed whenever the inventory position reaches a predetermined reorder point. In case of a stock-out, all demand is backordered and served when a shipment arrives. Using this backorder model, we can use steady state equations to calculate the expected service level and costs for any given set of reorder point and quantity.

A third option is a variant of AM, where emergency shipments are allowed. Using the fact that no tooling is needed for AM production, and production can start when needed, production can be started at any time and at any AM service provider.

When facing with a stock-out, we can thus, instead of waiting for a part to arrive, order the same product at another AM service provider at higher costs and a shorter lead time. This fast resupply option is modelled by a lost sales model where regular demand is served with the regular AM part, and stockouts are lost to the original system and served by the emergency order.

Next, we perform a sensitivity analysis on the additive parameters. This sensitivity analysis gives break even points under which conditions either a change to another souring method is recommended, or the service level is violated. The results of this sensitivity analysis give an overview on the allowable ranges and thus on the robustness of the estimated additive parameters.

A case study is performed on two SRUs, both of which have AM production costs and lead times smaller than the CM characteristics. For both parts, switching to AM is the preferred option, with the fast resupply being slightly more expensive than the standard backorder option.

LRU repairs with multiple SRU replacements

When two SRU replacements can occur in a single LRU repair, there exist dependency between two SRUs. An order consisting of both SRUs will thus only be completely handled if both SRUs are available. The performance of thus dual-SRU order is lower than a single SRU order. A model is created that calculates the order fill rates of all possible orders, and evaluates all different combinations of AM and CM production.

Since both SRUs in the single-SRU case study are part of the same LRU, we used them to evaluate the multiple SRU model. Using the reorder levels of the single SRU model as starting point, we can show that the performance of the multiple SRU order is below target, and stocking policies need to be recalculated. This results in higher reorder points and higher total costs than by using the single SRU model.

Conclusions

Our model is able to check if current conventional produced products can be replaced by products constructed using additive manufacturing. This can be done on an LRU-level and will mainly be used when information about changing prices or lead times reach TC, at which time a decision can be made to continue using the conventional product or to change to additive production of the product. Large scale implementation of this problem can be achieved by implementing the comparison between two different supply options in the stocking tool currently in use at TC. To do this, the estimation of AM parameters needs to be automated, and the current stocking level optimization program needs to be adapted to incorporate decision making between two versions of the same part.

Notation overview

Input parameter	Symbol	
Maximum SRU waiting time in months	a	
LRU backorder costs per month	c_{BO}	
Fast resupply cost increase factor	c_{speed}	
Demand during lead-time	D_L	$= m \cdot L$
Demand during effective lead time	$D_{L'}$	$= m \cdot L'$
Expected backorders	EBO	
Fill rate	fr	
Inventory level	IL	
Incremental order quantity	IOQ	
Inventory position	IP	
Order set	K	$k \in K$
SRU production lead time in months	L	$L' = Max(0, L - a)$
Fast resupply lead time decrease factor	L_{speed}	
Mean SRU demand per month	m	$= \mu_{LRU} \cdot rr_{SRU}$
Minimum Order Quantity	MOQ	
On time completion rate	OTC	
SRU purchasing price	p	
Lot size	Q	
Replacement rate	rr^k	
Reorder point	S	

Contents

1 Introduction

This Master thesis focusses on the use of Additive Manufacturing at The Company. We research the value to use AM in the repair of aircraft components. In this chapter, the company is introduced, and an introduction is given on additive manufacturing and the parts under consideration.

1.1 Company description

In The early years of the twentieth century, The Company was founded and the business grew into one of the leading aircraft manufacturers worldwide. TC has built aircraft for both military and commercial use. Upon their bankruptcy in the nineties, four aircraft types were still in production. After the aircraft builder's bankruptcy, the company was split up into four different business units. This research will be conducted at TCs service provider.

Customers of TC are airlines, original equipment manufacturers (OEMs) and maintenance, repair and overhaul services (MROs). The company's goal is to keep the Company's aircraft fleet operational and to design, maintain, certify and repair components to assure safe operations. In addition to the company's own fleet, TC also maintains other aircraft types.

TC is the type certificate holder for its own aircraft. This means that TC is certified to (re)design components, and to approve these components with a Certificate of Airworthiness. Issuing airworthiness is done with respect to EU and US regulations, set by the European Aviation Safety Agency (EASA) and Federal Aviation Administration (FAA).

1.2 Additive Manufacturing

Traditionally, parts were created by the removal of excess material (turning, milling) or casting of liquid material into molds. These production techniques are however slow due to long setup times or are only profitable when using large batch sizes due to high fixed costs. Additive Manufacturing (AM), or 3D printing, on the other hand creates products by building them layer by layer.
In the early years of AM, it was mainly used as a rapid prototyping technique, while its usage in production parts was minimal. Recently, AM became more acknowledged as a means to produce parts to temporarily repair broken goods until the regular product becomes available again, or as a permanent production alternative. In these instances, the short production lead time can reduce the time to market or can reduce the need to take inventory to remote locations while keeping high availability.

Production using AM can have many benefits. Since every product can be produced one by one due to low setup costs, it is possible to change the design to meet the needs of each individual customer. Because of the layered production, the design can be more complex than with other production techniques, without adding additional production time and costs. As a result of the design flexibility and geometric complexity, is becomes possible to consolidate parts into larger components, where savings can be achieved in the time required to assemble or the total weight of the parts. AM products can be produced without startup time and costs. This means that a part can be produced when needed, and no economic order sizes have to be produced, reducing the inventory costs. (Gao, et al., 2015)

1.3 Spare parts production at The Company

Because TC is the type certificate holder of the its aircraft fleet, they are certified to make changes to the design and maintenance for these aircraft. These certificates can be divided in three different certificates:

Part 21J, part 21G and part 145, and describe the capabilities of firms and their allowance to make changes to aircraft. The certificates are described below.

Part 21J (design),

> EASA part 21J describes the capability to design aircraft. TCs aircraft building has seized, but this certificate makes it possible to redesign parts of an aircraft and to approve these changes for production.

Part 21G (production),

> EASA part 21G describes the capability to produce parts for use in the aerospace industry. When TC subcontracts production to a third party, this company will have to be Part 21G certified too.

Part 145 (maintenance)

> EASA part 145 allows companies to maintain aircraft and their components. Inhibited in this certificate is the right to produce parts needed in a maintenance task, but excluding the production of parts to put on stock.

TC holds part 21G and 145 for all aircraft types with which it works, and part 21J for its own fleet. This means that they are capable to produce and maintain every component by themselves. They are therefore able to repair components using on-site produced parts. For their own aircraft, they are also allowed to redesign a part in order to improve its characteristics and/or reduce the costs.

Part 145 implies that, in order to finish a repair in time, a repair may be completed with other parts than originally used. These redesigned parts must still comply with regulations stated in Parts 21J and 21G, and are therefore fully airworthy. However, since the design of these subcomponents is not officially approved, these parts are not to be sold independently, and may only be used and sold as part of a larger subassembly. The repair bill sent to the customer will tell the customer that the component is repaired using alternative parts. When the same component is later on sent to another service provider, this part may be recognized as non-original, and replaced with an original part if deemed necessary by the other service provider.

Because of the allowance to finish a repair with a non-original product, the production run of these products is limited to the needs for the current repair. This means that it is not allowed to make use of economies of scale to put these alternative parts on stock. The reason behind this is that the original part is approved for usage, and is therefore seen as the optimal and favorable part and should therefore be installed whenever possible. Additive production is bounded to these rules, which means that the order quantity of AM parts is restricted to single orders.

1.3.1 LRUs and SRUs

Failing aircraft components are swapped for working components by airlines. This component is called a Line Replaceable Unit (LRU) since it is replaced with a working part at the most downstream level to ensure the continuation of aircraft operations. The failed LRU is declared unserviceable (not fit for service in an airplane) and sent to TC for repairs. At the workshop, the LRU is inspected and the internal failure is sought. If a failure has been found, the failed subcomponent can be repaired or replaced. This subcomponent is called a Shop Replaceable Unit (SRU). After repair of the LRU, its functionality is checked and declared serviceable, after which it is returned to the airline where it is put on stock until it is needed to replace another failed LRU.

Determining if a part is an LRU or an SRU can be done using Level of Repair Analysis, but falls outside the scope of this research. We assume that the determination has been performed, such that LRUs are retrieved from the aircraft and sent to TC to repair the LRU using replacement of the failed SRUs.

1.3.2 Multiple SRU replacements per LRU

In most after sales supply chain models, the assumption is made that each incoming item has either one or no defect. This simplifies calculations because downtime costs and lead time can be evaluated at the single component level. This research deals with multiple SRUs per LRU that may need repairing or replacing. This increases the difficulty of the model, since the number of theoretically possible repair options per LRU increases from n to 2^n for an LRU with n SRUs.
However, not all SRUs are printable, so we can reduce the number of options to 2^p, where p is the number of printable SRUs. We assume that a failing LRU is sent to the repair shop after the initial occurrence of an error, without cannibalization of its SRUs by the customer's maintenance crew. SRU replacements are therefore either related by failure and wear behavior, or by customer wishes and modifications to the LRU.
In theory, the number of possibilities is still large, but some combinations are more likely than others, so an expert's opinion is always needed to define SRU combinations that are to cover most of the LRU repairs. In the remainder of this report, we will discuss SRU combinations with a maximum of two SRU replacements per LRU repair. The logic used can however be easily adapted to accommodate more than two replacements per repair.

The implication of combining multiple SRU replacements in one repair is that the length of an LRU backorder is dependent on the length of the backorders of all SRUs under consideration. When waiting for more than one part, the effective length of the LRU downtime is the longest SRU waiting time, with its associated costs.

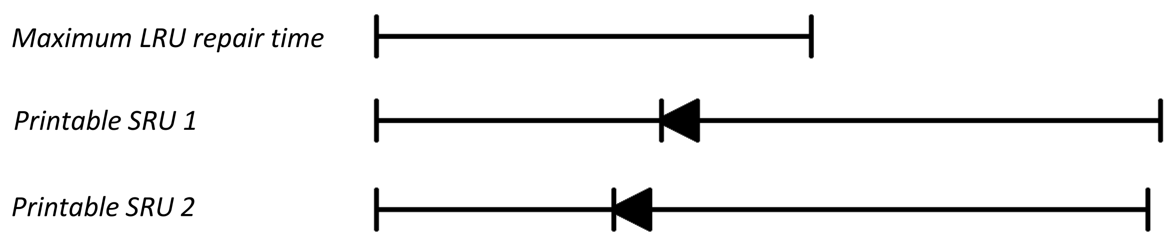


Figure 1, example of lead times of an LRU with 2 printable SRUs. The LRU repair lead time is fixed, while the conventional reorder lead times are longer than the repair lead time, resulting in large stock quantities to meet the fill rate. When the lead times can be shortened by using additive manufacturing, the lead times become shorter than the LRU repair time, reducing the need to keep stock while still satisfying the fill rate constraint. In this figure, the lead times for both SRUs are shorter than the allowed LRU repair time, reducing the need to keep inventory.

For every LRU, the options that can be evaluated are the combinations of all printable SRUs, and the reduction of the total repair lead time for all possible combinations of SRUs needing repair. For the given example of Figure 1, the options of printable SRUs are 'none', 'only SRU one', 'only SRU two' and 'both SRUs'. For each of these options, the average reduction of repair lead times can be obtained by calculating the possibility of occurrence and reduction in repair lead time of all possible combinations of maintenance tasks.
It can be reasoned that a choice to print only SRU 2 will have effect if only SRU 2 is needed, but no saving is achieved if both SRUs are needed, since the effective LRU repair lead time will be the lead time of SRU 1.

