Eindhoven University of Technology

MASTER

Using Additive Manufacturing in the RNLA Spare Parts Supply Chain

Hertog, Max J.C.

Award date:
2023

Department of industrial Engineering & Innovation Science
Operations Planning and Control Group

Using Additive Manufacturing in the RNLA Spare Parts Supply Chain

Master Thesis

14th June 2023

By:
M.J.C. Hertog
Student number: 1009869

In partial fulfillment of the degree:
Master of Science
Operations Management and Logistics

TU/e Supervisors:
Ir. Dr. S.D.P. Flapper
Dr. ir. R.J.I. Basten

RNLA Supervisors:
R.D. Cornelissen
C.G. Fokker
M.G. Tamis

Abstract

In this master thesis research we present a multi-echelon spare part inventory model for the RNLA mission supply chain incorporating additive manufacturing. We focus on deployment in an active combat scenario. We view additive manufacturing as an alternative to purchasing spare parts. We identify factors and uncertainties that influence the implementation of additive manufacturing in the RNLA setting. We describe a mathematical model to evaluate multiple additive manufacturing techniques in multiple locations under the influence of the identified factors and uncertainties. The evaluation is based on minimizing costs under an acceptable vehicle readiness. We write a computer tool so the RNLA can easily use the model to evaluate the best AM configuration in multiple scenarios. Through the analysis of a number of test scenarios we show whether or not AM leads to reduced stock or reduced costs. We show that when AM is used as a replacement for conventional manufacturing, the costs and stocks increase for polymer parts. We find this is mainly due to the quality difference between AM produced parts and conventional parts. We see that for example calculations with a metal part, the use of AM decreases the required stock. We also see that printing is most beneficial in a more upstream location with a more expensive and more reliable printer. The findings in this research are based on military deployments but can be important for other organizations who operate critical equipment in remote locations.

Executive Summary

This research is the product of a Master graduation project at the Royal Netherlands Army (RNLA). For the RNLA to complete their main goals, conservation of equipment is a key factor. The failure of equipment does not only lead to financial consequences but can also endanger the lives of military personnel. The amount of spare parts needed to keep equipment functioning is highly uncertain. Therefore, to avoid system downtime, currently large numbers of spare parts have to be shipped to and kept in mission areas. These mission areas are often remote, leading to a high expense of resources. RNLA experts and previous research have identified additive manufacturing (AM) as a way to source spare parts closer to the mission area and reduce the expense of resources. For the RNLA there are still questions on how to exactly use AM in order to improve the conservation of equipment and reduce the amount of resources required for this conservation.

In this research we focus on the remote spare part supply chain for an active combat deployment. We are interested in whether to implement AM in such a supply and if so where to implement what type of AM machinery. Based on these needs the main research question of this research is:

"How can AM be used in the RNLA mission supply chain to reduce the logistical footprint?"

We answer this research question with the help of a prototype decision support tool that can be used to identify the AM configuration that reduces reduce the logistical footprint in a given scenario. With logistical footprint we denote the total amount of resources required to supply units in the field. This includes material requirements such as transports or spare parts, the number of man hours required and the financial expenses required. We focus on reducing costs under a given material readiness (equipment availability). We also evaluate the number of spare parts required to reach a certain material readiness. The application of AM is subject to a number of uncertainties such as danger, the sourcing of raw material and the environment where the printing takes place. A detailed description of uncertainties and other factors influencing AM is identified based on literature and interviews. Furthermore an evaluation of AM technologies and their characteristics is made, also based on interviews and literature. Subsequently we formulate a model which incorporates the most prevalent uncertainties and factors. The model is subsequently integrated in a prototype tool in order to solve it for different input parameters. The AM technology and spare part characteristics are used as guidelines for a number of AM configurations that are evaluated using the tool. We use the tool to evaluate the best AM configuration for an example deployment. We also do other numerical experiments based on interesting input parameters to find the best AM configuration for these potential scenarios.

We used a mathematical approach to identify the optimal supply chain stocks for a multi-echelon inventory model. The model is optimized for a single item at a time and returns the optimal echelon stock levels and the corresponding costs for each AM configuration. We only review downtime critical components and use a Poisson distribution to describe spare part demand. We use a supply chain existing out of a depot in the Netherlands, a Deployed Central Stock (DCS) and a Main Operating Base (MOB). For all locations we use a (S-1, S)-policy, meaning an order is placed immediately when demand occurs. We review printing capabilities in all locations. At the depot we use a stable printing installation capable of producing both polymer and metal parts with relatively small production losses (1%). At the DCS we use an integrated solution with the same capabilities, but slightly more production losses (10%). At the MOB a cheaper and faster machine with more production losses (30%) and a more expensive and slower machine with less production losses (20%) are tested. We review the best configuration for various parts. The polymer parts in the research belong to the Fennek reconnaissance vehicle and Boxer armored vehicle. We also investigate a metal part from the NH90 helicopter, as it is the only metal part with sufficient data on AM production. We do a scenario analysis for a hypothetical active combat deployment in Lithuania. This deployment is characterized by frequent supply of spare parts and high levels of material wear. In the other numerical experiments

we investigate the effect of increasing the demand intensity, increasing the quality of printed polymer parts, simulating shipment blockades and simulating AM raw material shortages.

The results for the scenario analysis show that the scenario without AM, has the lowest total costs and required stock for polymer parts under a chosen readiness of 99.99%. We do see that printing at the depot, is the best performing AM scenario from a cost perspective. The scenario has a cost increase of 47.2% and 3 times the stock of the scenario without AM. Printing at the DCS, is the best performing AM scenario from a stock perspective. The scenario has a cost increase of 60.9% and 1.71 times the stock of the scenario without AM. Total spare part costs for the scenario without AM are *€688.56*, *€15.30* for printing at the depot and *€11.90* for printing at the DCS. The results for metal parts lead us to believe that there is serious potential for using printed metal parts as full replacements. The stock can be decreased by about 33.3%. Also we see that the total cost recorded through the model for the scenario without AM is *€64,508.59.* For printing at the depot the costs are *€76,220.87.* This is a price difference of 18.2%.

The main takeaways from the other numerical experiments are:

- The effect of the increased demand intensity caused by the higher failure probability for polymer AM parts is shown to indeed be significant. However, even for a decreased demand intensity the configuration without AM still performs better based on costs and the required spare part stocks.
- We see that delays or longer lead times at any specific installation have significant impact on the required spare part stocks and the total costs.
- The effect of a material shortage for the production of AM is detrimental for the overall performance of any of the AM configurations evaluated. We also see that the results for printing at the MOB suffer worst under these conditions.

The results show the quality difference of AM produced parts has a significant influence on the total costs and the required spare parts. This leads us to believe that printed polymer spare parts can only function as full replacements when the quality of these parts is equal to the quality of conventional spare parts. From the interviews we know this is not the case with current technology. Therefore using printed polymer parts as full replacements is currently not a viable option. From the results we can also conclude that printing metal parts can be an effective way of decreasing spare part stock for the RNLA for a relatively small increase in costs. We also see that although the demand for printed polymer parts is 10 times higher, the stock required for the AM configurations at the depot and DCS is not 10 times higher. This again shows that AM has potential to reduce overall stock, but is currently limited by the quality difference for the polymer printed parts.

That delays or longer lead times at any specific installation have significant impact on the required spare part stocks and total costs leads us to believe that placing stock points on equal lead time intervals, leads to a lower total stock. A potential solution for this could be to further decouple the supply chain and ad more stock points along the deployment supply chain. We do admit that this is very costly and the benefits hereof might therefore not outweigh the costs. To further identify the effect of further decoupling the supply chain, more research is necessary.

A limitation of the research is that the mathematical model parameters are all based on static values. Therefore the uncertain variables such as lead time, printing time and demand are not entirely accurate. As can be seen from the sensitivity analysis and numerical experiments, changes in these parameter values can lead to significant changes to the output. Therefore future research should work on a dynamic model including uncertainties as stochastic variables. For such a dynamic model uncertainties should be based on well fitted distributions or transition probabilities, which requires more data. Specifically data on the AM printing process and shipment delays could improve the current estimates and potentially lead to different results.

A further limitation is that the mathematical model is written for single sourcing and a single item at a time. This means that we regard AM as a replacement for ordered spare parts in our model. Future research should use the notion of AM parts being a full replacement and also incorporate ordered spare parts. This would create a dual sourcing situation in future research, which we believe could be an even more effective use of AM. We also only review one item at a time which is also a point where our model can be improved. The question also remains how to prioritize spare part and raw material demand for a limited printer and storage capacity.

We also recommend further efforts to collaborate with OEMs in order to help with certification and licensing of printed spare parts. Proving the quality of printed spare parts and working together with OEMs to establish licensing arrangements will boost the use of AM withing the RNLA. Such a combined effort with OEMs can also be a good way to improve the quality of printed polymer parts by identifying ideal printing methods and conditions for each part. As we have identified already, increasing the quality of polymer printed parts can enable them to eventually be used as full replacements for conventional spare parts. How much the quality needs to improve to enable the use as full replacements is something which requires further research. It also requires more research and data to identify if the necessary quality improvements are feasible with current or future AM technology.

We assume there is enough capacity to operate AM machinery, however in reality this might not be possible. Future research should also focus more on the capacity constraints that hold in the backfield. This can be done through investigations of how AM power consumption affects other operations. Also investigations of the physical space required for AM equipment and raw material to see if it is viable to keep the amount of raw material stock proposed by our tests.

The data on printable metal parts is currently also very limited. What metal parts can be printed is an area where more research at the RNLA is necessary in order to expand on the findings of this research.

Preface

This report is the result of 8 months of research at the Royal Netherlands Army as partial fulfillment of my Master of Science in Operations Management and Logistics at the Eindhoven University of Technology. This concludes my time as a student and marks the beginning of a whole new period. The research has consumed a good portion of my time and has been my main focus for these past months. It has been a difficult period with a lot of struggles, but also a great feeling of accomplishment. I am thankful for the support of all the people involved in the project and those who have supported me in my personal life.

First of all I would like to thank my TU/e supervisors. I want to thank Simme Douwe Flapper for his unyielding effort and the many hours he has put in to guide me through this research project. Without his very critical view and constructive feedback I would not have been able to complete this project. I also want to thank Rob Basten for taking the time to review my project and give me feedback on multiple occasions.

Second I would like to thank the supervisors from the Royal Netherlands Army. I would like to thank Ruben Cornelissen and Mark Tamis for their insights on operations and processes and help with reaching the correct people within the Royal Netherlands Army. Your continued help was very valuable. I also want to thank Chris Fokker for helping me with all administrative tasks at the Royal Netherlands Army and your continued concern and support of my project and my personal wellbeing.

I would also like to thank the other people from the Royal Netherlands Army, the ETAM, the NLR and Brightlands who have helped me through participating in interviews and answering my questions. Your insights where of great value for this research. I want to thank you for your time, effort and interest in my research.

Lastly I would like to thank my friends, family and most of all my partner. You have given me the necessary distractions throughout this project. Also you supported me in my day-to-day tasks when I was overwhelmed by the work and listened to me when I was lost. Without your help I would not have been able to complete this project.

For now I am glad I can conclude this part of my life and look back with pride upon a very difficult but rewarding period. I am looking forward to the challenges ahead at my new job and am curious what the future has to offer.

Max Hertog

Maastricht, June 2023

ROLIAC
ROBUST AND LIGHT AM COMPONENTS FOR MILITARY SYSTEMS

This thesis is part of the ROLIAC project, funded by the EU (European Defense Fund). ROLIAC is a 3-year research project with 10 partners across the EU and a budget of approximately EUR 4,000,000. The goal of this project is to demonstrate the benefits of Additive Manufacturing (AM) and to push towards a faster implementation of AM in European defense by showcasing AM along the whole production chain.

Funded by
the European Union

Table of Contents

List of Tables

List of Figures

List of abbreviations

Abbreviation	**Meaning**
AM	Additive manufacturing
BDR	Battle damage repair
CDF	Cumulative distribution function
CLAS	“Commando Landstrijdkrachten” i.e. land forces command
CM	Conventional manufacturing
DCS	Deployed Central Stock
FFF	Fused filament fabrication
IP	Intellectual property
KPI	Key performance indicator
MAE	Mean absolute error
MOB	Main operating base
OEM	Original equipment manufacturer
PDF	Probability density function
PMF	Probability mass function
POD	Point of debarkation
POE	Point of embarkation
RNLA	Royal Netherlands Army
RQ	Research question
SC	Supply Center
SLM	Selective laser melting
VEDN	Vital, Essential, Desirable and Non-supply parts

List of operational definitions

Operational term	**Explanation**
Additive manufacturing	The process of joining materials to make parts from 3D model data, usually layer upon layer.
Additive manufacturing technique	There are seven main additive manufacturing techniques; Vat photopolymerization, Material extrusion, Material jetting, Binder jetting, Powder bed fusion, Directed energy deposition, and Sheet lamination.
Additive manufacturing technology	The specific additive manufacturing technique and material type used to produce an item.
Battle damage repair	The repair of equipment in the field in a quick, non-permanent manner in order to get the equipment back to a location where proper maintenance can be done.
Conventional manufacturing	Established techniques more broadly used in industry, think of milling, casting or cold forming.
Fused Filament Fabrication	Continuous filament of a thermoplastic material is melted through an extruder nozzle and deposited on the workpiece (material extrusion).
Industry 4.0	The fourth industrial revolution where automatization and data are central themes.
Logistical downtime	The time when logistical connections in between stock points are unusable.
Logistical footprint	The total amount of resources required to supply units in the field. This includes material requirements such as transports or spare parts, the number of man hours required and the financial expenses required.
Main operating base	Most forward location in the RNLA supply chain where spare part stock is kept.
Mass customization	Production mode that provides customized products and services with low cost, high quality and efficiency in mass production with the support of technology, modern design methods, information technology and advanced manufacturing technology.
Point of debarkation	The point where goods arrive after being shipped from the Netherlands to somewhere in or near the deployment country.
Point of embarkation	The point where goods are shipped from the Netherlands to the POD. This is done through strategic movement.
Rapid Manufacturing	The fast production of (small) series of a product.
Rapid prototyping	The quickly producing of a physical prototype.
Rapid repair	The fast repair of a product through the quick production of a spare part or repairing a broken part.
Strategic movement	The shipping of goods from a POE to a POD by land, air or sea.

Subtractive manufacturing	Taking away material from a larger piece to produce a product. Also referred to as machining.
Vehicle readiness	The percentage of time a vehicle is in a usable state.

1 Introduction

In this chapter a short introduction to the research and the research context is given. We discuss the main topic and the company context in Section 1.1. In Section 1.2 we discuss some of the concepts used in this research, such as additive manufacturing. We explain how this specific research fits the company's' needs and expands current literature in Section 1.3.

1.1 Introduction to the RNLA context

This research is conducted at the Knowledge Center for Logistics, which is part of the logistical training organization of the Royal Netherlands Army (RNLA). The Knowledge Center Logistics aims at maintaining existing knowledge and accumulating new knowledge on logistics operations within the RNLA. This also includes the research towards novel logistics, using, for example, drones and additive manufacturing.

The Netherlands armed forces have three main tasks (Dutch Ministry of Defence, 2022):

1. Protect own territory and that of allies.
2. Promote the (international) legal order and stability.
3. Provide assistance in the event of disasters and crises.

For the RNLA this translates into three types of operating environments:

1. Active combat missions.
2. Peacekeeping missions.
3. Peacetime.

With the term mission we refer to both environment 1 and 2. All three of the environments have very different characteristics. During missions, equipment is used more frequently . They are also subject to more adverse conditions, such as harsh climates. Furthermore, the supply chain of missions is often more complex since urgency, uncertain supply of spare parts and danger play a role. The most downstream locations are mobile, which can be challenging. The supply related to missions can be anywhere in the world, which is an added difficulty for the RNLA. Active combat missions in particular often incorporate even more uncertainty due to the increased danger for equipment and personnel. In peacetime, these uncertainties are smaller and less impactful. Therefore, the focus in the research will lie on the mission supply chain. The supply chain generally starts at the original equipment manufacturer (OEM), which produces equipment and spare parts for that equipment. These are shipped to the depot in the Netherlands. Actually there are multiple depots, but since all goods travel through one point and the depots are relatively close together, the supply chain is simplified to contain one depot. From the depot the goods are transported to a point of embarkation (POE) for strategic movement, which can be through plane, train, ship or truck. The strategic movement is the transport from the Netherlands toward the country of deployment. The unloading from the strategic movement is done at a point of debarkation (POD). At the POE and POD no stock is kept, they are simply gathering points. From the POD, the goods are shipped through a deployed central stock (DCS)/ supply center (SC) that receives all goods shipped from the Netherlands. This point is between 150 and 200 kilometers from the frontline. From this point stock is transported to a main operating base (MOB). Crews doing repairs in the field are supplied from the MOB. In Main Task 1 this location can be mobile, encounters more danger and has worse infrastructure. Based on these factors it is more expensive to keep stock here. The supply chain for a deployment can be described as a 3-echelon system. In the situation of Main Task 1 only one supply chain is supported. This RNLA mission supply chain is depicted in Figure 1.

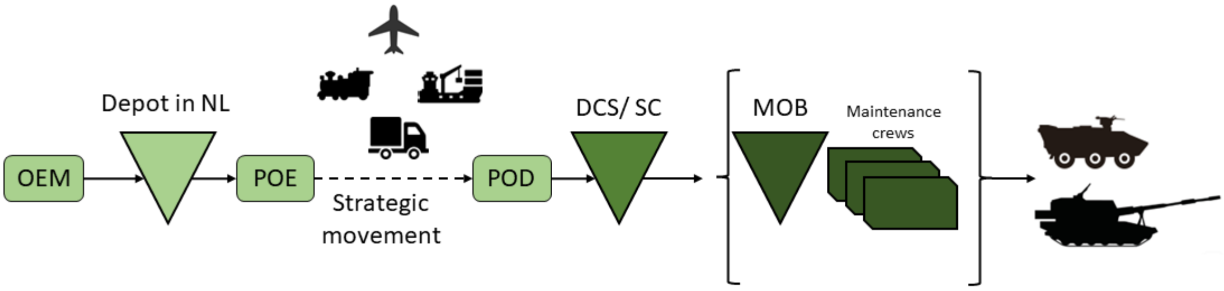


Figure 1: Main Task 1 supply chain

As we are only interested in the stock points, the supply chain for Main Task 1 as depicted in Figure 1 can be simplified to the following three-tiered diagram:

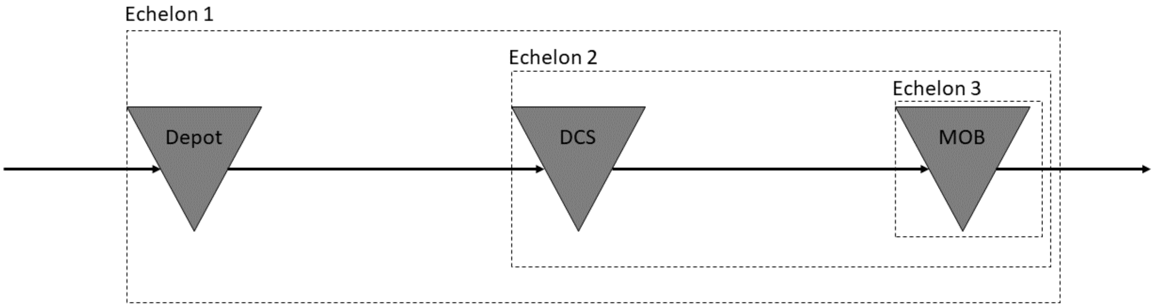


Figure 2: Supply chain under Main Task 1 simplified

In Main Task 2 scenarios, multiple missions can be active at the same time. This leads to depots needing to ship to multiple POD's and SC's. This leads to the distribution inventory system depicted in Figure 3. From the POD onwards, the supply chain remains the same. Note that this is a possibility, but not necessarily the case. Per mission, the supply chain remains identical to Figure 1. The MOB location is static in Main Task 2, meaning that keeping inventory requires less resources compared to Main Task 1 for the MOB.

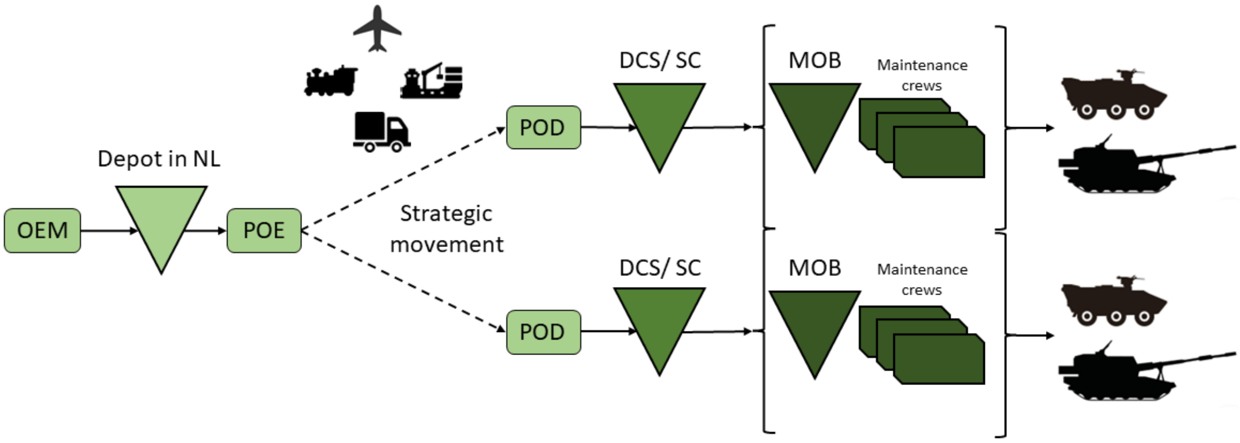


Figure 3: Main Task 2 supply chain

The supply chain for Main Task 2 as depicted in Figure 2 can be simplified to the following three-tiered diagram:

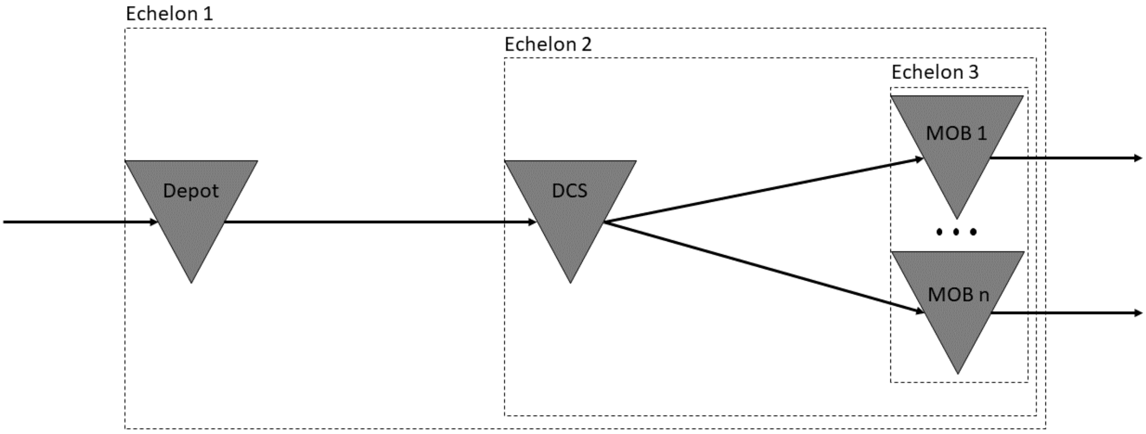


Figure 4: Supply chain under Main Task 2 simplified

The spare parts within the RNLA supply chain are specified by the VEDN-model by Tromp (2022). This model splits the spare parts into four categories. The first is vital. These spare parts have a high probability of failure or are of vital impact for operating the equipment. This makes them high risk and they are therefore stocked in abundance. The second is essential. These parts have a medium failure probability but are still essential to the operating of the equipment. They are therefore medium risk. The parts also tend to be parts of sub-assemblies. Third is the desirable category. These parts can have a low failure probability or are of little to no impact to the operations of the equipment. This makes them low risk. Finally there is the non-supply category. These parts are not kept in stock. This can be obsolete parts for instance.

There are multiple options to supply spare parts to mission environments:

1. External suppliers delivering parts to depots of RNLA in the Netherlands
2. Through AM applied by RNLA in the Netherlands
3. Through AM applied by RNLA at the mission location
4. Through external suppliers delivering parts to or near the country of deployment
5. Through emergency shipments from the Netherlands to the country of deployment
6. Combinations of the above

The applicability and optimal location of AM printing facilities in a mission context depend on the mission characteristics, for example:

1. Where the mission is
2. What the duration of the mission is
3. How much vehicles, weapons systems, etc. are used
4. Failure behavior of equipment (this also depends on the condition of equipment at the start of the mission, see for example Dijkstra (2013))

1.2 Introduction to Additive Manufacturing

In this section some general information concerning additive manufacturing (AM) is given. This general overview is given to better understand the opportunities that the RNLA sees around AM. From this point onward the term additive manufacturing is used conform the ISO terminology:

“process of joining materials to make parts (2.6.1) from 3D model data, usually layer (2.3.10) upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies.” (ISO Central Secretary, 2021)

In recent years the utilization and research towards AM capability has significantly increased. This is partially due to the latest industrial revolution called Industry 4.0. Dilberoglu et al. (2017) discuss that with the coming of Industry 4.0, the demand for mass customization has risen. This, according to the authors, has led to an increased use of non-traditional manufacturing techniques, which includes additive manufacturing. There are further applications where AM has advantages. Some of these applications and the advantages are summarized by Attaran (2017) and are shown in Table 1.

Table 1: Areas of Application and Advantages of AM from Attaran (2017)

Areas of Application	**Advantages**
Component Manufacturing	Enable mass customization at low cost, Improve quality, Shorten supply chain, Reduce the cost involved in development, Help eliminate excess parts. Components here is a subassembly of parts.
Customized Unique Items	Enable mass customization at low cost, Quick production of exact and customized replacement parts on site, Eliminate penalty for redesign. An item here is a unique finished product.
Machine Tool Manufacturing	Reduce labor cost, Avoid costly warehousing, Enables mass customization at low cost
On Site and On-Demand Manufacturing of Customized Replacement Parts	Eliminate storage and transportation costs, Save money by preventing downtimes, Reduces repair costs, Shorten supply chain, The need for large inventory is reduced, Allow product lifecycle leverage. This is decentralized production of spare parts.
Rapid Manufacturing	Directly manufacturing finished components, Relatively inexpensive production of small numbers of parts. This is not spare parts, but finished products.
Rapid Prototyping	Reduce time to market by accelerating prototyping, Reduce the cost involved in product development, Making companies more efficient and competitive at innovation. This is the production of prototype parts that are used for development.
Rapid Repair	Significant reduction in repair time, Opportunity to modify repaired components to the latest design. This is the production of spare parts.
Small Volume Manufacturing	Small batches can be produced cost-efficiently, Eliminate the investment in tooling
Very Complex Work Pieces	Produce very complex work pieces at low cost

1.3 Research trigger

Based on the promises of time and cost savings the RNLA has also started working with AM. Its vision on AM is the following:

“The main potential of AM envisioned by the Royal Netherlands Army is to reduce total logistical delay times of military systems in need of repair during military operations. The increased readiness levels will then enable the RNLA to maximize its effectiveness, of course within the capacity constraints of its logistics chain (logistical footprint).” (Knowledge Center for Logistics, 2022).

AM is already used within the organization for a number of applications. These currently mainly consist of rapid repair, rapid prototyping and rapid manufacturing, see Table 1.

- *5. Rapid manufacturing* is in many cases linked to rapid prototyping and is the subsequent production of the developed parts to be used in practice. Often in small batches and produced locally.

- *6. Rapid prototyping* is done chiefly by the expertise team for AM. They are asked by multiple defense branches to develop quick fixes or modifications for existing equipment to solve a problem specific to a use-case that was not considered by the original equipment manufacturer (OEM).
- *7. Rapid repair* is done by so-called Maintenance Platoons and other technical personnel. It is used to repair equipment in operational context. AM is used to produce temporary fixes for vehicles or equipment and is at the moment deemed inferior to spare parts ordered from the OEM.

The RNLA wants to expand upon the current uses. Elements from Table 1 that could be interesting are:

- *1. Component manufacturing* to produce spare parts and reduce dependence on manufacturers or to repair obsolete equipment.
- *2. Customized unique items* to fix specific problems with equipment for which other manufacturing techniques would be relatively expensive.
- *4. On-site and on-demand manufacturing* of customized replacement parts i.e. the printing of components in the field when demand for repair arises.

The knowledge center currently deems the (emergency) production of spare parts to be the application where AM can deliver the most value for the RNLA. Based on trends in the industry, the RNLA acknowledges that printed parts can sometimes be of better quality than conventional parts and that they can replace original parts with less problems than initially thought. The RNLA furthermore wishes to expand the technology to include more higher-end polymer printers and metal printing capabilities.

To better understand AM within the organizational context of the RNLA, a number of questions need to be answered (Knowledge Center for Logistics, 2022):

1. What to print?
2. Where to print?
3. How to organize (all organizational requirements to use AM) and facilitate (all practical things required to print the part) the AM printing process?

A closely related research, which has been completed within the RNLA to answer parts of the three questions, is that of Zijlstra (2022). She investigated possible locations for polymer AM machines in the context of a mission. In her thesis she shows that the implementation of AM capacity as an emergency option alongside conventional spare parts can increase vehicle readiness in a mission context. Specifically, the percentage of time the vehicle is ready for use could increase by around 0.1 % (which is a valuable increase in the RLNA context) and the costs lowered by about 5% depending on the deployment. The specific vehicle considered is the Fennek reconnaissance vehicle. The results might be different for other vehicles, as they have different initial readiness and parts. For AM to increase readiness and lower costs the most, it should be located closest to the source of demand and a more expensive, slower but more reliable AM machine yields to the optimal cost reduction. However in literature it is also shown that central printing locations might be beneficial. Khajavi, Partanen and Holmström (2013) show that for the F-18 fighter jet spare-part supply chain, AM can best be located in a central hub and parts distributed from there. Khajavi, Partanen and Holmström (2013) do however point out the potential of dispersed production when machine characteristics allow it.

In this research we want to help answer the questions still posed by the Knowledge Center for Logistics. We want to do this by expanding on current literature and investigating how AM can best be used in the RNLA supply chain in order to reduce costs and reduce the logistical footprint. The exact research approach is further explained in Chapter 2.

2 Research design

In this chapter we describe the research scope, the deliverables and research questions based on the research triggers described in Section 1.3. We start with the research scope in Section 2.1 to explain which parts concerning the problem context are left for future research. In Section 2.2 we introduce the specific deliverables and corresponding research questions within the research scope. Then in Section 2.3 we shortly discuss where in the report these deliverables and research questions are handled.

2.1 Research Scope

In this section the scope of the research is discussed. The focus is on the points which are not included in the research, but do play a role in the application of AM as a whole. These points require further research if AM is to be fully incorporated into the RNLA organization.

Acquiring the intellectual property (IP) rights needed for printing spare parts are left out of the scope for this research. Getting these IP rights is something that should already be regarded during acquisition of equipment. This is a prerequisites to the application of AM. For this research, the assumption is made that there are arrangements in place.

Another thing that has to be arranged beforehand is the warranties. This is something which does not specifically hold for AM, it holds for all spare parts not certified by the original manufacturer. If AM replacements are used, warranties of equipment could expire. This is therefore something the RNLA would have to arrange beforehand, similar to the IP rights.

The acquisition of the print files is left out of the scope as well. The files will have to be sourced from the manufacturer. They can also be created from scratch through modeling or scanning an object and generating a model. Both are quite time-consuming, however there is always a possibility to get printable files. Therefore we assume them to be available.

The number of AM technologies that can be used in the research is very large. It is therefore important that this is restricted. The technologies the RNLA already uses and plans to use are included in this set. To prevent the scope from becoming too large the set is restricted to four machine options introduced in Section 4.2. The acquisition of these technologies is outside of the scope. This is an investment decision that can be supported by the research outcomes, but is not part of the research itself.

Furthermore, the set of parts should also be restricted. As opposed to the case of Zijlstra (2022) where a specific vehicle was chosen, parts from different equipment is selected. The selection has to be made since not every part is printable. The selection of printable parts should be restricted in order to keep the scope of the project manageable.

Having enough trained personnel available is also crucial in military operations and for the use of AM. This is however an entirely different problem to what we are interested in. We therefore opt to leave this out of our research scope. We believe personnel would require separate research, which does not fit within the goals and timeframe of this research.