1.3.3 SRUs used in more than one LRU

The SRUs evaluated in this research are simple parts which can be used in more than one LRU. This means that the choice to print an SRU for one LRU will result in printing the same SRU in another LRU, which consequently may have a direct effect on the choices to print other SRUs for the second LRU. With an increasing number of printable parts, the number of possible combinations increases exponentially. Enumeration of all combinations of printable SRUs and the effects on the LRU lead times will therefore become more time consuming, and adaptive searches can be implemented to find a favorable option in the least possible time. In this research we only consider SRUs within a single LRU, enabling manual checks of the solution and to gain insight in the optimization process.

1.3.4 Possible sourcing options

When deciding on using AM, there are multiple options to implement this new production technique. In the current situation, the conventional part is purchased, with reorder point and quantity based on product characteristics like fixed order costs, holding cost rate and backorder costs. The optimal sourcing policy will then be found based on the control policy, which can be costs, fill rate or a combination of the two.
The same calculation can be done for the additive part, with the addition of a fixed cost component for development and certification of the AM part.

As described above in chapter 1.2, Additive manufacturing has unique production characteristics such as toolless production. This characteristic can be used to source the same product at another service provider if the main service provider is unavailable.
Also, by the nature of service providers, they want to optimize their production runs by consolidating different orders in an attempt to lower the startup costs. This might however lead to longer turnaround times than strictly needed. When TC needs to have their product quickly, they might try to persuade the service provider to start production with a non-optimized building chamber
We assume that the effects of both options are similar, in that a production run in these cases is more expensive but can deliver the same product in less time.
We will thus use the normal AM supply option when possible, but turn to the emergency source when stock levels turn to zero to quickly fill the current demand.

The three possible sourcing options (CM, AM & AM emergency sourcing) can be analyzed on the expected costs over the remaining product lifecycle. Conventional manufacturing is set as the default option. When AM is the optimal sourcing method, the AM part needs to be developed, and the inventory position is brought towards the new reorder point. All demand will be sourced from the AM service provider and is backordered in the case of stockouts.
If the emergency sourcing option is optimal, we will also develop the AM part and bring the inventory position towards the new reorder point. When the stock level is positive upon receiving demand, we will order the AM part at the regular lead-time and costs. When the stock is depleted, we will place an emergency order at emergency lead-times and costs.
In both AM sourcing options, development and certification costs are incurred.

2 Research proposal

In this chapter, the problem is defined, including the research question and the sub questions needed to come to the answer to the research question.

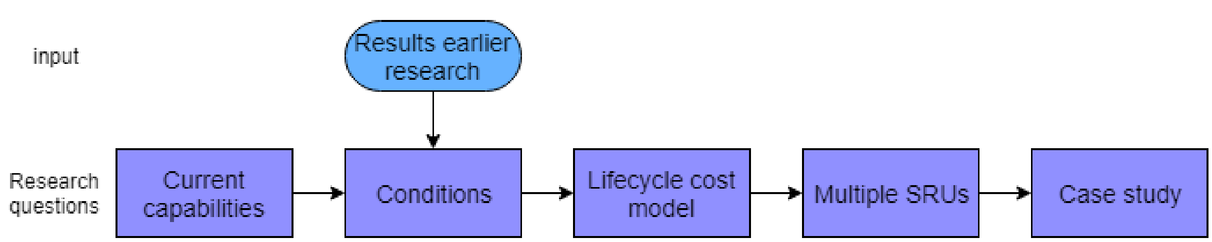
2.1 Problem definition

Since the discontinuation of the building of new aircraft, the development of TCs airplanes has stopped. The result is that all TCs airplanes are using old technology, while other aircraft manufacturers have moved to new technologies. This means that the demand for components used by TC is decreasing, which results in longer and more variable lead times. In out of stock situations, this may result in longer repair lead times, and can be countered with higher inventory levels, which in turn increases the total costs.
Besides, end consumer needs have changed in the last years. Different consumers are demanding small changes to tailor components to their specific needs, making the variety of different products even bigger. This also results in an increasing amount of SRUs. Since there is not enough space and budget to keep ample inventories of all SRUs, TC wants to investigate the possibilities of Additive Manufacturing (AM) to reduce the lead times and holding costs, while maintaining high service levels. In earlier researches, the use of AM has been investigated in the production of load bearing parts (Jansman, 2017) and tooling (de Kruiff, 2018). Based on the findings of the last research, tooling has been approved to aid the production and testing of components. The first research showed that it is possible to design and use components made using AM, but the certification costs are currently too high to make effective use of these parts. In this research, TC wants to investigate if AM can be used to print parts with less requirements on the load inflicted on the component. To test this hypothesis, this thesis focuses on the production of non-load bearing SRUs used in the repair of LRUs. The research question can therefore be stated as:

'Under which circumstances/criteria can AM be used to produce SRUs used in a maintenance environment and how do the possible solutions compare to conventional manufacturing'

2.2 Research questions

To address to the main research question stated above, several other questions have to be answered. We start our research by evaluating the AM capabilities and future usage of AM at TC, and use the results to determine conditions on parts for which the SRU model could be beneficial. Based on these conditions, a model is constructed with which the costs of different sourcing options can be evaluated. After a first model is built and evaluated, extensions will be made to accommodate multiple SRUs in an LRU.
The different research questions are displayed graphically below, and will be discussed in more detail in the remainder of this chapter.



2.2.1 RQ1: Current and future capabilities

What are the current capabilities of TC with regards to AM, and how are these capabilities expected to change in the future?

TC currently has some small AM printers available at the repair facility at Schiphol. We will evaluate these printers to find the quality of their output, and interview management of the repair facility about the needs and possibilities of the AM capacity in the future. Changes in the capabilities may include the purchase of new machines or outsourcing the production to a preferred AM service provider.

2.2.2 RQ2: Conditions

What are the conditions in which AM produced parts are expected to be able to compete with regular production techniques?

Based on the printing capabilities, results of earlier research and operational insight, properties of AM producible candidates can be explored.
Specific regulation applies in the aerospace industry, which places limits on the parts and quantities that can be produced. Next to that, the parts considered in this thesis are examined, and their specific parameters are reviewed.
A literature review is conducted on the most favorable part characteristics and the possible sourcing options.

2.2.3 RQ3: Lifecycle cost model

How can we evaluate the operational costs of parts produced with regular techniques and AM, and what are the break-even values when there are no shared SRUs between LRUs?

The decision to produce parts using AM will be made based on the lifecycle costs. A model will be made to optimize the different options, after which comparisons between the options can be made. The robustness of an outcome can be measured by calculating break-even points of SRU parameters. These points will indicate when the decision to use AM or CM will change.
In this basic model, each LRU will have only one SRU. This model serves to explain the working of the model, and will in later research questions be used to create working models with more or shared SRUs.

In this model, there are no commonalities between the different LRUs, which means that we assume that each LRU has a specific set of SRUs, which are not shared between other LRUs. While this is not expected to be a representation of reality, it does give an initial model, which can later on be refined.

2.2.4 RQ4: Multiple SRUs

What changes are needed to model an LRU with multiple SRUs, and how can this model be solved?

The model created in the previous chapter will need to be adapted to accommodate orders consisting of multiple SRUs. We will build and validate this model, and find the changes in the results between the single- and multi SRU model.

2.2.5 RQ5: Case study

Can AM be used as a cost friendly alternative for regular production?

A case study will be performed on an LRU with two printable SRUs. In the model from research question 3 these SRUs will be treated as two independent cases, but they will be combined to form the case study for the model of research question 4. Based on the case study, we will draw conclusions on the use of AM-produced parts in the repair of aircraft components.

2.3 Scope

The research will be conducted within The Company. Because TC is the type certificate holder for its own aircraft, changes made in the MRO of their own aircraft are expected to be easier and cheaper to certify than with components of other aircraft types, which results in lower development costs and thus lower lifecycle costs. The first candidates for AM production will therefore be original TC parts. However, parts for other OEMs can still be produced using AM.

Earlier research at TC has revealed that AM can be beneficial to produce parts in a maintenance environment, but that the certification costs for load-bearing items are too high to be economically feasible. We will therefore focus on SRUs which are not subjected to excessive force and are non-critical for the working of the LRUs in which they are used.

Repair of LRUs is done for airlines, with which repair lead times have been agreed upon in the contract negotiation. Repairs will therefore need to be finished within a given fixed time, after which the LRU can be sent back to the airline and put to stock to replace another failing LRU.

2.4 Assumptions

- AM components are subject to redesign regulations to guarantee equal or better performance than the original part. We assume the failure rate of both the CM and AM part to be equal, although both parts may be failing from different failure mechanics.
- LRU demand is assumed stable, while the arrival process can be estimated by a Poisson distribution. SRU demand can be derived from LRU demand based on replacement rates.
- While it is possible that every combination of SRUs needing replacement can occur, the computational efforts are expected to exceed the gained improvement of the model. We will therefore only consider the most occurring combinations.
- When a new policy is chosen, the inventory position moves to the new settings instantly
- Each LRU is allowed a predetermined repair lead-time, in which LRU inspection, SRU replacement and SRU sourcing (if applicable) are needed.

2.5 Report layout

The next chapters of this thesis cover the research questions formulated above. Chapter three describes TCs current and future capabilities, and chapter four describes favorable conditions for AM production. Chapter five is dedicated to the creation of the lifecycle cost model, which will be used to create the single LRU, multiple SRU-model in chapter six. Finally, a case study is performed in chapter seven, and chapter eight concludes with the thesis conclusions and recommendations.

3 Current and future capabilities

What are the current capabilities of TC with regards to AM, and how are these capabilities expected to change in the future?

3.1 Current capabilities

The company's workshop currently has two AM printers and a post-processing machine. These printers are mainly used for prototyping and obtaining knowledge on the possibilities of AM production.

3.1.1 Material Extrusion

Material extrusion is a technique in which the building material is fed from a spool. The moving printer head melts the tip of the spool and deposits the molten material on the building platform. This technique requires support material, which is deposited in the same way and is removed during post-processing. This relatively simple production technique is able to produce plastic parts with a low surface quality.

3.1.2 Powder Bed Fusion

Powder bed fusion is a technique to build a product from powder. Powder is rolled onto the building platform, after which a moving laser melts the powder at selective points to melt the powder together to form a product. After each layer has been produced, a new layer of powder is added. This technique is able to produce both plastic and metal parts. Support material is needed to gain support and to serve as heat overflow. Without this support, the product will cool unevenly, resulting in uneven shrinkage.
Because of the repeated heating and cooling, products may suffer from fatigue from overheating or unmolten parts due to under-heating of the product.

3.1.3 UV oven

Parts from the powder bed fusion machine are treated in the UV oven. This oven cures the outside and decreases the defects of the product, resulting in a stronger and more durable product.

3.2 Current operations

LRU repairs are done based on contracts with airlines. In these contracts the allowed repair time is agreed upon and will serve as a fixed constraint on all repairs under that contract. It is however impossible to achieve a 100% on-time delivery goal, so the internal goal is set to 90-95%. Current market conditions for the airlines are tough, which puts pressure on the costs the airlines are willing to spend on inventory and repairs. This may result in contracts requiring an increased service level or higher backorder costs to reduce the airliners risk of grounding an airplane. For TC, this means that the internal component service will have to rise to minimize the probability of a repair taking longer than agreed upon. This can be done by increasing the inventory levels or by reducing the order lead time, both of which can be achieved by using AM.

As stated before, TC uses a contracting model in which a fixed time for LRU repairs is agreed upon with the customer. Within this time, the LRU needs to be diagnosed to find the failed SRU(s), the failing SRU is replaced, and the LRU tested to guarantee its functionality. Also included in this repair time is some slack which can be used to guarantee on time completion of LRU repairs. This slack time can be modelled as an allowed delay time in which a backordered SRU may arrive without inducing backorder costs on the LRU repair.
In the current operations, this slack time is used only as workshop overflow time, since the long lead times of the conventional produced SRUs cannot be substantially shortened to have an impact on the on-time

completion rates of the LRUs. AM offers shorter lead times, and thus a higher impact on the on-time completion rates.