2.2 Deliverables and Research questions

The main goal of this research is to find where and how to implement different types of AM technology along the RLNA mission supply chain. The main deliverable is a prototype decision support tool that can evaluate the uncertainty parameters of the supply chain and help reduce cost and logistical footprint. It should then guide towards an optimal structure of AM within the supply chain based on the parameter values, maximizing for availability of equipment and personnel under acceptable costs.

The **main research question** of this research is:

"How can AM be used in the RNLA mission supply chain to reduce the logistical footprint?"

In order to answer the main research question the research is split into a number of deliverables. This results in a number of research questions. Completing all deliverables should achieve the main goal. For each research deliverable, first a short description is given. Then the related research questions are introduced. Each research question is briefly explained and the method for answering it is given. Deliverables 1 and 2 form the basis for the mathematical model. Deliverable 3 is the mathematical model. Deliverable 4 is the implementation of the model in a prototype tool and the subsequent validation and verification. Deliverable 5 are numerical experiments with example scenarios and numerical experiments with the model parameters.

Deliverable 1: Evaluation of what and how uncertainties and factors affect AM in the RNLA

It is important to know what uncertainties and factors play a role in the application of AM and how they affect the use of AM. For instance, how the climate affects the printing process, or how it affects the wear of spare parts. This is for a large part based on the local conditions of where the AM technology is located. Therefore it is key to first identify the local differences relevant for AM. After establishing this, the different uncertainties, factors and their impact can be reviewed. The uncertainty and factor evaluation are split up into three research questions.

RQ 1.1: What are the differences between operating environments and how do they affect AM?

By answering this research question the differences between operating environments will become clearer. We evaluate the three different types of operating environments for the RNLA, but also the different echelons of the RNLA mission supply chain. These dictate for a part the differences in uncertainties and factors that apply. The focus will be on the differences that are specifically interesting for AM. This does not only mean AM specific challenges, but also challenges to conventional sourcing that make AM beneficial.

In order to evaluate the differences between the operating environments relevant for AM, subject matter experts are consulted. First how the environments differ in general is investigated through interviewing experts from the RNLA. Based on the identified differences an overview of differences that impact the application of AM is identified.

RQ 1.2: What uncertainties and factors affect the application of AM in the RNLA mission supply chain?

After evaluating the differences between operating environments, the uncertainties and factors that affect AM must be identified. These are important since they tell something about the applicability of AM in different situations. They guide towards the parameters that should be included in the mathematical model. These uncertainties and fac

For this, the set of factors given by Zijlstra (2022) is used as a starting point. The goal is to expand upon it. Uncertainties of no longer using AM as just a temporary fix and the uncertainties around using different AM technologies are included. These uncertainties are sourced from two places. The first is literature, work by Zijlstra (2022) and den Boer, Lambrechts, & Krikke (2020) are examples of literature specifically aimed at AM in military context. Literature from other sectors is also reviewed to find more common uncertainties interesting for this research. The second source are interviews with experts, to find out what challenges are deemed relevant by people who work with AM within the RNLA or externally. All the findings are then cross-referenced with the interviewees once more to create an as complete as possible list of uncertainties. The uncertainties most prevalent in all sources are included in the model.

RQ 1.3: How do the identified uncertainties and factors affect the usage of AM?

Now the set of uncertainties and factors is clear, it is key to identify their impact. Based on this impact, their relevance for the problem becomes apparent. Some uncertainties, such as humidity, dust and wind will have an effect on the quality of spare parts for instance. The uncertainties and factors can affect the choice in location, technology, material or whether to deploy AM at all.

The impact can take many forms. It can be differences in printing time or failure rates of the parts for example. The identification of the effect is to be done based on data from interviews and literature. This is not a quantification of the impacts; this will be done under RQ 3.1 based on the findings from this research question and Deliverable 2.

Deliverable 2: Evaluation of AM Technologies and the characteristics interesting for the RNLA

To incorporate different AM technologies in the mathematical model and final supply chain the characteristics must be known. The evaluation of the characteristics reveals possible application areas of the different technologies. Based on this the parameters of the model such as print time, failure rate etc. can be adjusted. This deliverable is completed by answering three research questions.

RQ 2.1: What are the relevant differences between AM technologies interesting for the RNLA?

The different technologies use different machinery. This machinery differs in size, weight, mobility, resource consumption, post-processing, etc. For the different resources, there must be a logistical plan in place. Especially in mission context, keeping a sufficient supply of all the raw materials can be challenging. Furthermore, the machinery must be maintained in order to fully utilize AM potential. If machine breakdowns increase costs and lead times the benefits of AM quickly reduce. It is therefore key to map the differences between the technologies that specifically apply to the RNLA and its supply chain. Through literature and interviews the characteristics of the selected technologies are identified.

RQ 2.2: Where are the different AM technologies applicable in the RNLA supply chain?

Based on the uncertainties identified under Deliverable 1 and the answer to RQ 2.1, an assessment can be made on the applicability of certain technologies in a specific location along the RNLA mission supply chain. The aim here is location types where the AM technology gives an increased (vehicle) readiness and/or a decrease in logistical footprint.

Things that determine the usefulness of a technology in a certain location are for instance, the production lead time, the delivery lead time, the wear, the post-processing needs, the production costs, demand for resources. It is furthermore necessary to look at other characteristics, such energy consumption and environmental requirements that dictate whether or not a technology is applicable in a situation.

RQ 2.3: What are the characteristics of spare parts produced by the different technologies in the RNLA context?

Zijlstra (2022) investigates a case where spare parts produced through AM are only used as temporary fixes. The quality of AM produced parts diverge along different AM techniques. The goal is to identify the failure behavior of the spare parts produced by the different AM technologies. This is a key parameter for the mathematical model.

Based on the AM technology used, the spare parts have different input-material properties. Whether or not these properties are suitable needs to be determined by experts. TNO, BMC and NLR conducted the AMMAn (Additive Manufacturing for Military Applications) projects. These are projects aimed at the introduction and quality management of printing in the military. The experts from this will be consulted as well. Literature will also be used to further justify the choices made. Some of the spare parts need post-processing, which determines whether or not they can be produced in specific locations. Others are more lenient and therefore more fit to be produced closer to the field. These characteristics are mapped. Based on this, an indication of what spare parts can be produced where is made.

Furthermore in this research question a set of parts to investigate through the model is selected. This selection represents a broad set of spare parts available to print for the RNLA. This includes parts from multiple categories (VEDN) and with multiple characteristics (material, size, costs, etc.).

Deliverable 3: Mathematical model

A mathematical model is built with the purpose of minimizing costs under an acceptable vehicle readiness. Some of the model parameters are the location of AM capability, stock levels, failure rates etc. The specific set of parameters are introduced to answer RQ 3.1. It is furthermore important to choose a model that fits the needs of the RNLA best. By answering this we complete RQ3.2. The model is formulated and a solving method described as an answer to RQ3.3.

RQ 3.1: What type of mathematical model can be applied to solve the problem?

However, in order to choose the best fitting mathematical model, literature is consulted. To make the mathematical model applicable for the RNLA, not only the right type of model should be chosen, but also the right solving method. The model should also adhere to the needs of the RNLA.

For this research the temporary fix assumption is relaxed as much as possible. A model that is very interesting for this research is that introduced by Westerweel et al. (2021). They investigate the dual sourcing situation in remote locations under fixed order cycles at the RNLA. It is therefore a good example for the situation in this research. It expands on other dual sourcing literature by including two emergency supply options: printing lower quality parts, or expediting orders, these are similar to the sourcing options for this research. Another relevant model is that of Sgarbossa et al. (2021). They expand upon other literature by including more than one AM and conventional manufacturing (CM) technique. The model looks at Poisson demand for a single item problem.

Different from the model proposed by Zijlstra (2022) this research aims to incorporate a slightly different part of the supply chain. Since placing AM equipment further back in the chain is more effective according to the findings by Zijlstra (2022). Furthermore, the goal is to improve upon the setting of inventory levels and to incorporate the sourcing of raw materials. Therefore we will have to use a different model. The base stock levels in the model by Zijlstra (2022) are based on the heuristic by Shang & Song (2003). This can for instance be replaced by the approach described by Clark & Scarf (1960).

RQ 3.2: What uncertainty parameters should be used to get a model that depicts reality in a sufficient way and is still usable?

The mathematical model consists of different parameters. If the real-life situation is mirrored exactly there would be too many parameters and the model would be difficult to solve and interpret. It is therefore key to find a balance between realism and usability of the model. The aim of this research question is choosing the parameters from the identified uncertainties and variables that create the best model for the RLNA. Furthermore, experts are consulted as to what parameters they deem crucial to the model's success. This is not only done for validity, but also to promote the usefulness to the end-users.

Parameters that are included as expansion on other models are for instance criticality of different parts, production times on different machinery and in different locations, failure behavior of parts and machinery, resource consumption and subsequent delivery lead times. These are parameters based on the RNLA context and research scope, they will be elaborated and expanded through deliverables 1 and 2.

RQ 3.3: How can we formulate and solve a mathematical model to answer the main research question?

To finalize deliverable 3 we use the type of mathematical model identified under RQ3.1 and the parameters defined under RQ3.2 to formulate the mathematical model used in this research. In order to use the model to make the calculations to answer the main research question a solving method is also described.

Deliverable 4: Prototype decision support tool

For generating results and the RNLA to be able to use the mathematical model, it is incorporated in a small-scale software tool. To create this software tool it is crucial to know what software fits best. Furthermore the tool is tested. Therefore, there are two research questions to this deliverable.

RQ 4.1: How can the mathematic model be implemented in a prototype tool such that the RNLA can use it?

By answering this research question, the correct software packages can be selected. Furthermore, the goal is to deliver the tool. Before creating the tool the requirements by the RNLA are evaluated. When the correct package and method is chosen, the tool can be written. Results generated by the model should subsequently be validated. This is done in the next research question. The software package used is Python, as it is the most common at the RLNA. The packages used in the tool are chosen to both quickly and correctly solve the mathematical model introduced under Deliverable 3.

RQ 4.2: How can the model be validated and the tool verified?

To know how accurate the model is in predicting costs and benefits a test-case is evaluated. This shows whether the outcomes of the model are valid. It also shows how results should be interpreted. It is key to use extreme cases to test the model outcomes. Furthermore it is necessary to evaluate the impact of model parameters on the model outcome via sensitivity analysis. The behavior of the parameters under the model assumptions can give more insight in how to act under certain circumstances. It also helps better understand the model. Furthermore, if a parameter shows to be of little impact, the model can be simplified. On the other hand, this research question can reveal crucial parameters. For the verification of the tool both dynamic and static testing is applied in order to check if the programming of the model is correct. To finalize this research question the validation and verification are executed and the results are reviewed.

Deliverable 5: Scenario analysis and numerical experiments

The final deliverable gives insight in the outcomes generated with the model for a specific scenario interesting for the RNLA. The numerical experiments give insight into possible solutions for interesting parameter values and reveal more about the behavior of the supply chain in different situations. To conduct these analyses and experiments the tool created as Deliverable 4 is used.

RQ 5.1: What are the optimal values for decision variables according to the tool when AM is introduced in an existing deployment scenario?

Here we test one specific RNLA deployment scenario for which we have input data. This is done to show what the optimal setup of AM within this scenario would be based on the model outcomes. We do this to showcase how the model can be applied to a real life scenario.

RQ 5.2: What is the impact of the different parameter values on the model outcomes?

To answer this research question, multiple test cases are analyzed. The data can be based on an existing case. It can also be adjusted, where some of the data is approached by estimates or fabricated to mimic a certain situation. A potential scenario is a zero-stock scenario where all parts are printed as demand arises. This shows the ability of AM to supply the demand, but might also reveal opportunities for significantly lowering the inventory levels of spare parts.

2.3 Thesis outline

In Chapter 3, we discuss the uncertainties and factors that influence the application of AM for the RNLA in order to complete Deliverable 1. In Section 3.1 we discuss the differences in operating environments to answer RQ1.1. Section 3.2 answers RQ1.2 by discussing what uncertainties and factors influence the application of AM for the RNLA. In Section 3.3 we discuss the impact of the identified factors and uncertainties in order to answer RQ1.3. In Chapter 4 we discuss the differences between different AM technologies in order to complete Deliverable 2. First RQ2.1 is answered in Section 4.1 by elaborating on differences between the AM technologies interesting for the RNLA. Section 4.2 uses this information to identify where in the RNLA supply chain the AM technologies fit best in order to answer RQ2.2. Section 4.3 answers RQ2.3 by elaborating on the differences in spare parts caused by the use of different AM technologies. Chapter 0 introduces the parameters and mathematical model used for the research to complete Deliverable 3. The selection of the type of tool and identification of differences with tools in literature to answer RQ3.1 is done in Sections 5.1 and 5.2. Identifying model parameters and scenarios in order to answer RQ3.2 is done in Sections 5.3 and 5.4. The model formulation and solving method are described in Sections 5.5, 5.6 and 5.7 in order to answer RQ3.3. The mathematical model is implemented and validated in Chapter 6 in order to complete Deliverable 4. The implementation of the tool into a prototype decision support tool is described in Section 6.1 in order to answer RQ4.1. This prototype tool is validated in Section 6.2 in order to answer RQ4.2. In Chapter 7 a scenario analysis of the model parameters and numerical experiments are done in order to complete Deliverable 5. In Section 7.1 the impacts of the model parameters are investigated, and a sensitivity analysis is performed to answer RQ5.1. Then to answer RQ5.2 the model is used to run a number of numerical experiments in Section 7.2. Finally in Chapter 8 the conclusions, limitations and recommendations from the research are given.

3 Uncertainties and factors influencing AM in the RNLA

In this chapter the uncertainties and factors influencing the application of AM by the RNLA are brought to light in order to complete *Deliverable 1: Evaluation of what and how uncertainties and factors affect AM in the RNLA.*

Since the RNLA operates in different operating environments, it is first important to know how these environments differ from one another. This is handled in Section 3.1 to answer *RQ1.1: "What are the differences between operating environments and how do they affect AM?"*. Based on the differences in the scenarios, thereafter the implications of the differences for AM are described. Section 3.2 focusses on the identification of the uncertainties to answer *RQ1.2: "What uncertainties and factors affect the application of AM in the RNLA mission supply chain?"*. In Section 3.3 the impact of the uncertainties on the application of AM within the RNLA is described to answer *RQ1.3: "How do the identified uncertainties and factors affect the usage of AM?"*. For this section interviews are used, for a full overview of the respondents and interview procedure we refer to Appendix A. The summation of the factors over all the different sources (both literature and interviews) is given in Table 5 in Section 3.3.

3.1 Operating environments in the RNLA

The operating environments and their characteristics are for a large part dictated by the main tasks of the RNLA and the coupled type of deployment. We describe the three main tasks in detail below, a quick overview of the characteristics is given in Table 2.

As described in Section 1.1, Main Task 1 is the protection of Dutch territories and that of allies. The respondents mention this leads to a type of deployment that is identified as warfighting, often with an equal opponent. In this setting man and material is worn down substantially. Damage to material is often in the form of battle damage, this can sometimes be more complex than regular wear, as it is much more intense and can destroy multiple parts at the same time. The damage is also more frequent as the material is under more strain according to respondent 6 and 7. The respondents also mention that such deployments involve a high rate of mobility. Respondent 5 mentions units are required to be mobile within 10 minutes and on the move within the hour. It is therefore crucial that they do not have any equipment that requires careful and lengthy disassembly and transportation. The other respondents underline this. Furthermore, respondent 5 mentions that there is an extremely high level of threat in this mission environment. Specifically, a unit can be completely wiped out within 48 hours of operating. According to respondent 1 the repair units and infrastructure are particularly targeted in current examples of these types of mission environments such as the Ukraine conflict. The infrastructure in this setting is also not secure and steady according to all four respondents. Things such as energy and internet connections can be severely disrupted, which can lead to difficulty with operating equipment. Respondent 5 also mentions that supply is often over smaller distances, but can be severely disrupted due to the danger, and that local sourcing is almost impossible. All four respondents see great opportunity for AM to add to the readiness in this operating environment. This readiness is also more crucial in this deployment as it can save lives and resolve the conflict.