3.3 Future applications

It is expected that the current printers will continue to operate in the future to print tooling and experimental parts. Final products however will be outsourced to specialized AM production companies. These companies will have to be certified for aerospace production by TC before they are allowed to produce parts which can be used in repairs of aircraft components, as stated in EASA Part 21G. Outsourcing the production reduces the investment costs of the machines and makes improvements on the product characteristics possible by using larger industrial machines. This does increase the price and the lead time.

3.4 Conclusions

The current AM capabilities at TC are limited and can only be used for prototyping and testing. When AM production is used on a larger scale. Within TCs current repair operations, AM can add value with its short replenishment times such that high on time completion rates can be achieved with low inventories.

4 Additive manufacturing conditions

What are the conditions in which AM produced parts are expected to be able to compete with regular production techniques?

4.1 Shop replaceable units

Earlier research has proven that AM can be used in the after-sales supply chain of aircraft components, but the development and certification costs of AM parts are currently too high to give AM a competitive edge. Full production of AM will only be possible if development and certification costs will decrease by 80%, or by finding product categories with less strict certification requirements. (Jansman, 2017)
One product category with less strict requirements are the lowest indenture items or SRUs. These items can be described as small nonstructural parts of an LRU. Failures of SRUs will restrict the aircrafts ability to change some of its controls, but will not lead to damage to the airframes structure. However, failing SRUs do affect the airworthiness certificate of the LRU, requiring swapping the LRU with a functioning example and sending the LRU to the repair shop.
This category of parts can be found in the workshop as simple piece parts, and are mostly used in the repair of components. In this thesis, we will therefore focus on these shop replaceable units.

4.2 Reorder quantities

Because of the scope of the parts under consideration, TCs experts expect most CM SRUs to be cheap and simple parts with fixed order quantities. It is likely that parts can only be purchased in quantities larger than the minimum order quantity (MOQ), which can only be increased with Incremental Order Quantities (IOQ). If this is the case, the model will have to be built in such a way that the first possible order quantity is the MOQ, and is increased by the IOQ until the optimal stocking policy has been found.

Because of part 145 regulations, AM production is only allowed for a current repair. If we assume that only one part is needed for a repair, this leads to the constraint that the reorder quantity for AM parts is one. If the number of items needed from one part is larger than one, these products may be produced together. This will reduce the setup times and costs and increase efficiency of the post processing. In our model, we will only consider the single production-option because of the ease of calculations and part-145 regulations. Batching of multiple parts is seen by the model as the simultaneous arrival of multiple single-unit demands. We will use the option to purchase a part when the inventory position is larger than zero. This means that we will produce to stock when required to do so to achieve a target fill rate. It should be noted that this is currently not allowed by regulations, but the results of this research could be used to investigate changes to be made to these regulations.

4.3 Failure rate

The aerospace industry is one of the most regulated industries in the world. TC is certified to design, approve and produce their own parts, but each new design must be tested and compared to the previous design. The goal of these tests is to make sure that any new part has at least the same reliability as the old design. This implies that the failure rate of an additive part should be at least equal to the failure rate of the conventional part. It may be possible that the new design has better strength characteristics, but we assume an equal failure rate for both the conventional and the additive product.
Because of the different designs, parts may behave differently when subjected to the same loads and can therefore have different failure behavior. An example of this is the change from aluminum to titanium. While the aluminum CM part may wear out due to corrosion, the titanium AM part does not corrode, but may break due to porosity or different roughness values. We assume that these differences cancel each

other out. Further, both the CM and AM part are subjected to the same random incidents and maintenance imprudence, resulting in equal random failures for both parts. We therefore come to the conclusion that both the CM and AM part have a similar failure rate.

4.4 Sourcing options

4.4.1 Single sourcing with backorders

The standard sourcing option in every supply chain is a single sourcing model, where the full demand is ordered at one single supplier, with standard order sizes and predictable production lead times (Silver, Pyke, & Thomas, 2017).
The demand in spare parts supply chains are typically low, which results in single item demands at TCs workshop at unknown times, but with a known probability distribution. Because of the low demand, a restocking decision can be made each time an item is taken out of stock. This leads to the conclusion that a continuous review policy is optimal, and a reorder decision has to be made whenever the inventory level or on-hand stock drops to the re-order point s. (Silver, Pyke, & Thomas, 2017)
Next, the lot size must be determined. This can be either a fixed lot size of Q items, or a variable lot size to increase the inventory to a predetermined order up to level S. Because of the typically low demands in spare parts supply chains, each demand is assumed to arrive individual, and the probability of two items arriving at the same time is neglectable. When this happens, any fixed lot model can be represented as a variable lot model and vice versa. When the inventory drops to s, the inventory is replenished with either Q units or to S with $S = s + Q$. These policies are called a (s,Q) and (s,S) model respectively.
A special case of both policies is one-for-one replenishment or base-stock policy, where an order of size 1 is placed each time demand occurs, keeping the inventory position at a fixed level S. This policy can be represented as $(S - 1, S)$ (Sherbrooke, 2004). Since both the fixed and the variable lot size can be represented, we choose to work with the reorder quantity Q, and thus use an (s, Q) policy in our model.

When AM technology matures and printer purchasing prices drop, the fixed costs of setting up a repair facility will also decline, making it possible to set up repair locations at remote locations next to the installed base where demand arises (Pérès & Noyes, 2006). The current machine costs are too high to install printers at remote locations, but it is expected that it will become economically feasible to install distributed printers when the technology has improved (Khajavi, Partanen, & Holmström, 2014). In this research we will only consider centralized printing which delivers the parts to the repair workshop.

Additive manufacturing places some added restrictions on the models suitable to calculate the lifecycle costs. Because of the change to a different production technology, the parts will need to be designed differently, inducing costs for development, testing, tooling and certification. When using AM no tooling is needed, but the certification costs will be high for TCs intended use of the parts. AM-produced parts may have different weight and structural characteristics, such that a change of production method will result in changes to the costs structure such as reduced fuel consumption or holding costs.
These modeling considerations have been implemented in a model by Westerweel et al, which is designed specifically to decide on the sourcing option of a new product (Westerweel, Basten, & van Houtum, 2018). Since this model is created for a new product at the start of a production cycle, some changes will have to be made to make this model feasible in the spare parts industry.

4.4.2 Fast resupply: single sourcing with lost sales

Another sourcing option is the fast resupply option. This option might be used when there is a faster responding AM production option. Possible reasons for this faster resupply are that AM service providers usually wait until they have enough orders to optimally fill the building chamber. Speeding up production can be done by persuading the producer to start production with a sub-optimized building chamber by offering a higher product price, or by printing the product at a smaller, more expensive machine at either the same or a different AM service provider.

When using this fast resupply option, we need to make some changes to the standard model. The stock level in the standard model can become negative, implying an SRU is backordered and we are waiting for an item to arrive before finishing an LRU repair. In the fast resupply option, we fill demand using the regular source when possible, and demand leaves the queue when faced with an out of stock situation. In these cases, we will order the same product with a shorter lead time and higher purchasing costs. This can be represented by a lost sales system for the regular part, where costs are incurred for purchasing of the expensive SRU and LRU backorder costs.

In cases with one-for-one replenishment, where the reorder quantity Q is one, the lost sales model can easily be represented by the Erlang loss formula. In this formula, a Markov chain is used where the inventory position is represented by the number of servers, the arrival rate by the demand rate and the service time by the replenishment lead time (Karush, 1957).

For reorder quantities larger than one, an optimal solution cannot be found as easily as for the one-for-one case (van Houtum & Kranenburg, 2015). In this research this is not an issue since we assume that the fast resupply, and thus the lost sales model, is only feasible for AM production, which has a reorder quantity of one.

4.5 Conclusions

For AM produced parts to be able to compete with CM produced parts, certain conditions must apply. Because each individual part needs to be designed, tested and certified, large investments are incurred for AM produced parts. These investments grow with the size and requirements of the parts. Since development costs are a large cost factor in current AM operations, these costs should be minimized as much as possible. When AM production gets more accepted and regulations have been made involving the design and use of other, larger, AM parts can be considered again. For now, investment costs for small nonstructural parts are expected to have the lowest development costs and should be considered for introduction of AM techniques in TCs repair supply chain.

Production of AM parts does not require any tooling and can therefore be executed at any moment at any AM service provider. This gives AM production more flexibility than CM production, which needs tooling and thus setup costs for production, increasing the costs per unit and the optimal reorder quantity. The AM supply chain is more flexible and is able to achieve the same performance with a lower inventory position. Another advantage of the independence on tooling is the ability to source the same product at multiple suppliers at different costs and lead times. This results in a fast resupply option where a more expensive part with a lower lead time can be source in case of a stockout. We will thus research three different supply options: conventional manufacturing, additive manufacturing and AM with a fast resupply option.

5 Single SRU Lifecycle costs model

In this chapter a building block is created to evaluate the costs of a single LRU with one SRU. This building block is then used to create a model with multiple SRUs in an LRU in the next chapter. The model in this chapter will serve as an explanatory model to gain insight in the model before extending the model in the following chapters.

5.1 Conceptual model

In this section, we describe the structure for the mathematical models presented in section 0. The model determines the costs associated with an SRU stocking policy over the remaining LRU lifetime.

5.1.1 Problem description

The research objective is to find criteria for which AM can be implemented successfully at TC, based on optimal stocking policies. In this chapter, stocking policies are modeled which can provide answers to the research questions. Two sourcing models are created: a sourcing model which evaluates the sourcing of either conventional or additive manufacturing where unmet demand is backordered, and an AM lost sales model where emergency shipments are used to fill demand when no items are on stock.

Non-repairable SRUs

All SRUs in this research are assumed to be consumables and thus non-repairable. This means that all LRU failures due to a failing SRU can be addressed by replacing the failed SRU, after which the SRU is disposed of and a new SRU is procured.

For our model, this implicates that no SRU repair-facilities are considered, where fixed overhead costs are incurred independent of demand realization. The result is a problem that can be solved on SRU item-level instead of the more time-consuming system-level.

Deliver same LRU, only stocking of SRUs

Failed LRUs are sent to the repair shop by airlines. Because of the customers ownership and possible customization of the LRU (for instance the addition or switching of functions or buttons), the same LRU must be returned to the airline. Because only SRUs are kept on stock and no availability targets from on-stock LRUs have to be regarded, this transforms the two-indenture model into a much easier single-indenture model. In our model, the SRU reorder policies are optimized such that the costs are minimized and the LRU repair can be finished within the given time frame.

5.1.2 Key trade-offs considered

During the remaining LRU lifecycle several costs are incurred which are influenced by the chosen reorder policy. The models provide an optimal solution that minimizes the total relevant costs. Doing so corresponds to finding the balance between the following trade-offs:

Holding costs vs repair penalty costs

Adding more SRUs to stock increases the amount of demand filled directly from the shelf and thus decreases the LRU repair lead-time but does come at the expense of added holding costs. Adding an extra item to stock is only profitable when the increase in costs is less than the decrease in LRU repair backorder costs. The LRU backorder costs are defined as a penalty payable to the airline per day of delay.

Ordering costs vs holding costs
When fixed order costs are large, the lifecycle order costs can be lowered by increasing the order size. Under a fill rate constraint, the reorder point will become lower than in a system with smaller reorder sizes. However, in a spare parts supply chain where the demand is low, a low reorder point is expected. Decreasing the reorder point is then expected to result in a below-target fill rate, decreasing the expected decline of the reorder point. For items with low demand, increasing the reorder quantity may only result in higher average inventory when the reorder point cannot be lowered. This results in higher inventory costs.

Variable costs vs development costs
AM production benefits from shorter production lead times and can therefore achieve the same performance with less inventory. When production costs are larger than conventional replenishment costs, the total costs of AM should still be below the total costs of CM. An extra costs factor when sourcing AM is the development and certification costs. The operational benefit of AM over the remaining life cycle should be as least as large as the fixed development costs for AM to be profitable.

5.1.3 Model structure

At the basis of our model stands the maintenance supply chain of products at TCs workshop. In this supply chain, an aircraft requires maintenance due to a failure of an LRU, depicted in Figure 2 by a landing gear. The airline replaces the LRU at their base with an available spare LRU and sends the failed LRU to TC for repair. At TC, the failing SRU is found, which is indicated by a tire in the figure. The failing SRU is then replaced by an SRU from stock if available, or the LRU waits for an SRU to arrive. After installation of the SRU, the LRU is declared serviceable and returned to the airline, where it is available to replace a new failure.

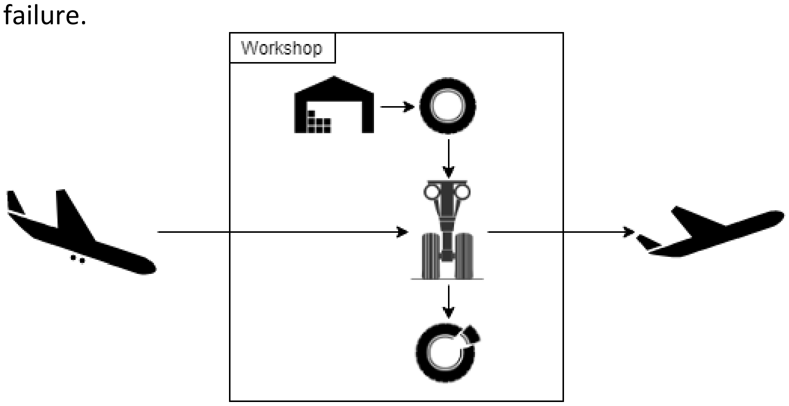


Figure 2, item flow in the supply chain. The failed LRU is send to TC, where it is repaired by replacing the broken SRU, after which the LRU is send back to the airline where it is available to replace another failing LRU.

The model thus follows a single-indenture structure where the decision space is which sourcing strategy to use for each SRU. The optimal sourcing strategy is found by evaluating the total costs over the remaining LRU lifecycle.

In the workshop, the LRU is diagnosed to find the failing SRU(s). Diagnosing a failed LRU takes a fixed time, independent on the number or severity of SRU failures. We assume that the required SRUs are only known after the full inspection. This assumption results in the arising of SRU demand after the full LRU diagnose. If there is stock of the SRU, the waiting time for the SRU is zero and the repair can start immediately. Else, the SRU has to be sourced with a fixed replenishment time. A representation of this can be seen in the upper part of Figure 3. The maximum allowed repair time of the LRU is known. With fixed diagnostics and repair time, this leaves a predetermined time for SRU production or procurement. When the SRU production time is small, a slack time is left. This means that no stock has to be kept, since all repairs can be completed in time. When the SRU production time is large, the allowed time is exceeded when producing an SRU on demand. This results in an LRU backorder with corresponding backorder costs as can be seen in the lower part of Figure 3.

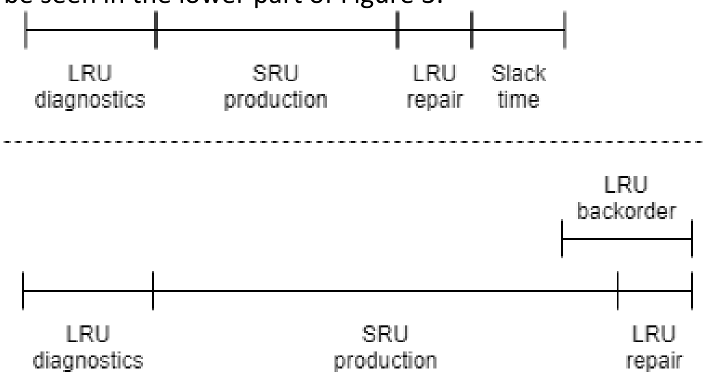


Figure 3, LRU repair process. In the upper part where there is slack time, no SRU stock needs to be held to ensure on time completion of the LRU repair. In the lower part, the SRU production time is longer, resulting in possible LRU backorder time. Reduction of backorder costs is done by having the SRU on stock such that the expected backorder time is acceptable.

There are multiple sourcing options to assure the availability of the SRUs and thus the LRUs. In the first option in Figure 4, the conventional SRU is purchased from the regular supplier and put to stock. The second option uses an AM service provider, which can deliver an equal SRU with different lead times and cost attributes. The third option is the fast resupply option. In this option, the additive produced SRU is used when it is available on stock, while an emergency order is placed to fill demand in an out of stock situation. This emergency order can be placed at the same or another service provider, and has different costs and lead time compared to the regular AM-produced SRU.

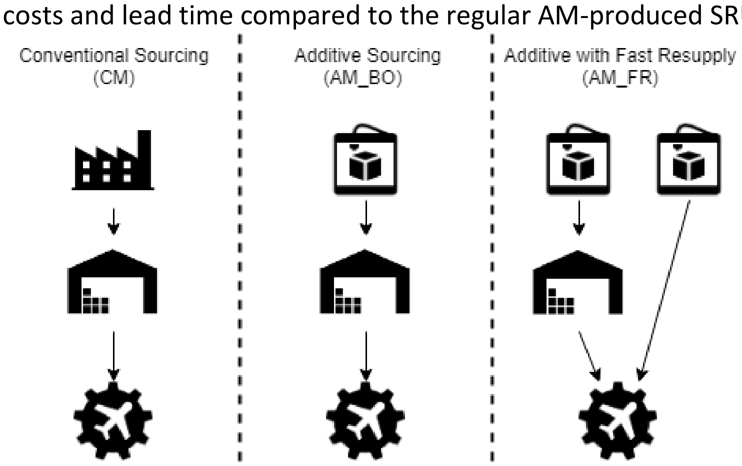


Figure 4, SRU sourcing options. In the left and center options, backorders are allowed and LRU repair is completed after receiving the backordered SRU. in the right model, an SRU is sourced via fast resupply to quickly repair the LRU.

5.2 Mathematical model

Following the literature review performed in chapter 4.4 and the model structure described above, we created two cost models to calculate and evaluate the sourcing options. Since all three sourcing options use the same data, the LRU and SRU characteristics are discussed first, after which the calculations for the backorder and lost sales models will be explained. We refer to the SRUs as parts from here on.

5.2.1 Modeling choices

Before introducing the model, some modeling choices and assumptions are explained. These choices and assumptions are made to keep the models both manageable and generic to apply for a large base of LRUs and SRUs. We use superscript x to denote a part characteristic for which the value can differ between conventional and additive parts. A superscript CM or AM is used for a specific characteristic.

As described earlier in chapter 1.3, the aerospace industry is highly regulated. Because of this regulation, a replacement product must undergo a series of tests to guarantee its functionality. This results in a product which is at least equal to, or better than the original product. We can thus state that the failure rate τ^{AM} of the AM-produced SRU, calculated as the expected number of failures per time unit, should be lower or equal to the CM failure rate. Because the AM parts still are to be developed, real time usage data is not available, so exact failure data is unknown. In order to keep from over-estimating the AM characteristics, we choose to define the AM failure rate as the worst possible failure rate, resulting in the largest failure rate possible given the condition that $\tau^{AM} \leq \tau^{CM}$. This results in the statement that both failure rates are equal.

$$Assumption\ 1: Failure\ rate\ AM = Failure\ rate\ CM$$

Since the failure rates of both the AM and CM part are equal, we can also state that the replacement rates are equal end will remain stable during the LRU life cycle.
SRU demand can be calculated as the LRU demand multiplied with the SRU replacement rate. The TC aircraft fleet in western countries have been phased out, but they are bought up by other airlines and will therefore remain flying in the coming years. This ensures a stable number of flying hours, and therefore a stable operational LRU installed base. When both the LRU demand and the SRU replacement rates are equal, we can assume that the SRU failure rate is also stable, resulting in assumption 2.

$$Assumption\ 2: SRU\ demand\ is\ stable$$

Other part characteristics are also assumed to be fixed, so there is no learning effect on the AM production costs and lead times. This means that all parameters remain stable during the remaining LRU lifecycle, and the model will behave as a static model. Because the model behaves like a static model, there is no need to construct a dynamic model. This simplifies the calculations needed and makes a sensitivity analysis possible.

The LRU demand at the workshop is known from previous repair instances and is expected to remain stable in the future. The LRU arrivals at the repair shop are assumed to be Poisson distributed with mean μ_{LRU} per month, indicating that the mean time between LRU arrivals is $\frac{1}{\mu_{LRU}}$ months. There is no recorded data on SRU failure rates, but there is information on the demand rates. These past demand rates contain both failures and preventive maintenance and are expected to give a reliable estimate of the future demand streams. Combining the demand rates from the LRU and SRUs gives a replacement rate. This can be expressed as the probability that an SRU needs replacement if an LRU enters the workshop. Since the engineering department at the workshop has the product knowledge, they can reflect on the calculated replacement rates and which SRUs explicitly need or don't need to be investigated.

While it is officially not allowed to produce items to stock, a reorder point larger than 1 might still be needed to obtain a service level. We thus assume that we are allowed to purchase a part when we still have stock, implicating that S^{AM} is allowed to have values larger than 0.

$$Assumption\ 3: Additive\ producing\ to\ stock\ is\ allowed$$

CM: Backorders, AM: backorders or lost sales

When faced with an out of stock situation, a repair needs to be fulfilled. In the conventional model, there is no opportunity to speed up the production, so a backorder is created which is fulfilled at the arrival of the backordered part. The inventory level in the conventional model can thus become negative until sufficient replenishments arrive. In the additive model, each unfulfilled demand can also be expedited at the AM service provider. The inventory level will then stay zero until the order arrives. When that happens, the system returns to the original situation with stock. When expediting an AM order, the supplier may charge extra costs if the product is needed with a shorter lead time than a regular shipment. An expedited order will thus have higher unit costs, with less backorder costs because of the shorter lead time and thus lower penalties payable to the airline.

$$Assumption\ 4: \begin{cases} All\ demand\ may\ be\ backordered \\ When\ sourcing\ AM, out\ of\ stock\ can\ be\ sourced\ via\ Fast\ Resupply \end{cases}$$

We can therefore distinguish three different sourcing methods:

$$\begin{array}{ll} CM & order\ CM, wait\ for\ CM\ order\ to\ arrive\ to\ fulfill\ current\ demand \\ AM\ Backorder & order\ AM\ , wait\ for\ AM\ order\ to\ arrive\ to\ fulfill\ current\ demand \\ AM\ Fast\ Resupply & order\ AM, place\ emergency\ order\ for\ AM\ part\ when\ no\ stock\ available \end{array}$$

5.2.2 Basic (S,Q)

In the basic backorder model, we use the standard set of input parameters, where the SRU demand can be calculated by multiplying the LRU demand with the SRU replacement rate.
The maximum SRU waiting time a, calculated as SRU production minus slack time in Figure 3, will be used to calculate the on-time completion rate.

Input parameter	Symbol	
Mean LRU demand per month	μ_{LRU}	
SRU replacement rate	rr_{SRU}	
Mean SRU demand per month	m	$= \mu_{LRU} \cdot rr_{SRU}$
Maximum SRU waiting time in months	a	
SRU production lead time in months	L	$L' = Max(0, L - a)$
Lot size	Q	
Reorder point	S	
SRU purchasing price	p	
LRU backorder costs per month	c_{BO}	

Table 1, model input parameters

When the system is in a steady state, we can describe the system performance using the inventory level IL and inventory position IP. Based on these distributions, we can calculate the backorders in the steady state, and thus the average expected backorders, denoted EBO. The expected demand during the lead time can be calculated by multiplying the expected demand with the lead time, while the expected demand during the LRU backorder is calculated by subtracting a from L.