Main Task 2 is internationally promoting the lawful order and stability, which leads to peace-keeping missions. Respondent 5 mentions such a deployment is generally much longer than with Main Task 1. These missions often take multiple years as opposed to shorter missions with Main Task 1 and Main Task 3. The level of threat is also lower in these missions as opposed to Main Task 1 as mentioned by all four respondents. This is mainly due to the overhand over the opponent that is generally in place. Respondent 5 mentions that there is also less risk of battle related damage. Damage to equipment will mainly be caused by wear, which makes it a little more predictable. The respondents also mention that as opposed to the high mobility of Main Task 1, this operating environment is rather static. In this type of deployment a steady and relatively safe home base is established. The infrastructure in the countries where this deployment often takes place is described by respondent 6 and 7 as below par, but safe. Improvement of infrastructure is also more feasible in this situation. Respondent 5 mentions that in this scenario the delivery can often form a problem. Due to the shipments over long distances, chances for complications and increased costs are a problem. The respondents mention the opportunity for AM to alleviate some of the difficulties caused by uncertain shipment lead times.

Main Task 3 is the aid in the event of a crisis. The respondents describe that these crises are within the borders of the Netherlands and its territories. This means that mobility and danger play no role in this situation. There is no combat situation, therefore supply lines, wear and infrastructure are similar to peace-time situation. The deployed material pool is also much smaller and limited to non-combat related equipment. Respondents 6 and 7 also describe that there is therefore little to no added value for AM in this scenario. Respondents 1 and 5 do see the opportunity to help the civilian population by producing useful materials to keep infrastructure running or aid hospitals. This is an entirely different way of working however and is therefore not incorporated in this research.

Outside of the main tasks there is the peace-time business operations, in this situation there is no danger, only regular wear and no time pressure, so AM is not as impactful here. All four respondents therefore see no reason to investigate this. AM will only be applied for prototyping and small insignificant repairs; these repairs can however be very cost effective. Therefore AM is also very useful in this scenario. Once again, this use-case is not what this research tries to investigate and will therefore be left out of the scope.

Table 2: Main tasks characteristics overview

	Main Task		
Characteristic	**1 (Active Combat)**	**2 (Peace keeping)**	**3 (Peace time)**
1. Material wear	Severe and frequent	Less severe but still frequent	Regular wear
2. Mobility	Very high (mobile within 1 hour)	Low (stationary operating base)	None
3. Threat level	Very high	Low	None
4. Infrastructure	Unreliable and often disrupted	Unreliable but less disrupted	Reliable
5. Supply	Short distance but often disrupted	Long distance but less disrupted	Stable

3.2 Uncertainty and factor analysis

In this section the uncertainties that influence the application of AM within the RNLA are identified from multiple sources. We also identify a number of important influencing factors from the same sources. These factors are not uncertain, but do influence the applications of AM quite significantly according to the sources. The first source is general AM literature. From this literature, general uncertainties and factors that hold for all applications of AM are identified. The second source is RNLA and Military specific literature. This literature reveals uncertainties and factors that specifically hold for AM applied in the RNLA context. The findings from these two sources are described in Section 3.2.1. The third source is the interviews. The RNLA and external AM experts identify even more uncertainties and influencing factors, these are described in Section 3.2.2.

Based on the identified uncertainties and factors, their impacts are also investigated. The impacts on the application of AM for the RNLA are described in Section 3.3.

3.2.1 Literature review on uncertainties and influencing factors

Based on eight sources in literature, uncertainties and influencing factors are identified. Google Scholar, ProQuest, ScienceDirect and Scopus are used in order to find relevant literature. The selection is initially made based on the title, abstract, introduction and conclusion. Forward and backward citation is also used to find more related literature. An overview of the findings is given in Table 3. We opt not to include the research by Zijlstra (2021) in this review as this research gives an overview of existing literature with the same goal as our research. We do compare our findings to the findings of Zijlstra (2021) at the end of Section 3.3. An overview of the findings is given in Table 3.

The first four sources are external literature about AM in general, not specific to military applications. Choudhary et al. (2021) investigate the barriers holding for medical applications. This research is chosen to get a view on the factors and uncertainties that play a role in other industries that might also be relevant for the RNLA. They mention the sourcing of raw materials, which is a factor that heavily dictates the effectiveness of AM. Furthermore the need for production facilities such as post-processing and getting trained personnel can form an issue. Savastano et al. (2016) did an explorative research on AM in the automotive industry. Since this is akin to the use of AM parts within the RNLA this research is chosen. They do however only bring to light some factors of influence and give little insight on uncertainties. They mention production costs and production speed of AM to be factors that influence the implementation. The increased speed is an opportunity whereas the increased costs are a challenge. Sobota et al. (2020) investigate the factors and barriers that influence the adaptation of metal AM for businesses. They describe some uncertainties and show some factors important to metal AM. They also mention cost of production and the sourcing of raw material. Furthermore they discuss that the quality of AM made parts can be inconsistent. Verboeket and Krikke (2019) investigate the effect of AM on the general supply chain of businesses. The insights from this are not entirely new, but they underline their importance for the research. The new factors they identify are the quality of raw material, the quality of the designed model and infrastructure. These are all factors that influence the quality of the final product. They also mention the sourcing of raw material, production costs, quality and need for production facilities .

The second four sources are RNLA or military specific research papers focused on the application of AM for military use. Bastiaans et al. (2015) describe the impact of AM for the Ministry of Defence. They identify quality as an inconsistent factor for AM that can cause problems with the end product. They also describe that speed is a crucial factor for AM. Lastly, they mention that energy consumption can be a problem. The printer demands a significant amount of electricity, which in turn needs to be supplied by infrastructure or generated on location. Den Boer et al. (2020) investigate the challenges and advantages of AM in a military context, specifically within the Dutch military. They identify vibrations and movement as a factor that can impact the quality of a finished part, specifically on a ship, this however holds in all situations. This also holds for the vibrations etc. in transporting the machinery. This can affect the calibration and therefore the finished part. The condition of the raw material is also important for a consistent end product. They furthermore mention that having trained personnel and a good computer model for the part are crucial in getting the best possible end product. They also mention energy consumption as an influencing factor. The report by TNO from 2021 for the implementation of AM within CLAS (Commando Landstrijdkrachten) also reveal some new factors and uncertainties. Van Veen (2021) mentions climate to be an uncertain factor that can influence the performance and longevity of an AM machine. High temperatures and humidity can also affect the finished product. Furthermore he identifies the need for production facilities , such as for post-processing to be of influence. Also the fact that the materials used for AM can be dangerous, means production facilities and precautions are necessary to implement it safely. He also mentions the quality of raw material, energy consumption and personnel. Finally the 2020 NLR report on metal AM is consulted. 't Hoen-Velterop and Kool (2020) describe that the high costs of producing AM parts can be of influence on whether it is justifiable or not. They furthermore identify that supply facilities such as AM printing stations are targets for opponents in the field. This adds danger to the operating of such equipment. Also the infrastructure in the printing location is important to keep the printer working optimally. They also mention climate, vibrations and movement, personnel and the need for production facilities as influential factors or uncertainties.

In Table 3 the information above is graphically represented to give an easy overview of the uncertainties and factors mentioned. The uncertainties and factors are tagged accordingly and cases that are dubious are tagged as ‘both’. They are categorized in such a way that it can be easily identified how many sources mention the same things. They are sometimes introduced for different reasons, however the factor and its impact remain the same. The factors are briefly explained below the table.

Table 3: Uncertainties and factors from literature

		Non-military literature				***Military literature***			
Uncertainty/ factor	**Type**	**Choudhary et al. (2021)**	**Savastano et al. (2016)**	**Sobota et al. (2020)**	**Verboeket and Krikke (2019)**	**Bastiaans et al. (2015)**	**Den Boer et al. (2020)**	**Van Veen (2021)**	**'t Hoen-Velterop & Kool (2020)**
1. Sourcing of raw materials	Uncertainty	X		X	X				
2. Production facilities	Factor	X			X			X	X
3. Personnel	Factor	X					X	X	X
4. Production costs	Both		X	X	X				X
5. Production speed	Both		X			X			
6. Quality	Uncertainty			X	X	X			
7. Quality of raw material	Uncertainty				X			X	
8. Quality of design	Uncertainty				X		X		
9. Infrastructure	Both				X				X
10. Energy consumption	Both					X	X	X	
11. Vibrations and movement during print	Uncertainty						X		X
12. Transport of machinery	Uncertainty						X		
13. Conditions of raw material	Uncertainty						X		

14. Climate	Uncertainty							X	X
15. Dangerous material								X	
16. Danger	Uncertainty								X

1. *Sourcing of raw material* means the acquisition of the input materials necessary to print a part through AM. This can be done through shipments from the Netherlands or locally.
2. *Production facilities* is the equipment, outside the AM machine, necessary to produce a finalized part. This can be hand-tools, mills, ovens, lathes or any other machinery necessary.
3. *Personnel* are the trained experts needed to operate the equipment. The number of trained experts and the level of training of these experts diverges along different AM machinery.
4. *Production costs* are all costs that occur when printing. The expensive machinery and input material is seen as a barrier by some. Therefore costs are an important factor when comparing AM to CM.
5. *Production speed* is the lead time to print a part. The quick lead times of AM are seen as a benefit and are therefore another factor when evaluating AM.
6. *Quality* is the quality of the finished part. As already discussed, this can diverge along different AM machinery, techniques and material. The quality is also susceptible to outside influences such as points 2,5,7,8,11,12,13 and 14.
7. *Quality of raw material* is the specific characteristics of the input material. Input material wise, there are many options to produce parts through AM. These options all have different characteristics which influence the quality of the finished part. The quality can also differ along vendors of the same input material.
8. *Quality of design* refers to the computerized model and how a poor computerized model can lead to a part with lower quality.
9. *Infrastructure* refers to the power connection, internet connection, satellite connection or any other infrastructure necessary to operate the AM machine. It also refers to the uncertain stability of such connections in some parts of the RNLA supply chain.
10. *Energy consumption* is specifically the energy consumed by the AM machine and possible production facilities . *Infrastructure* refers to the presence and stability of energy, among other utilities. *Energy consumption* refers to the amount of power consumed and whether this can be supplied.
11. *Vibrations and movement during print* can influence the quality of the final part.
12. *Transport of machinery* refers to vibrations and shocks during transport influencing the calibration of the machine. This can affect setup time.
13. *Conditions of raw material* different from the starting quality. This refers to the deteriorating influence of humidity, temperature or other outside factors on the quality of the input material.
14. *Climate* refers to the influence of humidity, temperature, UV-rays and dust on the quality of the printed parts or the power consumption. This can be through influence on the raw material, but also on the printer or printing process.
15. *Dangerous material* means that the input material requires extra care when handling or requires specialized equipment for storage.
16. *Danger* refers to the risk of an attack on the printing location during deployment.

Table 3 shows that factors or uncertainties that have to do with missions or printing on-demand in remote locations (point 10 through 16) are only discussed in the military specific literature. This is to be expected since production in remote locations is not something that applies to all types of industry. Although these factors and uncertainties are less prevalent in literature, they are still important for military applications of AM. Another interesting takeaway is that sourcing of raw material is not mentioned to influence the application of AM. This is quite strange since it is something that is believed to influence on-demand printing in remote locations. This might be due to these articles focusing very little on the logistics, especially in remote locations, necessary to facilitate AM. The articles focus more on the process, technology and organizational aspects of AM. That is one of the reasons research like this one and by Zijlstra (2021), focusing more on these logistics, are important.

3.2.2 Interviews on uncertainties and influencing factors

Interviews with ten respondents confirm and expand upon the uncertainties and factors described in Section 3.2.1. Refer to Appendix A for the respondents and the specific interview procedure used. An overview of the findings is given in Table 4.

Respondent 1 identified energy consumption as something that can become very problematic for AM. As already identified in Section 3.2.1, the machines use a significant amount of electricity. This means sufficient infrastructure has to be in place. This notion is shared among respondents 5, 6, 7 and 9. In this interview the sourcing of raw material is also mentioned as something that can influence the effectiveness of AM in the RNLA context. To produce AM parts, a steady supply of materials is needed in order to keep the productivity of the machine on point. Respondents 4, 6, 8, 9 and 10 share this view. Furthermore the mobility of current deployments became known as something that can influence the application of AM. Units must be highly mobile, meaning prints can be interrupted. Also the amount of equipment should be movable within the unit's time constraints. This also comes forth from the interviews with respondents 5 and 6. The respondent also mentions that repair stations are targets, meaning that danger is an uncertainty that plays a significant role and can dictate whether or not AM can be applied in a certain location. Respondent 5 also brought this up in the interview. Another uncertainty mentioned is the demand for spare parts. Especially in Main Task 1 deployment the damage to machinery can mean a very fluctuating and uncertain demand for parts. This can include parts that are not on the shelve and can therefore have long lead times when AM is not applied. Respondents 5 and 6 also brought this up in their interviews. Another influencing factor is the need for certification of a part to keep it as a permanent replacement. In Main Task 1 and for Battle Damage Repair (BDR) there are little restrictions, however permanent spare parts have to be certified. This can lead to problems and influence the demand for spare parts. This view is shared by respondents 3, 4, 5, 6, 7, 8 and 9.

Respondent 2 also mentions that the quality of the spare parts can fluctuate. This is mainly due to other conditions mentioned throughout this section. Respondents 3, 4, 6 and 9 also say this. Speed is mentioned as a plus for AM, however as respondent 5 says, this speed advantage must be maintained for AM to remain useful. Respondent 6 shares this view.

Respondent 3 adds the costs of printing to the list of factors influencing the application of AM. Parts are often more expensive, so the other costs of conventional parts must be higher or the benefits of AM very apparent (e.g. shorter supply lead times) to justify its use. The AM raw materials are also often dangerous in some way, meaning they need extra safety precautions as also identified from literature. Respondent 3 lastly mentions climate as an uncertain factor that can significantly influence the end result of the AM printing process.

Respondent 8 identifies wind, moisture and dust in an open printing system to worsen the final product. Respondents 5, 7 and 10 share these views.

Respondent 5 further adds to the list with the need for qualified personnel in order to get a consistent end product, respondent 6 also mentions this. Furthermore the respondent mentions that the supporting areas in a deployment are already filled quite heavily. Adding more units might therefore be problematic and lead to a shortage of energy or other infrastructure. Also the respondent ads that the quality and storage conditions of raw material heavily influence the end product. Nylon filament attracts moisture for instance, so this is again an uncertainty to keep in mind. This view is shared by respondents 6, 8 and 10.

Respondent 7 mentions that the machinery is susceptible to damage and can therefore suffer in transport to and during deployment. The machine needs careful calibration as is mentioned by respondent 8 to get a consistent end product.

Respondent 8 further adds that to get a usable end product, specifically for metals, specific production facilities are needed. Respondent 10 says that this is one of the more limiting factors influencing the applicability of AM during a deployment. Respondent 8 lastly adds that vibrations and movement can mean that a print can fail or be of lesser quality. Respondents 9 and 10 also mention this in the interviews.

In Table 4 the identified uncertainties and factors are again summed up so a good comparison between answers can be made. The uncertainties and factors are tagged accordingly and cases that are dubious are tagged as 'both'. Note that point 17 through 20 are exclusively mentioned in the interviews and that point 8 from Table 3 was not mentioned in the interviews. A short explanation of the new uncertainties and factors is given below the table.

Table 4: Uncertainties and factors from interviews

		Respondent									
Uncertainty/ factor	**Type**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1. Sourcing of raw materials	Uncertainty	X			X		X		X		X
2. Production facilities	Factor				X				X	X	X
3. Personnel	Factor				X	X	X				
4. Production costs	Both			X							
5. Production speed	Both		X			X	X				X
6. Quality	Uncertainty		X	X	X		X			X	
7. Quality of raw material	Uncertainty					X	X				
8. Quality of design	Uncertainty										
9. Infrastructure	Both	X			X		X	X		X	
10. Energy consumption	Both	X				X		X		X	
11. Vibrations and movement during print	Uncertainty								X	X	X
12. Transport of machinery	Uncertainty							X	X		
13. Conditions of raw material	Uncertainty						X		X		X
14. Climate	Uncertainty			X		X		X	X		X
15. Dangerous material	Factor			X							
16. Danger	Uncertainty	X			X	X					
17. Mobility of deployment	Uncertainty	X			X	X	X				
18. Demand for spare parts	Uncertainty	X			X	X	X				
19. Part certification	Factor	X				X	X	X	X	X	
20. Capacity of deployment	Factor					X					

Notes:

- *Respondents 9 and 10 are non-military (denoted by the vertical line)*
- *Points 17,18,19 and 20 are new (denoted by the horizontal line)*
- *Point 8 is not present in the interviews (marked as grey)*

17. *Mobility of deployment* means that based on the type of deployment and the state of that deployment, units might need to be increasingly mobile. This has an effect on the type of AM machine applicable and the operability of a deployed printer.
18. *Demand for spare parts* can vary heavily based on the type of deployment and the state of that deployment. Increased (combat) activity affects the consumption of spare parts.