Steady state parameter	Symbol	
Inventory position	IP	
Inventory level	IL	
Expected backorders	EBO	Eq 5.10
Demand during lead-time	D_L	$= m \cdot L$
Demand during effective lead time	$D_{L'}$	$= m \cdot L'$

Table 2, model steady state parameters

In a steady state, the inventory level is expressed as $IL = IP - D_{L'}$. With reorder level S and lot size Q, IP has approximately a discrete uniform distribution on $\{S+1, \dots, S+Q\}$. Because of the Poisson distributed demand rate with average m, $D_{L'}$ has a Poisson distribution. We can derive the distribution of IL by conditioning on IP (Axsäter, 2006):

$$P\{IL \geq x\} = \sum_{i=s+1}^{s+Q} P\{IP = i\} * P\{D_{L'} \leq i - x\}, x \leq S + Q \tag{5.1}$$

$P\{IP = i\} = \frac{1}{Q}$ and $D_{L'}$ is Poisson distributed with mean mL', such that we can rewrite equation (5.1) to

$$P\{IL \geq x\} = \frac{1}{Q} \sum_{i=s+1}^{s+Q} \sum_{n=0}^{i-x} \frac{(mL')^n e^{-mL'}}{n!}, x \leq S + Q \tag{5.2}$$

We define the lead time demand $D_{L'} = \sum_{n=0}^{i-x} \frac{(mL')^n e^{-mL'}}{n!} = 0 \; if \; i - x < 0$, such that the cumulative probability distribution for the inventory level is:

$$P\{IL \leq x\} = \frac{1}{Q} \sum_{i=s+1}^{s+Q} \sum_{n=\max\{i-x,0\}}^{\infty} \frac{(mL')^n e^{-mL'}}{n!}, x \leq S + Q \tag{5.3}$$

The density function is then:

$$P\{IL = x\} = \frac{1}{Q} \sum_{i=\max\{x,s+1\}}^{s+Q} \frac{(mL')^{i-x} e^{-mL'}}{i - x!}, x \leq S + Q \tag{5.4}$$

5.2.2.1 On-Time Completion

We use the PASTA-rule to calculate the performance of the system. This Poisson Arrival See Time Average states that every incoming demand sees the state of the system in its average state.

The on-time completion rate is defined as the fraction of time where an LRU is repaired within the given time a. Since an LRU repair can only be completed by replacing the failed SRU, an LRU is repaired on time if the SRU is available within the maximum waiting time a. The expected number of SRUs exceeding the waiting time is thus equal to the number of LRU repairs exceeding the waiting time.
We calculate the OTC as the fill rate with lead time L'. We can therefore calculate the OTC by summing the probability density functions for $IL \geq 1$.

$$OTC = P\{IL \geq 1\} = \sum_{i=1}^{s+q} P\{IL = i\} = \frac{1}{Q} \sum_{i=s+1}^{s+Q} \sum_{n=0}^{i-1} \frac{(mL')^n e^{-mL'}}{n!} \tag{5.5}$$

This formula can be simplified into Poisson probabilities as

$$OTC = \sum_{n=0}^{s} \frac{(mL')^n e^{-mL'}}{n!} + \frac{1}{Q}\left\{(s+Q)\sum_{n=s+1}^{s+Q-1} \frac{(mL')^n e^{-mL'}}{n!} - mL' \sum_{n=s}^{s+Q-2} \frac{(mL')^n e^{-mL'}}{n!}\right\} \tag{5.6}$$

5.2.2.2 Fill Rate

The fill rate is defined as the fraction of time that a demand can be satisfied directly from stock when the failed SRU is found. We can therefore calculate the fill rate by summing the probability density functions for $IL \geq 1$ where the expected lead time demand is mL. The result is equation 5.5, except that mL' has been changed to mL.

$$fr = P\{IL \geq 1\} = \sum_{i=1}^{s+q} P\{IL = i\} = \frac{1}{Q} \sum_{i=s+1}^{s+Q} \sum_{n=0}^{i-1} \frac{(mL)^n e^{-mL}}{n!} \tag{5.7}$$

5.2.2.3 Backorders

The expected backorders can be calculated for a given value of IP. A backorder occurs if the demand is strictly larger than the inventory position, such that the inventory level becomes negative. During a time period where the inventory position is negative, demand is backordered. The expected number of backorders can be calculated as demand minus inventory position, such that

$$E[BO|IP] = mL' \sum_{n=IP}^{\infty} \frac{(mL')^n e^{mL'}}{n!} - IP \sum_{n=IP+1}^{\infty} \frac{(mL')^n e^{mL'}}{n!} \tag{5.8}$$

Substituting 5.4 into equation 5.8 gives an unconditioned backorder formula, resulting in the following equation:

$$E[BO] = \frac{1}{Q} \sum_{i=s+1}^{s+Q} \left\{ mL' \sum_{n=i}^{\infty} \frac{(mL')^n e^{mL'}}{n!} - i \sum_{n=i+1}^{\infty} \frac{(mL')^n e^{mL'}}{n!} \right\} \tag{5.9}$$

Simplifying into Poisson probabilities gives:

$$\begin{aligned} EBO = \; & \frac{(mL')^2}{2Q} \cdot \sum_{n=S-1}^{S+Q-3} \frac{(mL')^n e^{mL'}}{n!} \\ & - \frac{(S-1) \cdot mL'}{Q} \cdot \sum_{n=S}^{S+Q-2} \frac{(mL')^n e^{mL'}}{n!} \\ & + \frac{(S-1)S}{2Q} \cdot \sum_{n=S+1}^{S+Q-1} \frac{(mL')^n e^{mL'}}{n!} \\ & + mL' \cdot \sum_{n=S+Q-1}^{\infty} \frac{(mL')^n e^{mL'}}{n!} \\ & - \frac{1}{2}\{Q + 2(S-1) + 1\} \cdot \sum_{n=S+Q}^{\infty} \frac{(mL')^n e^{mL'}}{n!} \end{aligned} \tag{5.10}$$

5.2.2.4 Order quantity

TCs products suffer from obsolescence, which results in changing commitment by the supplier. A lower incentive to produce the parts may result in rising prices or lead times, which can be easily implemented by changing the input parameters. Because the model is static, the model will then run with the updated price alone, instead of an adjusted price for each time the price is increased.

Another possible action is an increase of the minimum order size. Where in the past an order size of one might be reasonable because of the larger scale production. It may happen that the supplier must restart production after a request from TC. In order to reduce the supplier's costs, they may increase the batch size, requiring TC to purchase the entire batch size, resulting in a minimum order quantity MOQ. Increasing the order quantity can be done by increasing the order quantity with an integer multiple of an incremental order quantity IOQ.

The optimal reorder quantity will thus have the form $MOQ + n \cdot IOQ$. However, since demand is low, we assume that every order will have the size of the MOQ. This results in a model with fixed reorder quantity per SRU, where $Q = MOQ$.

5.2.3 Fast AM resupply

AM production is done at an AM service provider. Due to the nature of AM production, the added time of building multiple models in the same building chamber is marginal. For this reason, the supplier typically merges multiple orders in one production batch. This can mean that a production order has to wait for other orders until production is started. The benefit of this practice is that the fixed AM printing costs can be shared by multiple buyers, reducing the sourcing costs over the calculated lifetime. However, waiting for a full production batch might take some time, which is unwanted if the LRU repair lead time is exceeded, leading to LRU backorder costs.

In those cases, the AM supplier might be persuaded to speed up the production, which means starting its production run with a non-optimized building chamber and thus higher costs per product. Sourcing the AM part at increased costs and decreased lead time will only occur in backorder situations. This can be modelled by transforming the backorder model into a lost sales model. Demand will then be picked from stock if available, but when there is demand while the inventory level is zero, the LRU will be repaired with an SRU sourced using the fast resupply method.

In those cases, the production lead time can be shortened with a factor L_{speed}, while the costs increase with a factor c_{speed}.

When the fast AM supply mode is used, this means that an SRU is picked from stock when available but is sourced using the fast supply when the on-hand inventory is zero. We can model this by reformulating the model to a lost sales system. In a lost sales system, the regular order costs and lead times apply when the inventory is positive, but demand is lost to the system in case of a stockout. Each stockout will then be served with the fast AM production at fixed costs. The parameters for the fast AM supply will then become:

$$Production\ time\ FR = \frac{L}{L_{speed}}$$

$$Production\ costs\ FR = c_{speed} \cdot p$$

With a known maximum SRU waiting time a, we can calculate the expected overshoot of the LRU repair time as $Max\left(0, L/L_{speed} - a\right)$ months, so that the backlog costs for the lost sales model can be calculated as

$$c_{BO,FR} = Max\left(0, \frac{L}{L_{speed}} - a\right) \cdot c_{BO} + \left(c_{speed} - 1\right) \cdot p \tag{5.11}$$

5.2.3.1 Lost sales model

The lost sales model can be described by the Erlang-Loss system in the case of one-for-one replenishments. We will use this for AM-production, since demand is low and the minimum order quantity for AM production is one. We can therefore safely assume that the economic order quantity is one.
In this system, a fraction fill rate of the total demand will be picked directly from stock, while the rest is sourced using the fast supply at fixed costs. The fill rate for this lost sales model will thus be the sum of the probabilities where the inventory level is positive.

$$Fr^{FR} = 1 - \frac{\frac{1}{s!} \cdot (m \cdot L)^s}{\sum_{j=0}^{s} \frac{1}{j!} \cdot (m \cdot L)^j} \tag{5.12}$$

The on-time completion rate can be easily calculated from the fill rate. If the fast production lead time is equal to or smaller than the allowed repair lead time a, the fast supply will be available in time, resulting in an OTC of 1. If the lead time is longer, the OTC is equal to the fill rate. Thus:

$$OTC^{FR} = \begin{cases} 1, & \frac{L}{L_{speed}} \leq a \\ Fr^{LS}, & \frac{L}{L_{speed}} > a \end{cases} \tag{5.13}$$

5.2.4 Lifetime costs

For both the backorder and the lost sales model, cost functions need to be derived in order to calculate the total costs for a given set of reorder point S and reorder quantity Q. The total lifetime costs can be divided into four different sub-costs:

Purchasing costs are incurred for each repair, since the replacing SRU has to be bought. These costs are incurred depending on the sourcing type, but are independent of the choice between a backorder or lost sales model.

$$Purchasing\ Costs\ PC = T \cdot m \cdot p$$

Holding costs are incurred over the expected inventory level, and depend on the choice of reorder point and quantity per sourcing model.

$$Holding\ Costs\ HC = T \cdot \left(S + \frac{Q}{2} - D_L\right) \cdot h \cdot p$$

Backorder costs are calculated based on delays in the LRU repair times. In the backorder models the LRU delay costs per month are multiplied with the expected number of backorders per month.

$$Backorder\ Costs\ BC^{BO} = EBO \cdot c_{BO} \cdot m \cdot T$$

In the lost sales model, the length of each LRU backorder is calculated and embedded in $c_{BO,Lost\ Sales}$ (Equation 5.11). Since each backorder is of the same length, the expected number of emergency orders can be multiplied with the costs per LRU backorder to arrive at the LRU backorder costs.

$$Backorder\ Costs\ BC^{FR} = (1 - FR^{FR}) \cdot c_{BO,FR} \cdot m \cdot T$$

Because a new design has to be developed and certified when moving to a new production technique, development costs are incurred for both AM sourcing models.

$$Development\ Costs\ DC = I$$

When summing the cost factors above, we can see the total lifecycle costs of all three supply options. These costs are the costs for buying and using the SRUs, but do not include disposal costs at the end of the lifecycle. At the end of the LRU lifecycle, all excess SRU stock becomes obsolete, and they are disposed of. Calculation of the exact disposal costs requires knowledge of the parts materials and possible future use, and is not incorporated in the costs analysis.

5.2.5 Break even points

With the optimal reorder policies found for each of the sourcing options, we can perform a sensitivity analysis on the effects of changes to AM parameters. These parameters are the additive variable order costs, investment costs, production lead time and LRU demand rate. We perform a policy-sensitivity analysis, where we change the parameters until the cost difference between two sourcing options turns to zero. This is the maximum allowed change before a policy change is required.

This sensitivity analysis is done for the three combinations (conventional, additive and additive with fast resupply) and four variables $\left(c_p^{AM}, I^{AM}, L^{AM}, \mu_{LRU}\right)$, resulting in 12 equalities, of which the equations for the sensitivity analysis for production lead time are given below.

$$Cost\ sensitivity\ analysis, AM\ lead\ time: SA_{costs,L^{AM}} = \begin{cases} TC^{CM}(L^{AM}) = TC^{AM}(L^{AM}) \\ TC^{CM}(L^{AM}) = TC^{AM\_FR}(L^{AM}) \\ TC^{AM}(L^{AM}) = TC^{AM\_FR}(L^{AM}) \end{cases} \quad (5.14)$$

The variables production time and demand also influence the on time completion rate. This sets an extra constraint on the allowable range. For these variables, we change the variables such that the target on time completion rate is achieved. Because AM is not used in conventional sourcing, changes to the AM production lead time do not influence CM performance, leaving OTC sensitivity analysis to AM and AM with fast resupply. For this analysis, a total of five equations are needed, which are given below.

$$OTC\ sensitivity\ analysis, mu\ SRU: SA_{OTC,\mu_{LRU}} = \begin{cases} OTC^{CM}(\mu_{LRU}) = OTC_{target} \\ OTC^{AM}(\mu_{LRU}) = OTC_{target} \\ OTC^{AM\_FR}(\mu_{LRU}) = OTC_{target} \end{cases} \quad (5.15)$$

$$Fill\ rate\ sensitivity\ analysis, AM\ lead\ time: SA_{OTC,L^{AM}} = \begin{cases} OTC^{AM}(L^{AM}) = OTC_{target} \\ OTC^{AM\ FR}(L^{AM}) = OTC_{target} \end{cases} \quad (5.16)$$

When an OTC constraint is chosen, the lowest allowed in- or decrease of the variable is set as the bound. The rationale behind this is simple: if the policy changes with an increase of a, and the OTC constraint is violated at an increase of b, the maximum allowed increase is the minimum increase $MIN(a, b)$, at which level neither a change to another policy is needed, nor the OTC drops below target. The same holds for allowable decreases, where the smallest decrease is chosen as that value indicates that both the cost and on time completion are within their bounds.

When the allowable ranges have been calculated for the dual comparisons, the ranges are combined in the same way as described above with multiple ranges per variable. This results in allowable ranges where there is no violation of the fill rate or a change to one of the other sourcing options.

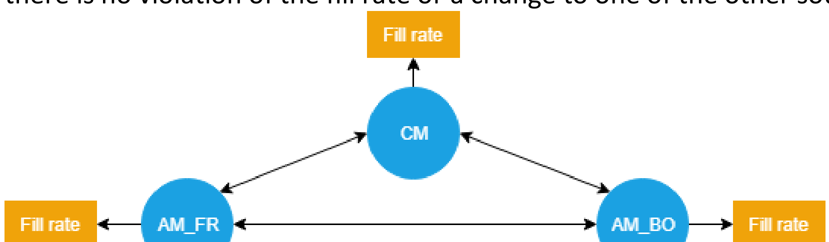


Figure 5, graphical representation of pair-wise sensitivity analyses

In total, a combination of six different sensitivity analyses is needed for the total sensitivity analysis, as can be seen in Figure 5. It can be seen that when the optimal sourcing strategy is additive manufacturing with fast resupply, changing to conventional and additive sourcing have to be considered, as well as the fill rate constraint when using the fill rate optimization.

5.3 Computational experiments

Before starting computational experiments, we verify and validate our model. Verification ensures that the model works according to the paper specifications and is behaving as we would expect it to. Validation ensures that the model output is similar to what is encountered in reality.

5.3.1 Verification and validation

We verified our backordering model with the example dataset from van Houtum and Kranenburg (van Houtum & Kranenburg, 2015). In this dataset, S_i denotes the order-up-to level, which is equal to $S + Q$ in our model.

The lost sales model is verified with the dataset from Silver Pike and Thomas (Silver, Pyke, & Thomas, 2017).

5.3.2 Experimental results

An experiment has been performed on two SRUs, both of which are part of the same LRU. These parts are similar in design, and therefore have equal additive characteristics. The conventional SRUs are different in price and lead time, which may be a result of low demand at the OEM, resulting in less attention being paid to the low-demand SRU.

We use this set of SRUs to make comparison of the multi-item model possible, but in this chapter both SRUs are assumed to be uncorrelated. This means that both parts can be treated as single SRUs part of an arbitrary LRU.

Both parts are guide cards, with the following input parameters:

LRU

The LRU of which both SRUs are part is an Electric Multiplex System (EMUX). This system is responsible for sending electronic messages through the airplane.

	h	N	μ	T	c_{speed}	L_{speed}	c_{BO}	a	OTC
	Holding cost rate per month	Installed base	Mean LRU demand per month	Time horizon			LRU backorder costs per month		
LRU	0,2/12	136	48/144	60	2	2	2000	0	0.95

Table 3, experiment LRU parameters

SRUs

On the inside of the LRU, Printed Circuit boards are placed to transfer the messages. These circuit boards are inserted in a mother board at one side but can still move slightly inside the LR due to vibrations. To counter these movements guides are inserted in the LRU, fixating the circuit boards and preventing them to lose contact with the mother board.

		c_p^x	I^x	L^x	Q^x	rr_{SRU}
Case study 1: Left	CM	3200	0	5	1	24/48
	AM	120	5000	0,5	1	
Case study 2: Right	CM	700	0	2,3	1	22/48
	AM	120	5000	0,5	1	

Table 4, experiment SRU parameters

The difference between the conventional and additive parts can be explained by the old technology, and therefore decreased use of the LRU in a decreasing number of aircraft. When wee transform this lower usage of the LRU into SRU demand, we see that the SRUs add limited value to the supplier. This results in lower stock of the part at the supplier's depot, and thus longer lead times for TC. Also, because each item has to be manufactured in a single bath, the purchasing costs have risen in the past years. The AM parts are similar in design, and thus have the same material input, lead time and purchasing costs. Because they are simple plastic parts, production is straightforward and no additional costs are incurred, making them up t0 25 times cheaper than the conventional part.

Left guide card

We will first look at the left guide card. This SRU has already been developed and produced, and serves as an example of SRUs where the regular supply can be changed to an additive supply of the part.

When we run the model such that we minimize the costs while meeting the service level. For all supply options (CM, AM with backorders, AM with Fast Resupply), we set $OTC \geq 0{,}95$. The results are displayed below in Table 5.

Sourcing option	S	Q	Fill rate	OTC	EBO	PC	HC	BC	DC	Total costs
CM	3	1	0,948	0,954	0,00154	32000	8533,33	30,89		40564,22
AM BO	1	1	0,920	0,959	1,18E-05	1200	170	0,24	5000	6370,24
AM FR	2	1	0,997	1		1200	290	7,67	5000	6497,67

Table 5, performance indicators left guide card

We can see from the results that additive manufacturing is the preferred option, because of the high holding cost and related purchasing costs of conventional manufacturing. When we compare the additive backorder and fast resupply models, we see that the backorder model is slightly cheaper. In the fast resupply model every realization of S results in an OTC of 1, since $L/L_{speed} = a$. Ordering a fast AM part at the arrival of demand will thus result in exactly meeting the LRU repair time. A reorder level S of 0 should thus be adequate to fulfil the fill rate, but at the current reorder point the total lifecycle costs are minimized. A graphical representation of the costs for each option is given in Figure 6. It can be seen that the purchasing costs for CM are extremely high, and that the development costs for AM contribute to most of the AM costs, but both AM options are over €30000 cheaper than CM in the 60 months LRU lifetime.

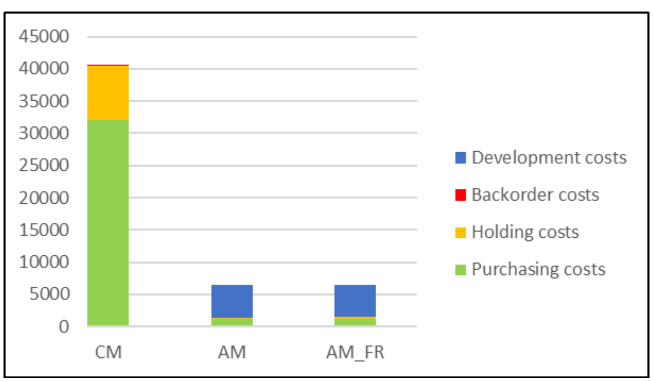


Figure 6, cost breakdown left guide card

Sensitivity analysis

A sensitivity analysis is performed on the current stocking policies, resulting in the allowable changes presented in Table 6.

	Min	Current	Max
Production costs (€)	0,22198119	120	3115,09342
Investment costs (€)	0	5000	39193,9832
Production time (m)	0,25	0,5	0,55774765
(d)	7,609375	15,21875	16,9764441
Mean demand (/m)	3,2552E-06	0,333333333	0,41034589

Table 6, allowable ranges AM parameters left guide card

With the current best option being Additive sourcing with backorders, changes to the production costs and investment costs will not result in changing to additive sourcing with fast resupply. The production costs are allowed to increase up to €3115 before conventional sourcing becomes the optimal sourcing strategy, so the calculation of the production costs is not critical. The same holds for the investment costs, which can increase by €34000 before the conventional sourcing becomes the preferred option.

At the maximum allowed change of the AM production time, the on-time completion rate is equal to 95%, so an increase of the production time to a value greater than the maximum will require recalculation of the model to find a new optimal stocking policy.

The same holds for the mean demand, but it should be noted that at this change of the demand rate, the on time completion rate for conventional sourcing has already been lowered to below 95%.

Right guide card

The right guide card is similar in appearance to the left guide card, and has exactly the same additive parameters. The conventional parameters are however different, in that it has a shorter lead time and lower purchasing costs.

When we look at the performance indicators in Table 7, we see that CM is still more expensive than both AM options, but the difference is smaller. As was the case with the left guide card, the costs for the fast resupply model are slightly higher, which is a result of the increased purchasing price for the fast mode.

Sourcing option	S	Q	Fill rate	OTC	EBO	Purchasing costs	Holding costs	Backorder costs	Total costs
CM	2	1	0,943	0,953	0,000474	6416,67	1482,64	8,70	7908,00
AM BO	1	1	0,926	0,963	9,11E-06	1100	170,83	0,17	6271
AM LS	2	1	0,997	1		1100	290,83	5,95	6396,78

Table 7, performance indicators right guide card

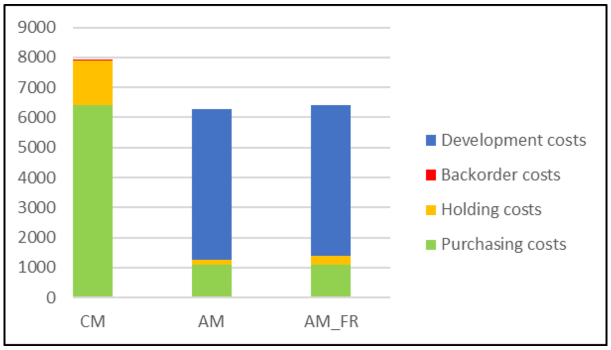


Figure 7, cost breakdown right guide card

The purchasing costs for CM are still high but because of the lower part cost, the total lifecycle costs are lower. This means that because of the AM development costs, which are still the largest cost factor for AM, the costs differences between the three sourcing options are small.