19. *Part certification* relates to the necessity for vital and essential parts to be up to a certain standard before they are allowed to be used permanently. If this standard cannot be proven, in the current state of things, AM parts cannot be used as full replacements for conventional parts.
20. *Capacity of deployment* refers to the capacity of infrastructure, resources and manpower to support non-combat elements in the rear area.

The interviewees are individually contacted and shown the results as described above. They are asked for any additions or content-related adjustments they might have. This follow-up yields no additional information or adjustments to the findings.

3.3 Impact analysis of the identified uncertainties and factors

The uncertainties and factors identified are not specific to any AM technology, machine or operating environment. For the implementation of the uncertainties and factors as parameters, a selection is made based on prevalence. The summation of the factors over all the different sources (both literature and interviews) is given in Table 5. All sources are weighted equally when counting prevalence. This does mean that a factor being known to one respondent and unknown to another could influence the perceived importance. However, it is believed that the spread of respondent roles is broad enough to equalize this effect along all stakeholders. Also it is believed that a prevalent factor is important, since it is known to many respondents, despite their different functions. The formulation of parameters will focus on the two most prevalent sets of uncertainties and factors.

Table 5: Prevalence of uncertainties and factors

Uncertainty/ factor	**Prevalence**
1. Sourcing of raw material, 2. Production facilities , 6. Quality	8
3. Personnel, 9. Infrastructure, 10. Energy consumption, 14. Climate.	7
5. Production speed, 19. Part certification	6
4. Production cost, 11. Vibrations and movement during print	5
7. Quality of raw material, 13. Conditions of raw material, 16. danger, 17. Mobility of deployment, 18. Demand for spare parts	4
12. Transport of machinery	3
8. Quality of design, 15. Dangerous material	2
20. Capacity of deployment	1

The most prevalent factors are the *sourcing of raw material*, *production facilities* and *quality*. Since the delivery of goods to a deployment can often be uncertain, this also holds for the *raw materials* necessary for AM. This makes the production capacity of AM somewhat uncertain. Local sourcing is an option to partially negate this, but it is not possible in all types of deployment. *Production facilities* are not uncertain, however they do form constraints to the implementation of AM in a certain location. Closer to the demand, the availability of post-processing equipment limits the applicability of for instance metal AM machinery. The *Quality* of AM parts is somewhat uncertain. It is affected by many other factors, such as climate, raw material, infrastructure, mobility and danger. If the quality cannot be guaranteed, AM parts will likely not be accepted as full replacements by the RNLA.

From the next set of uncertainties the most interesting are the *climate*, *personnel* and *energy consumption*. *Energy consumption* is coupled with *infrastructure*. If the power supply is not sufficient, printers cannot be used to their full potential or cannot be operated at all. *Climate* means that dust, wind or moisture can affect the quality of a print. Having adequate *Personnel* is a prerequisite for AM. However, as discussed in Section 2.1, this is outside of our research scope.

There are also uncertainties and factors that are mainly prevalent in military specific sources. The *transport of machinery* is again something that can cause quality standards to not be reached. As discussed, mistakes in calibration of the machinery or damage can cause production to fail more often or the machine to break down all together. *Danger* and *mobility of deployment* are uncertainties with similar impact. They both mean that prints can be interrupted, which will affect the required printing time. It furthermore affects the ability to implement AM in certain locations due to movement constraints of units and safety considerations. As discussed earlier, the demand for spare parts is also uncertain. The *quality and conditions of raw material* and *vibrations and movements* are all uncertain factors that influence the quality of a finished part.

The other factors are not really prevalent in multiple sources and not as useful to quantify for the model. *Quality of design* is based on 3D-models, which are prerequisites and outside the scope of this research. The *capacity of deployment* and *dangerous material* are factors that add certain constraints to the implementation of AM.

Many of the factors and uncertainties identified in this chapter are the same, or similar to those identified in the research by Zijlstra (2021). Zijlstra regards the thirteen most prevalent factors identified from literature and interviews at the RNLA. *Lead time* in between stock points is one of these factors that is not present in our interviews or research. We think this is due to the interviewees seeing lead time as something that is determined by other factors and uncertainties such as danger. We do use lead time in this research, as it influences costs and partially determines the required spare part stocks and production. *Spare part inventory* is another factor identified by Zijlstra missing from our identification. Again we believe this is due to the connection of spare part inventory to other points from the interviews such as demand for spare parts. We include spare part inventory as it is required to evaluate the performance of the supply chain. A third factor missing is *holding costs*. We believe this is not mentioned as it is not a parameter the RNLA supply chain experts use in practice. We do require holding costs to evaluate the performance of the supply chain. *Temporary fix* is also not present in our identification. We opt to not include this as we want to regard AM parts as full replacements.

There are also some uncertainties and factors that are identified in this research, that we do not see in the research by Zijlstra (2021). One of these factors is *Production facilities*. Zijlstra (2021) refers to infrastructure at the base, but we see from the interviews that machinery (other than the printer) required to produce a finished part plays a role in the applicability of a certain type of printer. It is a prevalent factor in the interviews and also in literature, we therefore believe it is an important factor to incorporate. A prevalent uncertainty not present in the research by Zijlstra (2021) is *Sourcing of raw material*. She does not regard raw material in her research, but we identify it as one of the more prevalent uncertainties. The sourcing of raw material also plays a role in whether or not AM can be applied successfully, so neglecting it is not an option in our opinion. Another factor that is very prevalent within the RNLA, but not mentioned by Zijlstra (2021), is *Part certification*. It is exclusively mentioned in interviews, meaning it is a RNLA specific concern. From the interviews we also see that it is a leading factor for further expanding the use of AM within the RNLA. *Mobility of deployment*, *Quality of raw material* and *Conditions of raw material* are also not mentioned by Zijlstra (2021). This might be since they can be seen as part of other factors such as *Type of print material* and *Type of mission*. Other less prevalent factors that are not mentioned by Zijlstra (2021) are *Transport of machinery, Quality of design* and *Capacity of deployment*. These can again be seen as part of other factors and uncertainties such as *Quality* and *Type of mission*. This does show that some uncertainties such as printed part quality are influenced by many individual uncertainties such as *Quality of raw material, Transport of machinery, Quality of design* and *Conditions of raw material*. Trying to reduce a more prevalent uncertainty will therefore most likely require the reduction of a number of other less prevalent uncertainties.

4 AM technology characteristics for the RNLA

In this chapter the different AM technologies used by the RNLA are discussed. Furthermore some technologies that might be interesting for the future are reviewed. This review is done to identify important characteristics of all the technologies to complete *Deliverable 2*: *Evaluation of AM Technologies and the characteristics interesting for the RNLA.* The technology characteristics are introduced in Section 4.1 in order to answer *RQ2.1*: *"What are the relevant differences between AM technologies interesting for the RNLA?*". In Section 4.2, based on the identified characteristics, an indication is formed on where in the supply chain and in what type of environments a specific technology is viable. This forms an answer to *RQ2.2*: "*Where are the different AM technologies applicable in the RNLA supply chain?*". Lastly, in Section 4.3 part characteristics are introduced based on the different technology and location combinations as an answer to *RQ2.3*: "*What are the characteristics of spare parts produced by the different technologies in the RNLA context?*". For this, first a set of parts is chosen. The set includes parts of multiple input materials, multiple levels of the VEDN-model and other characteristics such as size, cost, failure-rate, production lead time and order lead time.

4.1 Characteristics of AM technologies applicable to RNLA context

To start, the technologies already used by the RNLA are identified. This is done through the interviews conducted with RNLA AM experts. Respondents 1, 3, 5, 6 and 7 all give a description of what AM machinery is currently used, currently installed and currently researched within the RNLA. An overview of some characteristics for the most relevant AM machines is given in Table 6.

The installed base within the RNLA mainly exists of *UltiMaker S5*'s. This system is widely used already within the RNLA, both in and out of mission context. This printer uses polymer filament with a technique called fused filament fabrication (FFF). Here filament is heated and deposited in layers on a heated print bed to get a finished product. The filament is often nylon based, but can be made from other polymers such as PLA or PETG. Respondent 8 identifies it as the workhorse, fulfilling most printing orders. It is also the printer used by the maintenance platoons. This type of UltiMaker does not have a conditioned printing environment. This means that this printer is more susceptible to ambient temperature, wind and dust. Respondent 8 describes that when there is a gust or breeze the quality of the final product can be affected. The same holds for moisture and dust. The benefit is that the printer does not use an enormous amount of power. It is also quite mobile and easy to use for the units in the field. The power consumption of this printer at maximum 0.5 kWh and on average 0.3 kWh. The operating humidity should be below 60 percent and the temperature between 15 and 35 degrees Celsius.

The *Markforged Mark 2* is another printer that the RNLA already uses quite heavily. This is also a FFF printer using similar filament types. This machine also has specific filament called Onyx, which can be reinforced with fillers such as carbon fiber. This machine is not widely spread among the organization, but is used for many applications by the expertise team. The printer is more expensive, but also has some benefits. The printing is done in a printing chamber. This lowers the chance of quality problems with the prints due to climate effects. Internal AM experts state that they are therefore better fit for uncertain environments. This is also underlined by Zijlstra (2021). The power consumption of this printer is at maximum 0.15 kWh. The operating humidity should be between 0 and 90 percent, the temperature between 18.8 and 35 degrees Celsius.

Another option with Markforged is the *Metal X7 system* to use the FFF method to print metals. This does however require some post-processing. The part must be washed in a solvent to clear out the nylon. Thereafter it requires sintering to bind the metal powder. For some applications heat treatment is necessary to increase the part strength. For this two separate machines are necessary. Washing takes 12-72 hours and sintering 17-31 hours. The tensile strength and hardness of these parts comes very close to conventional parts of similar or the same material after heat treatment. For instance the 17-4PH Stainless Steel is heat treatable to 95% of wrought strength (Markforged, 2022). The maximum power consumption of such a machine is also triple that of the regular filament printer. This does not include the production facilities . Should be operated in humidity between 40 and 60 percent and temperatures between 20 and 26 degrees.

The '*AM container*' being designed by the RNLA is also mentioned in the interviews. This is a transport container containing AM printing equipment that can be shipped to and from deployment locations. This partially counters the transportation dangers mentioned in the interviews. It also provides a somewhat protected environment for the printer to be operated in. The container will, with relative certainty, contain the *UltiMaker S5*, the *Stratasys F370*, the *Markforged Mark 2* and the required facilities to operate them. More uncertain inclusions are a raise3D machine and a MakerBot machine (two other manufacturers of FFF printers). Since these are uncertain inclusions, for the purposes of this research they are not taken into account. The focus for the container is on polymer AM, so metal capability is not yet introduced.

The *Stratasys F370* is a new machine for the RNLA, specifically chosen for the AM container. The printer is similar to the Markforged in that it also has an enclosed environment for printing. The range of materials available is also larger. However, based on tests, the Markforged produces stronger parts and has a better surface finish. The reason for this printer is that it provides other possible build materials than nylon or reinforced nylon. The printer requires 1.5kWh of power. For operating the humidity should be between 30 and 70 percent, the temperature should be between 15 and 30 degrees Celsius. Currently it is best to combine this printer with a Markforged printer.

The RNLA also purchases metal printing capacity from an external supplier. This external metal printer is a selective laser melting system (SLM) utilizing metal powders. This is monthly capacity bought for a fixed price over a 3-year period with K3D. This company specializes in printing on contract and can deliver prints within 10 working days. The machine they use to complete the prints is supplied by Additive Industries. The specific machine is a MetalFABG2. This is a SLM printer with up to 4 lasers, meaning it can print up to 150cm^3/h depending on the material. Orders are communicated to the expertise team AM, who order the product with K3D. The process is subjected to both K3D's and the expertise team's standards.

The RNLA AM expertise team also has access to a *liquid resin printer* using the stereolithography (SLA) technique. However this is more of a niche machine within the RNLA and is not widely used. The respondents also do not see this machine as something useful to spread throughout the RNLA or use during deployment. Therefore this machine is left outside the scope of this research.

Outside of the current and upcoming AM machinery, respondents 6,7 and 8 also mentioned some things that might be interesting for the future. All three state that it would be interesting to investigate other metal printing options that might be beneficial.

One of the mentioned technologies is cold spray technology, such as a *Spee3D* machine. This is a very specific technology that is not fit for every part as the surface finish and materials are not always suitable. It does however have a speed and cost advantage over other metal printing techniques. They also offer an integrated solution useful for remote applications.

Respondent 8 mentions the integrated solutions supplied by *Fieldmade* as an option for remote printing. Since they offer an integrated solution in a container easily placeable in a deployment area. This company makes use of SLM metal printers, which is more commonplace. For the characteristics the chief technology officer of the company is consulted. The average lead time for metal parts on this solution is one to two days. It requires one trained expert to operate up to three containers at a time. The power consumption is quite high due to the conditioned environment in the container. The power consumption is 2kWh on average with 11kWh peaks. It has a battery installed to be resistant to inconsistent power infrastructure. Post-processing needs are a mill, lathe and sanding equipment.

Currently they offer optimized modeling, so there is no need for heat-treatment. The container can be transported on the ‘Wissellaadsysteem’ (WLS) trucks. The container takes 1 hour to fully setup and 2 to 3 hours to get on the move again. It has a fully conditioned input material storage, leveling system and robust calibration. It is therefore resistant to humidity, temperature and dust. High temperatures do however cause a higher power consumption. It is furthermore resistant to vibrations and shocks, both when transported and when stationary. The printed parts that have already been tested, are up to certification for the Norwegian army.

Based on the above information the selected machinery for the research are the *UltiMaker S5* and the *Markforged Mark 2*, since they represent a widely used machine of slightly lower quality and a less used, higher quality machine for the FFF printing technique. These machines are also used in the research by Zijlstra (2021) and therefore make for a good comparison between the research outcomes. Furthermore for the SLM metal printing technology the external K3D metal printer is regarded. The *Fieldmade* printer is regarded for the remote printing of metal parts. The characteristics of this solution are favorable and compatible with the systems already in use by the RNLA such as the WLS trucks.

The *AM container* and the *Fieldmade* solution have a controlled climate section to keep raw materials in the right conditions. For the simpler printers in remote locations this is not the case. The AM experts would like to locally source the raw materials during a deployment to reduce the risk of conditions during shipment affecting the materials. This is not always possible as already described in Section 3.1. Therefore the assumption is made that in a Main Task 1 deployment, local sourcing of raw materials is not possible.

Table 6: Machine characteristic overview

Machine	**Power Consumption per hour of use average/ peak**	**Setup/ break down time**	**Need for post-processing**	**Climate resistance**	**Vibration resistant**
UltiMaker S5	0.3kWh/ 0.5kWh	Negligible in current configuration	Hand tools	Humidity ≤ 60% Temperature: 15-32 °C	No
Markforged Mark 2	0.3kWh/ 0.5kWh	Negligible in current configuration	Hand tools	Humidity: 0-90% Temperature: 18.8-35 °C	No
Stratasys F370	0.15kWh/-	Negligible in current configuration	Hand tools	Humidity: 30-70% Temperature: 15-30 °C	No
Markforged X7	0.9kWh/ 0.15kWh	Negligible in current configuration	Mill, lathe, sanding tools, solvent bath, sintering equipment	Humidity: 40-60% Temperature: 20-26 °C	No
AM container	-/ 30kWh	unknown	Hand tools	Fully conditioned	Yes, when stationary
Fieldmade	2kWh/ 11kWh	1hr/ 3hrs	Mill, lathe, sanding tools	Fully conditioned	Yes, when stationary

Table 6 contains an overview of the AM machinery characteristics discussed in this section. The external AM printer is not included as the only relevant characteristics for this machine are the costs and lead time. The costs and lead time are dependent on the application and therefore not included for any of the machinery in this general table. Furthermore it can be seen that the machines have some restrictions. The integrated solutions make it possible to work with these restrictions. These solutions are however restricted by their size, power consumption and need for post-processing equipment. These are therefore more suitable further upstream in the supply-chain and the simpler machines further downstream.

Based on RNLA printing documentation we know the average build speed of some of the printers. The average build speed of the UltiMaker S5 is 14.5 cm^3/hour. The Mark forged mark 2 only requires an infill of 55% and has an average print speed of 19.9 cm^3/hour. However, from print speed records at the RNLA we see that this speed only holds for larger parts. For small parts under 20 cm^3 the speed for the Markforged mark 2 is on average 8.12 cm^3/hour. The Fieldmade solution is assumed to have similar performance to the more advanced Markforged printer for polymers, so the polymer build speed is 8.12 cm^3/hour. The depot printers are the same machinery so a polymer print speed of 8.12 cm^3/hour is assumed. So $S_U = 14.5$ cm^3/hour, $S_M = S_F = S_D = 19.9$ cm^3/hour for large parts and 8.12 cm^3/hour for small parts.