Sensitivity analysis

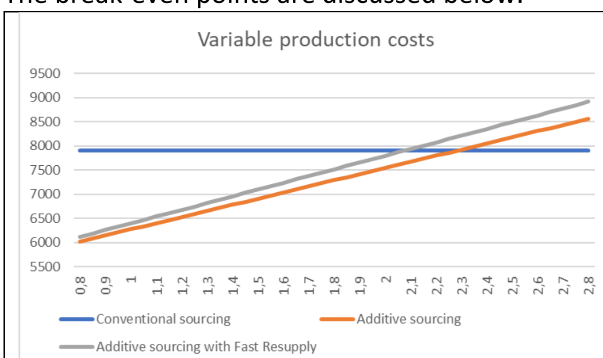
A sensitivity analysis is performed on the current stocking policies, resulting in the allowable changes presented in Table 8.

	Min	Current	Max
Production costs (€)	0,15914966	120	274,576116
Investment costs (€)	0	5000	6637,00401
Production time (m)	0,25	0,5	0,58573748
(d)	7,609375	15,21875	17,8283847
Mean demand (/m)	0,22593825	0,333333333	0,44760179

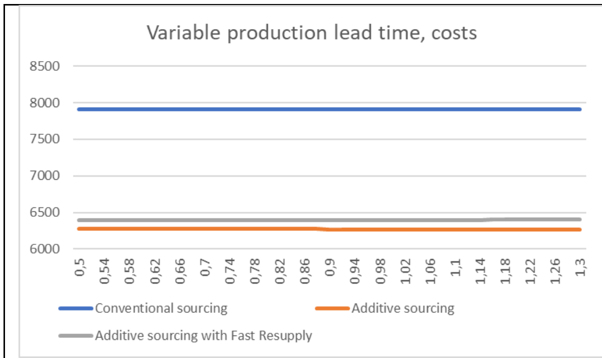
Table 8, allowable ranges AM parameters right guide card

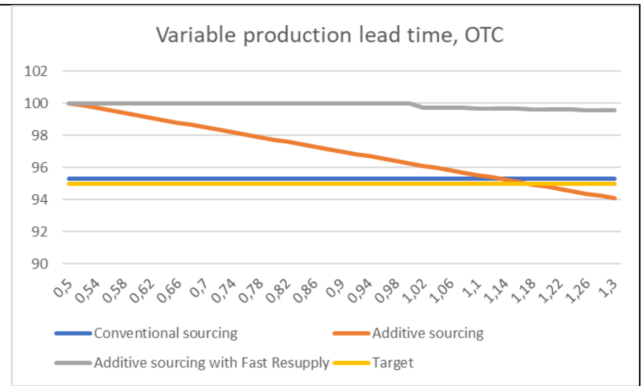
Compared to the sensitivity analysis of the left guide card, the allowable ranges for the production- and investment costs are smaller. For the production costs, the allowed increase is now only €150, and €1600 for the development costs. This means that, when deciding to start AM production on the right card, more attention has to be given to the actual values of these cost parameters. For instance, unexpected additional development costs can easily reduce the AM potential in such a way that conventional production can still be the most cost-effective option after all.

The break-even points are discussed below.

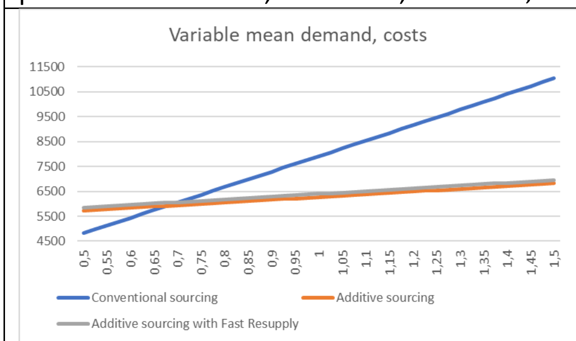


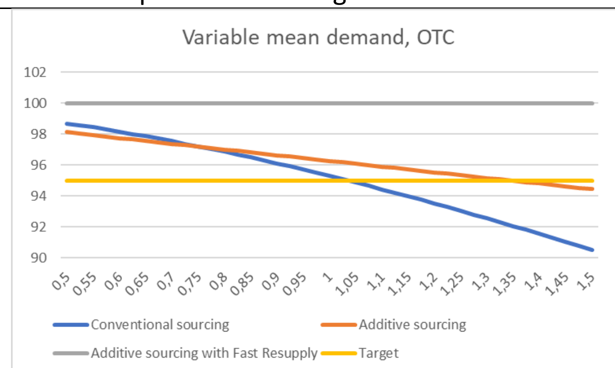
Changing the additive production costs results in increased costs for both additive sourcing options.
AM will be equal to CM at $p^* = 274{,}5$ or $p^* = 2{,}29 \cdot p$
AM_FR will be equal to CM at $p^* = 250$ or $p^* = 2{,}08 \cdot p$





Changing the additive production lead time results in cost changes of less then €10 and can be neglected. The changes to the OTC are larger, since the possibility of a backorder is increasing. At a production time of 0,58 months, or $L^* = 1{,}17 \cdot L$ the OTC drops below the target OTC.





Changing the LRU demand results in extreme changes to both the costs and the OTC. AM and AM_FR will see their costs rise above the CM costs at μ^*=0,23 and 0,24 respectively.
Because the lead time is equal to the LRU repair time in the fast resupply option, the OTC for AM_FR remains high. The regular AM model does see more backorders, which results in a lower OTC, dropping below the target at $\mu^* = 0{,}44$.
CM, with its longer lead times, is more sensitive to demand changes, as can be seen by the faster increasing costs and decreasing OTC. CM drops below the target OTC at a demand rate of 0,34 which is barely above the estimate value.

5.4 Conclusions

When there are no shared SRUs, and each LRU has exactly one SRU, the model behaves like any other (S, Q)-model. When Q=1, the model resembles the special case of the (S,Q)-model where the order-up to level is the base stock in the base stock model. Usage of the emergency order in the fast resupply model is only recommended when the reduction in lead time and thus LRU backorder costs is larger than the increased costs of purchasing.

In the case studies performed in this chapter, we can see that both the lead time and production costs for the additive part are lower than the same parameters for the conventional part. This results in better performance of the additive parts, and the recommendation to develop and use the additive designs for both the left and right guide card.

6 Multiple SRUs

When facing multiple defect SRUs in a repair, we have to introduce an LRU repair service level. Furthermore, we have to consider that an LRU is only functional if all defect SRUs have been replaced. For an LRU with two SRUs, the On Time Completion rate for both SRUs needs to be high enough to not inflict waiting time when both parts are needed in an LRU repair.
Compared to the single SRU model of chapter five, we expect the SRU reorder points S to rise, in order to achieve high service levels for a combination order.

We use the model constructed by Song (Song, On the Order Fill Rate in a Multi-Item, Base-Stock Inventory System, 1998) as the basic building block for the multiple SRU case. We will explain the 2-item model below and use this model to adapt the model to our needs. This model can be expanded to an n-item model, but for sake of simplicity we will use a two-item model to explain the model. Introducing combinations with three or more SRUs will only be needed when the expected occurrence of a combination is high enough to have an impact on the sourcing policies.

6.1 Model

Suppose there is an LRU with a demand rate μ, and two SRUs with known lead times, indicated with a subscript 1 or 2.
Order demand occurs in a set K. Each order characteristic is indicated with a superscript k, where k is the set {1,2,12}. Demand realization of each demand type is given by the replacement rate rr^k

item	demand	Lead time	Reorder quantity	Reorder point
LRU	μ			
SRU1		L_1	$Q_1 = 1$	S_1
SRU2		L_2	$Q_2 = 1$	S_2

Table 9, SRU parameters

Repair order	k	Replacement rate rr^k
Only 1	1	rr^1
Only 2	2	rr^2
Both 1 and 2	12	rr^{12}

Table 10, repair order parameters

The total demand of an SRU can be calculated by summing the replacement rates of all orders k using the SRU. We introduce a subset (i, K) of all orders K using SRU i, and sum the replacement rates of all orders in this subset to get the total SRU demand, such that

$$\mu_i = \mu \sum_{(i,K)} rr^k \tag{6.1}$$

The total lead time demand for an SRU is the sum of all demand realizations using the SRU, so $D_{L_1} = \mu_i \cdot L_i$. The fill rate can then be calculated as the Poisson probability for the (S, Q)-model with Q=1:

$$Fr^1 = \sum_{i=0}^{S-1} \frac{e^{-D_{L_1}} \cdot D_{L_1}^{\ i}}{i!} \tag{6.2}$$

Changing the model to the general (S,Q)-model can be done by replacing equation (6.2) by equation (5.7).

Calculation of the fill rate for both SRUs is explained by Song (Song, On the Order Fill Rate in a Multi-Item, Base-Stock Inventory System, 1998), and relies on the assumption that $L_1 \leq L_2$.

The fill rate of the combination of SRU1 and SRU2 is the cumulative probability that demand is smaller than the reorder point for both items used in the repair. Since the lead time for SRU2 is longer than the lead time for SRU1, the demand for the remaining time period for both SRU2 and the combination order is added to the lead time demand from SRU2. When the lead times are equal, the fill rate will just be the product of the individual fill rates.

$$
\begin{aligned}
Fr^{12} = \quad & \sum_{k=0}^{Min(S_1,S_2)-1} \frac{e^{-Mean12} \cdot Mean12^k}{k!} \cdot \sum_{i=0}^{S_1-k-1} \frac{e^{-Mean1} \cdot Mean1^i}{i!} \cdot \sum_{i=0}^{S_2-k-1} \frac{e^{-Mean2} \cdot Mean2^i}{i!} \\
with \quad & Mean12 = rr^{12} \cdot L_1 \cdot \mu \\
& Mean1 = rr^1 \cdot L_1 \cdot \mu \\
& Mean2 = \left(rr^2 \cdot L_1 + (rr^2 + rr^{12}) \cdot (L_2 - L_1)\right) \cdot \mu
\end{aligned}
\tag{6.3}
$$

Validation of the multi-item fill rate is done by calculating a lower and upper bound on the fill rate (Song, On the Order Fill Rate in a Multi-Item, Base-Stock Inventory System, 1998). The lower bound weighted average of the SRU fill rates F^i plus the non-correlated expectancy of the fill rate.

$$LB^{Fr12} = rr^1 \cdot F^1 + rr^2 \cdot F^2 + rr^{12} \cdot F^1 \cdot F^2 \tag{6.4}$$

The upper bound is given by the statement that all SRUs are available, except one. The upper bound is thus given as:

$$UB^{Fr12} = rr^1 \cdot F^1 + rr^2 \cdot F^2 + rr^{12} \cdot Min(F^1, F^2) \tag{6.5}$$

Obviously, it should hold that $LB^{Fr12} \leq Fr^{12} \leq UB^{Fr12}$

6.1.1 On time completion

Using the same logic as in the previous chapter, we can calculate the on-time completion rate by decreasing the lead time L with the maximum allowed waiting time a. The Poisson means for equation (6.3) will then transform to the means in equation (6.6), where $x^+ = Max(0, x)$.

$$
\begin{aligned}
& Mean12 = rr^{12} \cdot (L_1 - a)^+ \cdot \mu \\
OTC^{12} = \quad Equation\ (6.2)\ with\ & Mean1 = rr^1 \cdot (L_1 - a)^+ \cdot \mu \\
& Mean2 = (rr^2 \cdot (L_1 - a)^+ + (rr^2 + rr^{12}) \cdot (L_2 - L_1 - a)^+) \cdot \mu
\end{aligned}
\tag{6.6}
$$

6.1.2 Backorders

The expected backorders for single SRU-demand are calculated using the same steps as in chapter 5, such that $EBO_i =$ equation (5.10) with mean $\mu \cdot \sum_{i \in K} rr^i \cdot L_i$.

To calculate the expected backorder for each order k in the set K, we have to find the correlation between the demand streams for both products in an order. This has been researched by Song (Song & Zipkin, Supply Chain Operations: Assemble-to-Order Systems, 2003), who states that a direct exact approach is possible, but can be approximated with high accuracy when the fill rate is high. This approximation is based on the average between the lower and upper bound. We will discuss both bounds below.

For all realizations of the reorder point, it holds that $LB^{EBO} \leq EBO^{12} \leq LB^{EBO}$, but for relatively high fill rates $EBO^{12} \cong \frac{LB^{EBO} + UB^{EBO}}{2}$

The lower bound on the expected backorders is given by the assumption that only one SRU is missing, which will happen at a rate $\frac{order\ k\ demand}{SRU\ i\ demand} \cdot EBO_i$. The lower bound can thus be represented as:

$$LB^{EBO,k} = rr^k \cdot \mu \cdot \max_{i \in K} \left(\frac{EBO_k}{k} \right) \tag{6.7}$$

The upper bound on the expected backorders is given by the assumption that both SRUs are on a backorder. the backorders for both SRU 1 and SRU 2 will then be encoutered by the order, giving an upper bound of:

$$UB^{EBO,k} = rr^k \cdot \mu \cdot \sum_{i \in K} \left(\frac{EBO_k}{\lambda_k} \right) \tag{6.8}$$

The expected backorders for both single-item and multi-item orders can be estimated by taking the average of both bounds such that the expected backorders for each order can be written as:

$$EBO^i = \frac{LB^{EBO,k} + UB^{EBO,k}}{2} = \frac{rr^k \cdot \mu \cdot \left(\max_{i \in K} \left(\frac{EBO_k}{k} \right) + \sum_{i \in K} \left(\frac{EBO_k}{\lambda_k} \right) \right)}{2} \tag{6.9}$$

The total LRU backorders can be calculated by summing the order backorders, such that $EBO^{LRU} = EBO^1 + EBO^2 + EBO^{12}$

6.2 Computational experiments

Before starting computational experiments, we verify and validate our model. Verification ensures that the model works according to the paper specifications and is behaving as we would expect it to. Validation ensures that the model output is similar to what is encountered in reality.

6.2.1 Verification and validation

The multiple SRU model is verified using the test data provided by Song (Song, On the Order Fill Rate in a Multi-Item, Base-Stock Inventory System, 1998).

6.2.2 Experimental results

In order to see the difference in results between the single- and two SRU model, we use the same SRUs as in the previous chapter. We set the LRU and SRU demand rates such that the total SRU demand rates are equal to the demand rates in the single SRU model.
For clarification, we repeat the input data in Table 11 and Table 12 below.

	Time horizon	Demand rate	Maximum LRU waiting time	LRU backorder cost	Lost sales lead time decrease factor	Lost sales costs increase factor
	T	m	a	C_BO	L_{speed}	F_{speed}
LRU	60	1/3	0.25	2000	2	2

Table 11, LRU input parameters multiple SRU repair

The replacement rate for the combination of both SRUs is set to 10 percent of the total LRU demand. To compensate for this compensation, the replacement rates for the single replacement orders are decreased with the same factor. When calculating the total SRU demand, we can see that it is equal to the case from the previous chapter.

	Replacement rate	Lead time	Purchasing cost	Development costs
	rr	L	p	I
Right_ CM	22/48 - 0.1	2.3	700	
Right_ AM	22/48 - 0.1	0.5	120	5000
Left_ CM	24/48 - 0.1	5	3200	
Left_ AM	24/48 - 0.1	0.5	120	5000
both	0.1			

Table 12, SRU input parameters multiple SRU repair

In total, four different sourcing combinations are feasible:

1. No AM production, source both using CM
2. Produce Right using AM
3. Produce Left using AM
4. Produce both SRUs using AM

For all combinations, we set all order quantities Q to 1 and choose reorder levels S such that the on-time completion rates are at least 0.95 while minimizing the total costs. The results are given below in Table 13, together with a comparison with the single SRU-model. The last column gives the cost increase of the multiple-SRU model compare to the same sourcing combination when using the basic one-SRU model.

	Reorder point		Costs			On-time completion	Cost increase w.r.t. single SRU repair
Basic	S_R	S_L	Right	Left	Total	OTC^{12}	
Combination 1	2	3	7908	40564,22	48472,22	0,917	
Combination 2	1	3	6271	40564,22	46835,22	0,925	
Combination 3	2	1	7908	6370,236	14278,24	0,924	
Combination 4	1	1	6271	6370,236	12641,24	0,931	
Multiple SRUs	S_R	S_L	Right	Left	Total	OTC^{12}	
Combination 1	4	3	9299,34	40564,22	49863,56	0,955	1391,33
Combination 2	2	3	6390,84	40564,22	46955,05	0,959	119,83
Combination 3	2	2	7908	6490,002	14398,01	0,961	119,77
Combination 4	1	2	6271	6490,002	12761	0,962	119,77

Table 13, comparison single and multiple SRU repairs

The reorder levels for the multiple SRU model are slightly higher than for the single repair model. This can be explained by the fact that the single item reorder levels are sufficient to achieve the single item demands, but result in a multi-SRU order OTC which is below the target of 95%. The cost increase can be explained by the increased holding costs. For each item put to stock, holding costs are incurred, while the expected backorder costs decrease slightly.

6.3 Conclusions

Extension of the single-SRU model to a multiple-SRU-model is possible for AM sourcing when the reorder quantity is one. In this model, the average backorders are lower than in the single SRU model with similar reorder points. However, since a fill rate needs to be achieved for a combination order of two SRUs, we see that the reorder points of the individual SRUs needs to be raised.

Changing the model from a single SRU to a multiple SRU repair comes at the expense of added calculations because every combination of AM and CM has to be considered. Moving to the multiple SRU model is thus only recommended when performance issues are expected by using the single SRU model.

7 Implementation

Decisions on when to change from CM to AM production are made by the product managers and reliability engineers. Probable causes to look into the possibilities of a change are changes in the conventional sourcing parameters, such as increasing prices or lead times. These changes might indicate a supplier's unwillingness to keep supplying a part. Changes to these characteristics will be presented in new order information supplied by the suppliers.

The problem might be solvable by using a last time buy, which means that a large final production order is placed to get enough inventory until the end of the LRU life time. While this last time buy saves on AM development costs, it does require calculations on the risks and benefits to ensure the right amount is being bought, since you have to get enough to fulfill all future demands but want to minimize end-of-life disposal costs.

Our model can be used to find out if the problem can be solved by changing the production method from CM to AM. For the LRU and the CM part, all relevant information can be found in TCs ERP system. Since the decision has to be made before the AM part has been developed, information on the expected prices of the AM-produced part are not known. To get information on the AM part, we use an AM costs estimation tool previously created at TC. This tool determines the best additive production process based on the part dimensions, required strengths and product drawings. Because of the use of required strengths and drawings, the tool needs to be used by a skilled engineer, and every part which is considered a possible candidate for AM production has to be selected and evaluated separately.

For LRU repairs where only one SRU is replaced per LRU repair, the single LRU model can be used to calculate the expected lifetime costs for both the CM and AM part. When the engineers have estimated the AM parameters, the model is run, resulting in stocking options for all models (CM, AM, AM with Fast Resupply). The product managers can then decide on the best sourcing strategy.

For LRUs where it is expected that more than one SRU has to be replaced, the model extension for multiple SRUs can be used. This model is more accurate because of the increased input, but requires more time to calculate the optimal stocking decisions.

After completion of this project, a comparison with the project by van Jaarsveld came up (van Jaarsveld, Dollevoet, & Dekker, 2015). In this research, which is performed at TC, the spare parts control is optimized using (s, S)-policies. These spare parts are part of repair orders which include orders with multiple parts, just like chapter six of this research.

Our model is created to support decision making for one LRU at a time by the product managers, and will mainly be used when the CM producer announces new prices or lead times, indicating to TC that supply disruptions may be at hand and action is required. When this will happen at larger scales, implementation of our model in the model by van Jaarsveld might be useful to automatically discover supply chain improvements on a company-wide scale.

For now, since the estimation of AM parameters needs to be done manually, we recommend using our model as a stand-alone tool to support decision making. When a change to AM is required, the ERP system is then updated with the new AM parameters, and the van Jaarsveld model is used as before.

When the estimation of AM parameters can be done automatically, or when a large amount of estimations can be made easily, out model could be integrated by implementing the three different sourcing options in the van Jaarsveld model, such that that model can be run automatically and decide on changing the sourcing method.

8 Conclusions and recommendations

The goal of this thesis is to create an easy tool to calculate possible supply chain benefits of additive manufacturing. Since there already exists an AM cost tool which calculates the expected printing and development costs, this tool focusses on the impact on the supply chain. Our tool is thus a decision tool in which the combination of the most optimal production technique and sourcing option has to be found. We have achieved this by comparing conventional sourcing with backorders, additive sourcing with backorders and additive sourcing with a fast resupply option. For all three options, the most optimal reorder quantity and reorder point can be calculated such that the total lifetime costs are minimized while achieving a service level. The chosen service level is the on-time completion rate, which is the expected percentage of LRU repairs which is delivered back to the airline in time.

We recommend using the tool as a stand-alone tool to decide whether investing in AM might pay off. The result of the costs comparison combined with the result of the sensitivity analysis on the estimated AM values give an overview of the possible gains of investing in AM and the risk involved with the decision.
When a solution can be found to the manual input of the AM cost calculation, the tool can be implemented into the van Jaarsveld model. This requires adding the fast resupply option to the model, as well as iterative process to calculate the best stocking parameters for each combination of printable SRU.

In this research we focused on simple spare parts that might be used in multiple LRUs. The model we created optimizes the stocking policies for a single LRU. a further study can be done on the effects of incorporating multiple LRUs and the effects of different LRU repair times or on-time completion rates on the stocking policies of the SRUs.

9 Discussion

All model parameters are assumed to be stable. It might happen that prices or lead times of the conventional part are increasing over time. This will result in increasing purchasing costs or higher reorder levels. Both factors will result in higher total costs for the conventional SRU and thus an improved potential for the additive SRU.
Because of increasing development on additive manufacturing, AM production will become more used, which result in decreasing prices and lead times of the additive part. This will result in lower lifetime costs, further improving the potential for AM production.

A large contributing factor of AM is that changing parameters because of the unwillingness of a supplier to produce the part are not present. When a supplier is not willing to produce a part any more, any other AM service provider will be able to produce the same part with similar costs and lead times. This results in a more stable resupply of the part which improves TCs supply chain control.

The models compare the conventional and the additive part on costs and delivery performance. Both are quantifiable but lack information on the customer satisfaction and supply chain control. It is reasonable to assume that a faster repair lead time will improve the customer satisfaction, and more control on the supply of spare parts increases the performance of stocking models and costs estimates. These effects are however not measurable in terms of money, and can therefore not be used in the comparison of the sourcing method. Our results should thus be regarded as a cost-comparison only, and changes to the customer satisfaction and supply chain control should also be taken under consideration when deciding on a possible change to AM production techniques.

Stocking of AM SRUs

We assumed that SRUs can be produced to stock. Part 145 regulation states that non-original parts may only be produced to finish a current repair, and production for stocking is not allowed. When introducing AM-produced parts, it is advisable to discuss the new design possibilities of AM with the FAA and EASA, such that parts produced using AM are given a status that allows for their usage in the same way as the original CM-produced parts. Until that has been done the usage of AM is limited to usage as quick-fix where the reorder point is zero.

Improved contracts

When AM is used and the production lead times are slightly longer than or shorter than the allowed repair time a, the on-time completion rate can become so large that different repair contracts can be investigated. In these contracts, LRUs can be repaired in shorter times at increased costs. This might benefit airlines since their stock levels can be lowered due to the shorter turnaround times.

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