Raw material costs c_m^{rm} is dependent on the printer and the part. To keep things manageable we assume one type of polymer per printer. The UltiMaker S5's most used polymer is Nylon filament, which has a cost of 0.09 €/cm^3. The more advanced Onyx filament used by the Markforged mark 2 is estimated at 0.17 €/cm^3 (based on 55% infill). We assume the same price for the Fieldmade and depot level solutions as for the Markforged mark 2. Note that this does not take energy costs into account. Westerweel et al. (2020) and Zijlstra (2021) also include depreciation costs in the printing costs. We believe purchasing AM equipment is an investment decision that has to be made separately. From an operational standpoint the purchasing costs and depreciation costs of AM equipment are sunk costs. Another reason we do not include depreciation is that we have no indication on the wear of the AM equipment caused by use. It can be argued that most of the wear will be caused during use, but we also have no indication on the depreciation horizon and the actual utilization of the equipment. Therefore we choose to not include depreciation costs in the printing costs.

4.2 Potential locations for AM technologies in the RNLA supply chain

Based on further questions in the interviews described in Appendix A, the characteristics identified in Section 4.1 and literature on the subject, viable locations and operating environments are identified for the different AM machinery.

Respondent 1 notes that they believe metal AM is not something to do remotely. The size, specialized nature, large power consumption and facilities needed are the factors this notion is based on. The choice between keeping other equipment running or printing spare parts might be required. This is something the RNLA wants to avoid. Respondents 2 and 3 share the view of installing the metal printers in central hubs together with NATO partners. So not on the frontline, but as a secondary sourcing option in a location where careful manufacturing is possible. Otherwise they find the best option to outsource the metal AM process to the industry, this notion is shared by respondent 5. Respondent 8 thinks that there are options such as Fieldmade to enable metal AM during deployment.

Respondent 1 further mentions that they believe printers should be sent into the field with repair units. A better location would be somewhere where the AM container can be operated. This notion is based on the increased threat level in the field and the perceived lower quality of parts printed in remote locations. In Main Task 1 the container would have to be placed further upstream than for Main Task 2, due to the increased danger. This view is shared by respondents 6 and 7. They describe that further upstream, producing value adding parts is easier due to better production facilities. Moreover, the location of the printer should be in proportion to the quality constraints of the items that are printed. Respondent 8 also describes that where the demand arises, technical capabilities currently cannot support AM. Respondent 5 would prefer AM machinery to be placed at the demand. However printing possibility is limited to non-essential parts so far downstream. A more viable option is to place an integrated solution where the local infrastructure can support it. This is most likely a main operating base, as it is less mobile and in a safer location.

Hartig and Wulfsberg (2021) propose a structure for locating different AM technologies along an axis based on the relative distance from a home base. The authors regards autonomous systems for the German Navy such as boats, ships and submarines. The reasoning behind the structure also applies to the RNLA context as it is based on complexity versus capability. Hartig and Wulfsberg split the structure in four levels, with level 4 being the closest to the home base and level 1 being the furthest away. Production in Level 1 is characterized by lower complexity spare parts, a size restriction of 1 cubic meter, low need for training and is therefore useful for small boats. This is comparable to units like the maintenance platoons. Level 2 is characterized by a medium level of complexity, the ability to work with stronger or reinforced polymers, washing stations, more in depth training is required. It also requires a workspace with sufficient energy, ventilation and space. Level 2 is fit for large ships, making level 1 and 2 the mobile levels. For Level 3 and 4 there is risk for personnel due to dangerous materials like metal powders. They also need complex production facilities such as milling machines, more infrastructure such as gas storage or a solid foundation are necessary and training is even more in depth. Level 4 is characterized by the highest level of complexity, the ability to fabricate certified parts, the ability to produce small series of parts and high investment costs. Based on the level characteristics the following diagram is made for FFF, SLM, MJM (Multi Jet Modeling) and SLS (Selective Laser Sintering) type machines:

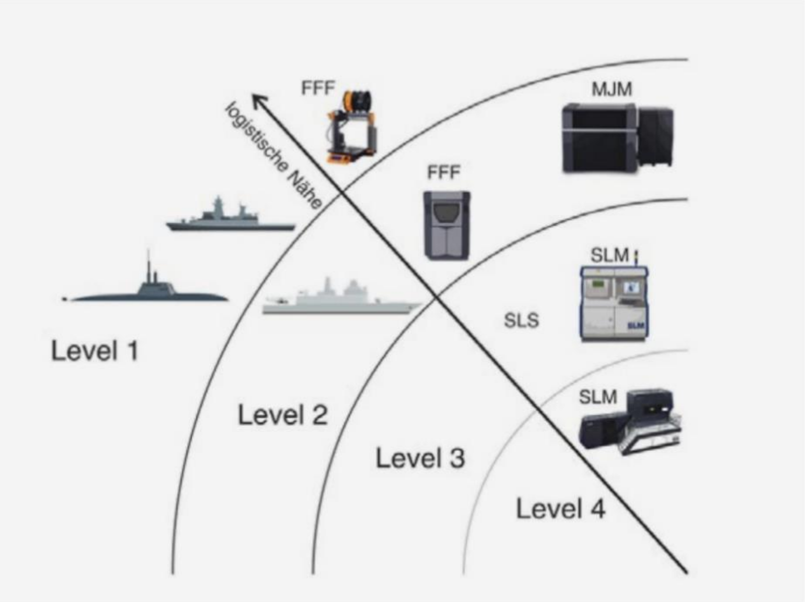


Figure 5: Levels of AM based on logistical distance from Hartig & Wulfsberg (2021)

When translating Figure 5 to the RNLA context, the following becomes clear: The simple FFF printer, like the *UltiMaker S5* is viable in the more remote locations. More advanced FFF printers, potentially with FFF metal capabilities are in Level 2. This relates to the *AM container* or the *Fieldmade* option, potentially at a main operating base. The smaller scale SLM printer is viable in less remote locations. For instance printing hubs established with NATO partners. The advanced SLM printers with all the facilities needed to certify parts is at or near the home base. This structure will form the possible scenarios for AM application.

4.3 Characteristics of printed spare parts

This section focusses on the complexity, needs and characteristics of the AM parts. First the views from the AM experts are identified through the interviews. Literature on the characteristics of AM produced spare parts is also used.

Respondents 2 and 3 state the spare parts that are printed should not be essential or vital since there is too little known about the printing to justify this. The other respondents state the opposite.

Respondents 1, 6, 7 and 8 mention that essential and vital parts contribute the most to vehicle readiness. Desirable parts have no impact on readiness, therefore reducing lead time for these parts is of little value. All respondents state non-supply parts are lucrative to print since there is often no other option to acquire them.

Respondent 8 states that for printed polymer parts, the strength is often worse than for conventional parts. Therefore the durability of these parts is often also worse. The respondent assigns this to the fact that the better density of an injection molded peace ensures higher strength in all directions. In literature we also see this phenomenon as Zijlstra (2021) and Westerweel et al. (2020) only regard printed parts as temporary fixes. Westerweel et al. (2020) note a 10 time increase of the failure probability of polymer parts if they are printed. For metal parts however, currently the strength is often higher for the AM produced parts. The parts do have to be heat treated, milled, and sanded to achieve this strength. These parts can have up to three times the strength of conventional parts as described by the RNLA experts. This view is also shared in literature as 't Hoen-Velterop and Kool (2020) and Khajavi, Partanen and Holmström (2013) show that printed metal parts are standard components in aircraft as they are lighter and stronger than conventional parts.

Furthermore, it depends entirely on the use-case whether it would be beneficial to produce a part through AM. For example 't Hoen-Velterop and Kool (2020) describe a use-case for a NH-90 door hinge. Producing the door hinge through AM costs approximately €11,074, a conventional door hinge costs €6,840. The lead time of the print is 8 weeks whereas the delivery lead time of this item is 6 weeks. This gives no ground to apply AM in this use-case. It is necessary to make a careful selection of what parts to acquire through AM.

The spare parts evaluated in this research are selected based on different characteristics. First it is important to filter based on the VEDN-classification. As already stated we are most interested in downtime critical parts i.e. vitals and essentials. Furthermore some general spare part information is needed. This includes a part description, the equipment it is a part for and size, weight or volume. The part material is also important to know. Furthermore to compare the printing of spare parts with ordering spare parts from an outside supplier it is improtant to know the purchasing costs and the lead time of a purchased spare part. Based on available data at the RNLA on printable spare parts the following list is identified:

Table 7: Spare parts list

Spare Part	**Delivery time (days)**	**Purchasing cost (€)**	**VEDN -class**	**Material type**	**Print level**
1. Fuel line cap	3.29	2.18	E	Polymer	1
2. Dipstick cap	3.29	525.38	E	Polymer	1
3. Protective hood	3.29	0.58	E	Polymer	1
4. Engine cap	12.33	17600	E	Polymer	1
5. Sealing cover	3.29	30.37	E	Polymer	1
6. Air compressor cover	3.22	69	E	Polymer	1
7. Protective cover for drop box	6.18	938.36	E	Polymer	1
8. Backrest button print	3.29	6.9	N	Polymer	1
9. Button for weapons system print	3.29	0.69	N	Polymer	1
10. Door hinge	28	6840	V	Metal	3/4
11. Bearing bush	3.29	32.84	V	Polymer	1
12. Battery clamp	3.29	31.23	V	Polymer	1

The delivery time is an average time recorded in the RNLA's ERP-system database. All other values are also extracted (or based on data) from this database. The print level is based on the material type and complexity of the part. These print levels refer to Figure 5. Most of the above parts are for the Boxer armored vehicle (depicted in Figure 6), which sees broad use within the RNLA. Part 10 is for the NH90 helicopter (depicted in Figure 7). This is the only metal part for which currently sufficient data is available on AM production. Parts 11 and 12 are vital parts for the Fennek reconnaissance vehicle (depicted in Figure 8).

Figure 6: Boxer armored vehicle

Figure 7: NH90 helicopter

Figure 8: Fennek reconnaissance vehicle

5 Mathematical model

In this chapter, the mathematical model to evaluate AM in the RNLA supply chain is formulated in order to complete *Deliverable 3: Mathematical model.* The model we selected for this research is discussed in Section 5.1. Based on this we then explain how this model is different from models in closely related literature in Section 5.2. These two sections answer *RQ3.1: "What type of mathematical model can be applied to solve the problem?"*. In Section 5.3 we describe the uncertainties included in the model and the formulation thereof to answer *RQ3.2: "What uncertainty parameters should be used to get a model that depicts reality in a sufficient way and is still usable?"*. We then describe a number of scenarios that need to be tested with the model in Section 5.4. To answer *RQ3.3: "How can we formulate and solve a mathematical model to answer the main research question?"* we give the model formulation in Section 5.5. How we solve the model is described in Section 5.6.

5.1 Model type description

An option to optimize stock in a multi-echelon system is the Clark and Scarf (1960) approach. Another as described by Axsäter (2015) is the METRIC approach. These specific approaches are chosen as the Clark and Scarf (1960) approach is exact and proven optimal for a serial system, while METRIC is a better approximation method for a distribution system. We focus on Main Task 1 since it is currently a more prevalent topic within the RNLA, and to limit the research scope. Therefore we the supply chain is as described in Figure 1 and Figure 2. We therefore opt for the Clark and Scarf (1960) approach for this research.

From now on we refer to the depot as Installation 1 i.e. the most upstream location, Installation 2 is the DCS and Installation 3 is the MOB.

5.1.1 Assumptions

The Clark and Scarf (1960) approach requires a number of assumptions:

- Demand originates exclusively at the lowest installation. In our setting this assumption holds, since demand arises at the maintenance crews who need parts to repair equipment, which are the most downstream entity in the supply chain.
- Shipping costs from one installation to another are assumed to be linear. This is also a correct assumption.
- We do not regard fixed ordering costs. This is acceptable since spare parts are often shipped together with other goods, for which shipments are done every day. These shipments arrive regardless of the spare part orders placed.
- The holding costs are assumed to be linear. This is also holds for the RNLA supply chain.
- Excess demand is assumed to be backordered. This also holds in practice for the RNLA. The equipment still requires repair when a part is unavailable.
- The outside supplier is assumed to have infinite supply. In reality the supplier can also have insufficient supply, but an order is always eventually fulfilled. This leads to delays at the supplier. we approximate this delay by including an estimation of this delay in the supplier lead time.
- The assumption is made that the review is done every period. The RNLA currently uses this method for their mission supply chain. We use a period of 1 day, as supply is done once every day according to RNLA experts. Demand, lead time, print time and holding costs are also expressed in days for the model.
- We assume single sourcing in our model, this means that there is only one option to supply the vehicles with spare parts. So we do not include emergency shipments, expediting or dual sourcing with AM and CM.

- A (S-1, S) replenishment policy is assumed. The order-up-to-level S is stock to safeguard against demand during lead times and uncertain delivery in order to retain equipment readiness. As the RNLA pursues maximum equipment readiness this policy is a good fit. The order-up-to level S does not include the parts installed in the vehicles. These installed parts are not included as they are no longer part of stock and cannot be used to fulfill demand.
- The time needed for exchanging spare parts is currently neglected in the model. This means in our research the vehicle is only unavailable as long as the demand for a spare part is outstanding. In reality the vehicle is also unavailable during repairs. This means the actual vehicle readiness will be lower than the modeled readiness.
- Clark and Scarf (1960) introduce the echelon stock policy, which is most commonplace for serial supply chains such as the one depicted in Figure 2 according to Axsäter (2015). Echelon is described by Clark and Scarf (1960) as the inventory at an installation in addition to the inventory between that installation and the final customer. This policy works well for serial systems as it not only controls inventory based on installation stock, but also takes in transit stock and stock at downstream installations into account. This reduces the amount of inventory shipped and the total storage costs.
- We only regard one part at a time in the model, this is due to the way the Clark & Scarf (1960) approach works.
- We assume a specific part is only present once in each vehicle. For the parts selected for this research this is the case. This does mean the model cannot be applied to parts that occur multiple times in a vehicle.
- Another assumption for the Clark & Scarf (1960) approach is that the lead times in between installations are constant. In our case the lead time is not constant due to stochastic delays. We use the expected value of the lead time including delays. The realized stochastic lead time can be different from the mean, meaning that the actual results might also be different. Based on estimates of the delays made by expert, the probability for delays longer than 1 day is small. Therefore the expected effect on the results of using the mean is also small.
- The review of the scenarios is done over an infinite horizon. In reality missions are finite and have a build-up and break-down period for which the model results will not hold. For this research we are interested in the operational period in between build-up and break-down and how AM fits into this period. Therefore the review over the infinite horizon is justifiable.
- The demand rate for spare parts in the Clark and Scarf (1960) approach is based on steady state number of parts. This assumption is made in order to keep the demand rate equal over the time horizon. In reality when vehicles break down, the demand rate lowers. We do not regard this reduction, leading to a slightly higher overall costs. As the demand rate per part is small (approximately 5 parts per year), the effect of this assumption is also expected to be small.

The assumptions we add to apply the approach are:

- We assume that there is always sufficient shipment capacity to fulfill demand. The assignment of shipment capacity is a separate issue, which we do not include in the research scope. We assume there is always enough capacity.
- The spare part demand is defined by a Poisson distribution. Demand occurrences are independent of one another and demand arrives one by one. These assumptions also hold for the RNLA demand.
- We also assume that when a vehicle is defect, it cannot get any other defects. This is also due to the assumption that parts are singular in each vehicle and since we only regard one part at a time. Also, no extra defects occur during repair.
- The Poisson demand rates are based on the recorded yearly spare part demand. This average demand rate will generally be lower than actual demand because it is based on historical data, which is based on Main Task 2 and 3 scenarios. For Main Task 1 scenario the damage to

vehicles and therefore spare part demand will be significantly higher. The lower demand rate will lead to lower costs and less stock than necessary, forming a lower bound for the solution. This is adjusted by multiplying the demand by an intensity factor estimated by the RNLA for a Main Task 1 scenario.

- Each vehicle in the fleet is continuously needed for operations. This means that the fleet does not include vehicles that are not used. This means that all vehicles are under approximately the same strain, meaning spare part wear is also the same along all vehicles in the operation.

5.2 Differences with models in literature

In this research we consider a similar supply chain and setting as used by Zijlstra (2021) and Westerweel et al. (2020). Therefore these models and our model are comparable in many ways. Here we discuss the differences and similarities between our model and these two models from literature. This is summarized in Table 8.

Different from Zijlstra (2021) we do not consider the forward operating base as a spare part stock point based as the interviews and Zijlstra reveal it is not a place where stock is kept in significant numbers or where AM is optimal. Furthermore Zijlstra (2021) uses Shang and Song heuristic to find optimal spare part stocks which is derived from Clark and Scarf (1960), we use the approach by Clark and Scarf (1960) itself. Furthermore we see the printed spare parts as full replacements as opposed to temporary fixes. This means demand rate for parts in the model are influenced by the quality of the printed parts. Westerweel et al. (2020) and Zijlstra (2021) view the parts as temporary replacements. Furthermore Westerweel et al. (2020) introduce demand based on a failure probability of the part as opposed to the Poisson demand distribution suggested for our model. They use a Markov decision process to find an optimal policy. As opposed to Westerweel et al. (2020) we do not have expediting and emergency options but view AM as an alternative to ordering parts. The supply chain in our research is serial, for such a system the Clark & Scarf (1960) approach is proven to give an optimal solution. Another notable difference with the models by Zijlstra (2021) and Westerweel et al. (2020) is the inclusion of raw material supply into the model.

Table 8: Differences models from literature

	Model		
Characteristic	**Westerweel et al. (2020)**	**Zijlstra (2021)**	**This research**
1. Supply chain configuration	Single location model for an installation in the deployment area.	3 echelon serial supply chain under deployment. Only uses the echelons near the country of deployment i.e. no depot, but forward operating base is included.	3 echelon serial supply chain under deployment. Not including the forward operating base, but adding the depot and transport from the Netherlands.
2. components	Single component	Multi component	Single component
3. Solving method used	Markov decision process	Heuristic by Shang and Song (2003)	Approach by Clark and Scarf (1960)

4. *Demand distribution*	Bernoulli process	Poisson distributed	Poisson distributed
5. *Delivery options*	AM, expediting and scheduled replenishments	Scheduled replenishments and emergency AM	Single sourcing: Either AM or scheduled replenishments
6. *Use of AM*	Emergency option for lower quality parts	Emergency option	Single sourcing alternative to CM
7. *AM part policy*	AM parts are temporary fixes	AM parts are temporary fixes	AM parts are full replacements
8. *Raw material*	Not in model, evaluated separately	Not incorporated	Incorporated

5.3 Uncertainty formulation for the model

In this section we discuss the uncertainties to be incorporated in the mathematical model. Also we discuss in detail how we implement them. The uncertainties chosen to be incorporated in the model are:

1. *The lead time for deliveries to each installation.* The lead time of a specific delivery to an installation is assumed to be known and rather stable in between installations. The uncertainty originates from the availability of a specific transport connection between two installations. There exists a chance that due to external circumstances a delivery cannot take place, the duration of this varies based on the origin of the delay. We do not consider shipment loss between installations as this complicates the model too much for our purposes. When AM is used, the delivery lead time is extended by the printing time. Furthermore, shipments of raw material are needed to enable production. These shipments are the same as spare part shipments and therefore experience the same delays. Instead of one spare part, the shipment will contain the amount of raw material needed to produce one spare part.
2. *The quality of the spare parts produced.* This is taken up in the mathematical model as a fixed percentage chance that an order is completed successfully through AM. This fixed percentage chance depends on the machinery and installation. Due to less infrastructure, unfavorable climate conditions and stability in lower installations and less assurance of good quality products with cheaper, more mobile machines the chance of success will be lower. These percentages are justified through expert opinions. A print can be unsuccessful due to many different factors as identified in Chapter 4, triggering a cancelation of the print. The additional printing time is described by a stochastic variable. The total realized printing time is denoted by the regular printing time and the additional time taken up by failed prints. The other assumption that is made is that failed prints cannot be re-used for new prints or repaired. Therefore each print attempt takes up new materials. This is an extreme situation as in reality a failed print will most likely not use the same amount of material as a successful print. Furthermore a small percentage of failed prints could potentially be salvaged. This means outcomes will most likely be slightly more favorable in real life compared to the calculations. When a print fails, the print is started again, meaning that the other orders have to wait longer in the queue.
3. *The realized availability of the AM machinery at the different installations.* A printer can fail due to outside influence or during operations. As AM is currently used as an emergency option

within the RNLA the assumption is made that defects to the machinery is only noticed as soon as an print order is initialized. When a machine is found to be down, the time to repair is taken as a fixed amount of time denoted by the mean time to repair for each specific machine and installation combination. A printer can also fail during operations, meaning the repair time is triggered and the print has to be restarted. This last assumption is made since a failure or interruption during the printing process will in most cases lead to the part being of low quality. Also repairing the printer will in most cases require the unfinished part to be removed and the printer to be reset. The result of this is additional waiting time for all products in the queue.

4. *Waiting time for an order at the AM machinery.* As can be seen from points 2 and 3, the uncertainties are correlated to a certain degree. For instance a printer failure also leads to a part failure that in turn leads to a longer processing time. This all leads to other orders at the printer also being delayed. These delays can be captured in the waiting time of a print order. The waiting time is based on the regular printing time and the distribution of the delay caused by both print quality and printer breakdowns.
5. *The uncertain demand for spare parts*. This demand is assumed to be Poisson distributed in accordance with van Oers (2022), Zijlstra (2021) and Knofius et al. (2021). As described in Section 3.3 the quality of AM produced parts can diverge from that of CM produced parts. Dependent on the part, material, printer and print location AM produced parts can have an adjusted failure rate. This is modeled as an adjusted arrival rate for the Poisson demand distribution for CM produced parts. This does mean that raw material demand is not equal to the demand for spare parts. It also includes the number of failed print attempts. So the demand for raw material does not follow the same Poisson distribution as spare part demand. Also an order of raw material is required to be in stock at the installation in order to initiate the printing process. So when the inventory level of raw material is not sufficient the print is backordered.

Lead time uncertainty: The realized lead time for an order placed at installation j is denoted by $\hat{L}_j$. The lower bound for the lead time is denoted by L_j. Y_j denotes the amount of additional time that passes due to delays, which is determined by a statistical distribution. This distribution is fitted based on expert opinions on the delay probability and length. As this is an estimation and the RNLA might want to adjust it in the future we keep the formulation general here. The fitting of the distribution used for the analysis is described in Appendix B. Delays are independent of one another, so a current shipment failure does not affect the duration of a next shipment failure. The general equation for the expected realized lead time is given by:

$$\mathbb{E}[\hat{L}_j] = L_j + \mathbb{E}[Y_j] \tag{1}$$

Y_j is chosen to be continuous as it denotes a time. For Y_j with probability density function f_{Y_j} the mean is given by:

$$\mathbb{E}[Y_j] = \int_0^\infty x \cdot f_{Y_j}(x)dx$$

For now, based on the description given in Appendix B, we use an Exponential distribution.

Print time uncertainty based on quality of end result and printer downtime: We denote the realized printing time of an item n on machine m at installation j including time taken up by potential reprints due to quality issues and machine failures by $\hat{P}_{j,n,m}$. The delay duration is denoted by $Z_{j,n,m}$. The distribution is fitted based on expert opinions on the printing time and extra duration for failed attempts. As this is an estimation and the RNLA might want to adjust it in the future we keep the formulation general here. The fitting of the distribution used for the analysis is described in Appendix B. The general equation for the expected realized print time is given by:

$$\mathbb{E}[\hat{P}_{j,n,m}] = P_{j,n,m} + \mathbb{E}[Z_{j,n,m}]$$

(2)

$Z_{j,n,m}$ is chosen to be continuous as it denotes a time. For $Z_{j,n,m}$ with probability density function $f_{Z_{j,n,m}}$ the mean is given by:

$$\mathbb{E}[Z_{j,n,m}] = \int_0^\infty x \cdot f_{Z_{j,n,m}}(x)dx$$

For now, based on the description given in Appendix B, we use the product of a geometric distribution and a continuous uniform distribution.

We are interested in the time until an order is completed. The printer can be seen as a M/G/1 queue, as the system has 1 server and we assume Poisson distributed arrival of demand. We use the Pollaczek-Khinchine formula (Gass & Fu, 2016) to find the queue length and subsequently the expected time an order spends in the system before it is completed. In the formulas λ denotes the arrival rate of orders at the print station. The variance is based on the distribution fitted in Appendix B, the printing rate μ is $\frac{1}{\mathbb{E}[\hat{P}_{j,n,m}]}$. The utilization of the printer $\rho = \lambda \cdot \mathbb{E}[\hat{P}_{j,n,m}]$. The queue length L_q is given by:

$$L_q = \rho + \frac{\rho^2 + \lambda^2 VAR(\hat{P}_{j,n,m})}{2(1-\rho)}$$

(3)

The system in our research is stationary in the sense that the probability distributions do not change over time. Therefore, we can use Little's law (Little, 1961) to find the expected time an order spends in the system. This expected time W is given by:

$$W = \frac{L_q}{\lambda} + \mu^{-1} = \frac{\rho + \lambda\mu VAR(\hat{P}_{j,n,m})}{2(\mu - \lambda)} + \mu^{-1}$$

(4)

The lead times and production times adjusted for uncertainty are used in the formulation of the mathematical model as lead times in between installations. This way the uncertainties are considered when calculating the optimal stock levels.

5.4 Scenario formulation

In all three tiers of the supply chain AM printing is a possibility. The type of printer(s) possible is different for each location. Therefore the spare parts that are producible through AM differs per location. At the depot level all types of printing facilities will be available. At the DCS larger portable solutions, such as the Fieldmade printer are viable, so also most parts can be printed up to good standards. At the MOB level, printing is limited to more portable polymer printers such as the UltiMaker. This means the quality and variety of printed parts is limited. Four standard scenarios are introduced:

Scenario 0: Situation without AM, single item, single source. For this scenario the three installations from Figure 2 are considered. All three installations hold finished spare part stock to adjust for lead times and uncertainty. This scenario is added as a reference for the other three scenarios and also since the RNLA might not want to use AM in some situations.

Scenario 1: AM at Installation 1, single item, single source. In Scenario 1 the source for spare parts is AM and the printer is located at Installation 1. This means that raw material is ordered directly from the supplier and spare parts have to travel through all stages of the three-stage supply chain. At

Installation 1 this means that prints are made to order and shipped through installations 2 and 3 to the maintenance platoon. Since there are many printer options and solid infrastructure at Installation 1, the printing process is the most reliable.

Scenario 2: AM at Installation 2, single item, single source. In Scenario 2 the source for spare parts is also AM and the printer is located at Installation 2. This means that raw material is ordered from the supplier and shipped through Installation 1. Installation 1 is now a customer order decoupling point for raw material. Spare parts have a smaller supply chain. At Installation 2 this means that prints are made to order and shipped through installations 3 to the maintenance platoon. There are fewer printer options but acceptable infrastructure at Installation 2, therefore the printing process is only slightly less reliable.

Scenario 3: AM at Installation 3, single item, single source. In Scenario 3 the source for spare parts is also AM and the printer is located at Installation 3. This means that raw material is ordered from the supplier and shipped through Installation 1 and 2. Installation 1 and 2 are now a customer order decoupling point for raw material. Spare parts have an even smaller supply chain. At Installation 3 this means that prints are made to order and shipped to the maintenance platoon. There are minimal printer options and unstable infrastructure at Installation 3, therefore the printing process is the least reliable.

5.5 Model formulation

In this section the formulation of the mathematical model for the RNLA mission supply chain is handled. We will now first introduce the KPI for the RNLA on which we base our calculations. Thereafter we discuss the full formulation of the cost functions based on Clark & Scarf (1960).

5.5.1 KPI

Vehicle or material readiness is an important performance metric for the RNLA. The parts considered in this research are downtime critical. The parts are singular in each vehicle and backorders only originate at Installation 3 where the actual demand arises, meaning the expected readiness can be found from the number of expected of backorders under the chosen policy. Under the above conditions the backorders directly relate to the number of vehicles inoperable. The expected number of backorders $E(IL_3^-)$ can be found through Axsäter (2015, p.202) formula 10.21. This equation uses the expected on-hand inventory $E(IL_3^+)$ and the echelon order up to level for Installation 3 to calculate the expected backorders. The expected number of backorders $E(IL_3^-)$ is given by:

$$\begin{aligned} E(IL_3^-) &= E(IL_3^+) - \left(S_3^e - \lambda_3 \hat{L}_3\right) \\ &= \sum_{u=1}^{S_3^e} u \cdot P(IL_3 = u) - \left(S_3^e - \lambda_3 \hat{L}_3\right) \end{aligned} \tag{5}$$

Since we define spare part demand with a Poisson distribution, $P(IL_3 = u)$ from Equation (5) under the *(S-1, S)*-policy is given by:

$$P(IL_3 = u) = P\left(D_3(\hat{L}_3) = S_3 - u\right) = \frac{\left(\lambda_3 \hat{L}_3\right)^{S_3^e - u}}{(S_3 - u)!} e^{-\lambda_3 \hat{L}_3} \tag{6}$$

Dividing $E(IL_3^-)$ by the deployed fleet size shows the expected percentage of vehicles that are unavailable at any given period. The following things are important to note:

- The Clark & Scarf approach controls inventory based on holding and backordering costs. The approach minimizes the total costs by adjusting echelon stocks to balance holding and backordering costs. We are interested in minimizing costs under an acceptable readiness. Equation (5) can be used to determine the required echelon stock at Installation 3 in order to reach a desired readiness. We can use this echelon stock to further calculate the echelon stocks at the other installations and the total costs.
- Backordering costs are necessary to apply the Clark and Scarf approach. However, we want to reach a certain material readiness. So we determine the backordering costs based on the maximum backorders allowed to still reach the readiness. This is described in more detail in Algorithm 2 in Section 5.6.
- This alternative approach eliminates the need for a user to estimate the backordering costs of a vehicle or part themselves. This is a good thing, since estimating how much costs are associated with a vehicle being unavailable for the RNLA is difficult. It is also not an intuitive metric for the RNLA as it is currently not used by the supply chain experts to make analyses. The readiness is a better alternative as it is already used as a metric by the supply chain experts.
- Note that this does introduce an extra restriction to the Clark & Scarf approach that limits the range of possible input values. We discuss this in more detail in Section 5.6.

5.5.2 Mathematical model for Scenario 0

We refer to Clark and Scarf (1960) for a more detailed description of the specific approach used. In this research only the main formulas are given. This section will also discuss how the formulas are adapted for the KPI calculation and the scenarios relevant for the RNLA. Note that the following description holds for *Scenario 0*. The notation of the equations is based on the Clark and Scarf notation used by Axsäter (2015). Throughout the description of the mathematical model, the following notation is used:

$b =$ backordering cost of an item measured at the end of each period

$D(n) =$ stochastic demand during *n* periods

$e_j =$ echelon holding cost per unit and period at installation *j.* It denotes the holding cost on the value added for going from installation $j-1$ to *j*

$h_j =$ holding cost per unit at installation *j,* $h_1 = e_1, h_2 = e_1 + e_2, h_3 = e_1 + e_2 + e_3$ (Axsäter, 2015, p.193)

$IL_j^i =$ installation stock inventory at *j* just before demand is realized

$IL_j^e =$ echelon stock inventory at *j* just before demand is realized, where $IL_j^e = IL_j^i + IL_{j+1}^e$

$J =$ The set of installations used in the scenario, where $J = \{1,2,3\}$

$L_1 =$ Lead time for a replenishment at Installation 1. Here this is described by the expected lead time from the supplier including delays i.e. $\mathbb{E}[\hat{L}_1]$

$L_2 =$ Lead time for a replenishment at Installation 2. Here this is described by the expected lead time from Installation 1 to Installation 2 including delays i.e. $\mathbb{E}[\hat{L}_2]$

$L_3 =$ Lead time for a replenishment at Installation 2. Here this is described by the expected lead time from Installation 2 to Installation 3 including delays i.e. $\mathbb{E}[\hat{L}_3]$

$S_j^e =$ echelon order up to level for echelon *j*

$S_j^i =$ installation order up to level for installation *j*

$x^+ = max(x,0), x^- = max(-x,0)$ and $x^+ + x^- = x$

$y_1 =$ echelon inventory position at Installation 1 in period t just before demand is realized

$y_2 =$ realized echelon inventory position at Installation 2 in period $t + L_1$ just before demand

$y_3 =$ realized inventory position at Installation 3 in period $t + L_1 + L_2$ just before demand

$\lambda =$ the demand rate for the part evaluated

Figure 9 shows the concepts of echelon and installation stock and the corresponding holding costs. So echelon inventory position includes all orders at the installation, in transit to the installation and downstream from the installation. The realized inventory position at an installation does not include orders backordered at a previous installation.

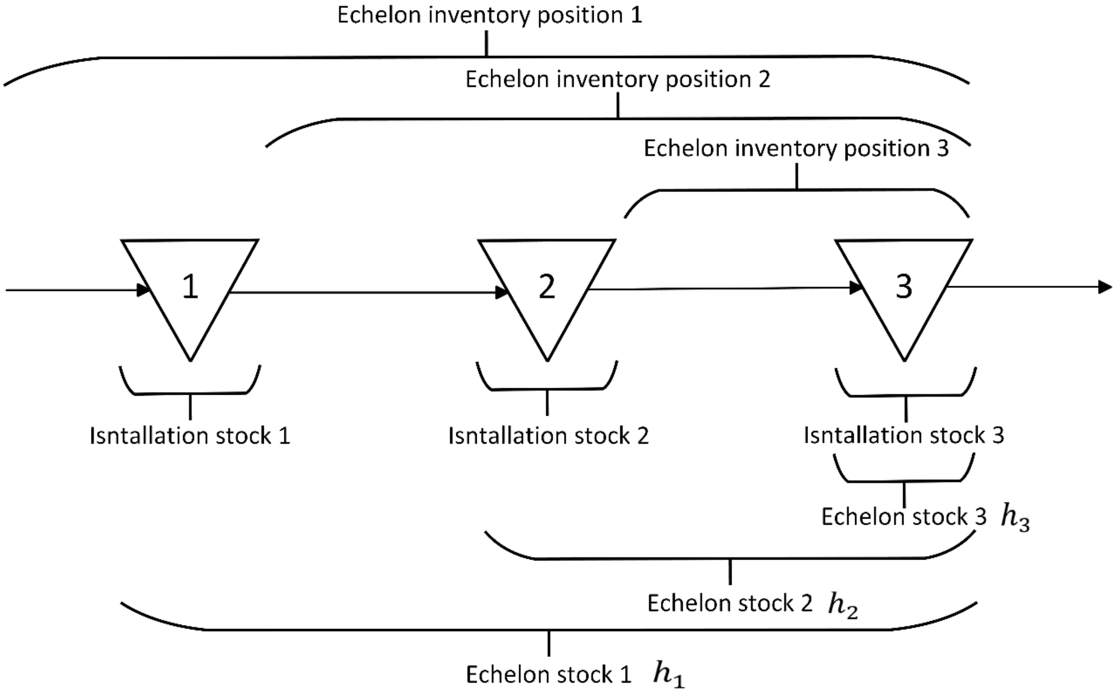


Figure 9: The concepts of echelon stock and echelon inventory position adapted from van Houtum (2006)

We do not include holding costs for in transit parts from installation *j* to *j+1*, $h_j \lambda L_{j+1}$, in the optimization. These costs do not affect the optimization and are not affected by the control policy. They do affect total costs, therefore we evaluate in transit costs for the optimal policy identified separately to show the costs of the policy. Production costs and purchasing costs are also calculated separately to show the costs.

The echelon inventory $IL_j^e = y_j - D(L_j)$ where $D(L_j)$ has a mean given by λL_j. We denote the beginning of a cycle of ordering events as period t_0. Installation 1 orders at the beginning of period t_0. Installation 2 orders at the beginning of period $t_0 + L_1$. This means that for echelon stock 1 we are interested in the demand over periods t_0 through $t_0 + L_1 - 1$ i.e. $D(L_1)$, which is given by λL_1. Installation 3 orders at the beginning of period $t_0 + L_1 + L_2$. . This means that for echelon stock 2 we are interested in the demand over periods $t_0 + L_1 - 1$ through $t_0 + L_1 + L_2 - 1$ i.e. $D(L_2)$, which is given by λL_2. For echelon stock 3 we are interested in the demand for the remaining periods of the cycle i.e. $t_0 + L_1 + L_2 - 1$ through $t_0 + L_1 + L_2 + L_3$. i.e. $D(L_3 + 1)$, which is given by $\lambda(L_3 + 1)$.

The optimal policy y_j^* denotes the echelon stock for which the cost function is minimized. As discussed in Section 5.5.1 we use Equation (5) in order to determine the minimum value for S_3^e. The cost function for echelon 3 is given by:

$$\begin{aligned}\hat{C}_3(\hat{y}_3) &= e_3\hat{y}_3 - h_3(\lambda(L_3+1)) + (h_3+b)\cdot E[\hat{y}_3 - D(L_3+1)]^- \\ &= e_3\hat{y}_3 - h_3\big(\lambda(L_3+1)\big) + (h_3+b)\sum_{u=\max(\hat{y}_3,0)}^{\infty}(u-\hat{y}_3)\frac{\big(\lambda(L_3+1)\big)^u}{u!}e^{-\lambda(L_3+1)}\end{aligned} \tag{7}$$

The formula for $\hat{y}_3 < 0$ is added as setting the order up to level to a negative value always leads to a backlog. Since negative demand is not possible, the summation in Equation (7) has to be made from 0 to infinity as opposed to from $\hat{y}_3$ to infinity.

Note that whatever policy is followed the following must hold:

$$\hat{y}_j \le \hat{y}_{j-1} - D\big(L_{j-1}\big) \qquad \forall j$$

The next installation is approached under the assumption that y_3 is optimal. The next stage includes the holding costs at this stage, the costs of the previous stage and the costs made at Installation 3 due to insufficient availability at Installation 2. The cost function for echelon 2 is given by:

$$\hat{C}_2(\hat{y}_2) = h_2(\hat{y}_2 - \lambda L_2) + \hat{C}_3(S_3^e) + \sum_{u=\hat{y}_2-S_3^e}^{\infty}\left[\hat{C}_3(\hat{y}_2-u) - \hat{C}_3(S_3^e)\right]\frac{(\lambda L_2)^u}{u!}e^{-\lambda L_2} \tag{8}$$

The optimal value is denoted by $\hat{y}_2^*$. The optimal echelon stock policy for Installation 2 is denoted by $S_2^e = \hat{y}_2^*$. The cost function for echelon 1 i.e. the total costs is given by:

$$\hat{C}_1(\hat{y}_1) = h_1(\hat{y}_1 - \lambda L_1) + \hat{C}_2(S_2^e) + \sum_{u=\hat{y}_1-S_2^e}^{\infty}\left[\hat{C}_2(\hat{y}_1-u) - \hat{C}_2(S_2^e)\right]\frac{(\lambda L_1)^u}{u!}e^{-\lambda L_1} \tag{9}$$

Similar to the other installations, the optimal value is denoted by $\hat{y}_1^*$. The optimal echelon stock policy for Installation 1 is denoted by $S_1^e = \hat{y}_1^*$.

5.6 Solving method

Clark and Scarf (1960) show that the cost functions in their approach are convex. As the only adjustment we make to the cost functions is using a Poisson distribution for demand, the convexity also holds for our cost functions. This simplifies the methods required to solve the model.

To make sure the optimal echelon and installation stocks found trough the model reach a desirable readiness we use Equation (5) to find the minimum value for S_3^e. The maximum number of expected backorders allowed under the readiness is given by:

$$max[E(IL_3^-)] = \frac{1 - readiness}{fleet\ size}$$

Readiness denotes the minimal required percentage of vehicles in working order at any time. Fleet size denotes the number of vehicles deployed. We can then find the minimum value for S_3^e by setting it as 0 and increasing it by 1 until $E(IL_3^-) \le max[E(IL_3^-)]$ ($E(IL_3^-)$ can be found through Equation (5)). The pseudocode for this calculation is:

Algorithm 1 Finding the minimal allowed value for S_3^e

```
$S_3^e = 0$
$E\left(IL_3^-\right)$ for $S_3^e = \sum_{u=1}^{S_3^e} u * \frac{(\lambda_3 \hat{L}_3)^{S_3^e - u}}{(S_3 - u)!} e^{-\lambda_3 \hat{L}_3} - \left(S_3^e - \lambda_3 \hat{L}_3\right)$
while $E\left(IL_3^-\right) > max\left[E\left(IL_3^-\right)\right]$ do
    $S_3^e \leftarrow S_3^e + 1$
end while
```

We determine backorder costs b based on the minimum value for S_3^e. We do this by finding the lowest value of backorder costs for which $\hat{y}_3^*$ equals the minimum value for S_3^e. We start with $b = 0$ and increase b by 1 until $\hat{y}_3^*$ equals the minimum value for S_3^e. The pseudocode for this calculation is:

Algorithm 2 Finding the backorder cost for the minimal value for S_3^e

```
$b = 0$
$\hat{y}_3 = 0$
$\hat{C}_3\left(\hat{y}_3\right) = e_3 \hat{y}_3 - h_3(\lambda(L_3 + 1)) + (h_3 + b) * E[\hat{y}_3 - D\left(L_3 + 1\right)]^-$
while $\hat{C}_3\left(\hat{y}_3\right) > \hat{C}_3\left(\hat{y}_3 + 1\right)$ do
    $\hat{y}_3 \leftarrow \hat{y}_3 + 1$
end while
while $\hat{y}_3 < min[S_3^e]$ do
    $b \leftarrow b + 1$
end while
```

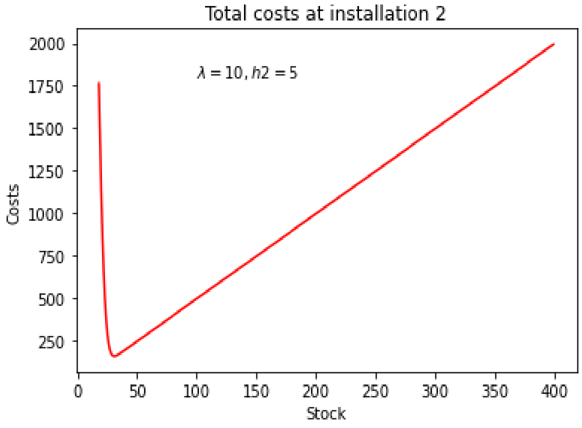
The backordering costs b is required for the optimization, but because it is determined based on Algorithm 2, it does not represent real cost. Backorder costs are therefore removed from the total cost used to evaluate the scenario.

The minimum value for S_3^e is also the optimal value as a higher value will only lead to more holding costs and is therefore not better. Increasing S_3^e might decrease backordering cost, also for other installations. Backorder costs do however not represent real cost. Therefore, increasing S_3^e beyond the minimum value will only increase the real total costs.

For the optimization of Equation (9) an adjustment to Equation (8) is necessary. We know $\hat{y}_2 \leq \hat{y}_1 - D(L_1)$ has to hold. However, for $\hat{y}_1 = S_2^e$ and $S_3^e > 0$, the situation can occur where $0 < (\hat{y}_1 - u) < S_3^e$ in Equation (9). This causes a negative value for u in Equation (8). Therefore the following adjustment is made to Equation (8) in the implemented model:

$$\hat{C}_2(\hat{y}_2) = h_2(\hat{y}_2 - \lambda L_2) + \hat{C}_3(S_3^e) + \sum_{u=\max\left((\hat{y}_2 - S_3^e), 0\right)}^{\infty} \left[\hat{C}_3(\hat{y}_2 - u) - \hat{C}_3(S_3^e)\right] \frac{(\lambda L_2)^u}{u!} e^{-\lambda L_2}$$

We want to find the optimal value of $\hat{y}_j$ for the scenario cost functions. To show the method, the cost function for Installation 2 under *Scenario 0* is sketched using Python and shown in Figure 10. We use a setting where the daily demand is 10 parts so that the function is better visible for large values of $\hat{y}_j$. We use values of $\hat{y}_j$ up to 400 parts as keeping more stock is highly unlikely. Then zooming in on the figure we can reveal the optimal value for $\hat{y}_j$ where $\hat{C}_j\left(\hat{y}_j\right)$ is minimal:



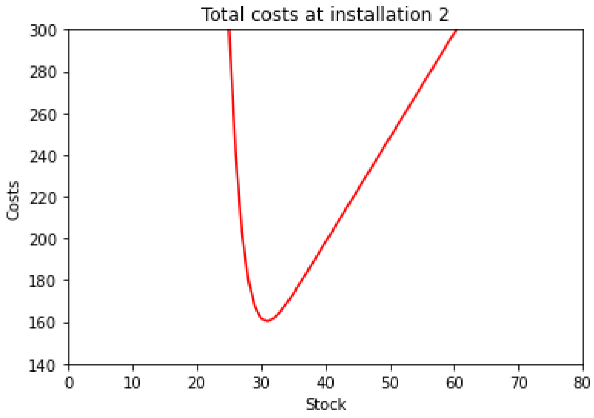


Figure 10: Cost figure range 0 to 400

Figure 11: Cost figure zoomed in

Figure 11 shows the minimal value of the cost function to be €160.40 under an optimal stock of 31 for the parameter values in the showcase instance. This optimal value is found by checking all stock values in the interval 0 to 400 with a step size of 1. A smaller step size is not necessary as we are talking about a number of parts, which can only take integer values. We know $\hat{y}_2^* = 31$ gives minimal costs since $\hat{C}_2(\hat{y}_2^* - h) > \hat{C}_2(\hat{y}_2^*)$ and $\hat{C}_2(\hat{y}_2^* + h) > \hat{C}_2(\hat{y}_2^*)$ for all integer values of $\hat{y}_2^* + h$ and $\hat{y}_2^* - h$ in the interval 0 to 400. A similar approach is taken to find the minimum for the other cost functions. This approach is applied to all cost functions and parameter values in order to find the optimal values. As they are very similar we do not show them. Finding the minimum with the Python model through this interval search approach is quick (around 3 minutes per calculation) and can be easily applied to other scenarios and parameter values.

The approach controls based on echelon stocks, we can however easily convert the optimal echelon stocks to installation stocks. The only prerequisite is that the policy is nested, meaning an installation only orders after demand occurs, which is the case in our research. The optimal installation stocks can be found by $S_j^i = S_j^e$ if *j* is the most downstream location, otherwise $S_j^i = S_j^e - S_{j+1}^e$ (Axsäter, 2015).

5.7 Changes to mathematical model for Scenario 1, 2 and 3

Equation (7), (8) and (9) are based on *Scenario 0*, adjustments to the formulation need to be made in order to use the formulas for the other scenarios. In scenarios 2,3 and 4 we are interested in the production time and the storage and supply of raw materials. In order to include raw material supply and printing time in the model, the printing installation is modeled as an additional installation. Essentially splitting the installation where the printer is located into two individual parts. Part A is the production part, here and in all prior installations, raw materials are stored. Part B is the start of the spare part supply chain, so here and in all subsequent installations, spare parts are stored. The lead time between part A and B is given by the printing time of a spare part described in Equation (2) and Equation (4). This makes the system into a 4-installation supply chain for scenarios 2, 3 and 4 meaning an additional formula is required for this extra installation. It depends on the scenario where this additional installation is needed. Since we work with a single item, which requires a set amount of material, the formulas do not have to be adapted for raw materials and can be used as is, only the parameter values have to change.

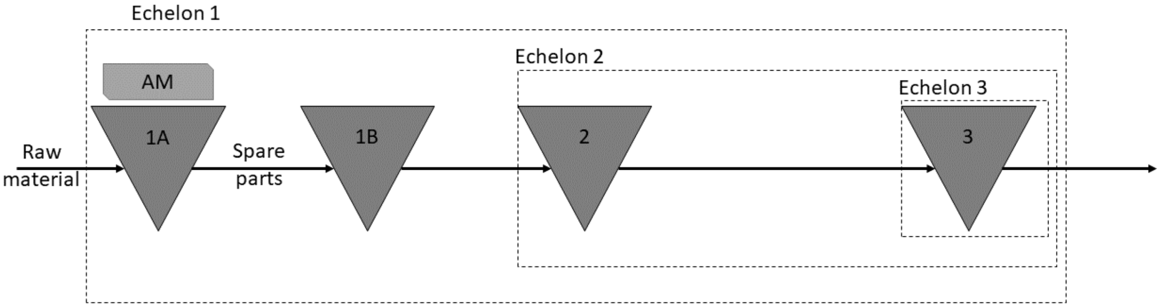


Figure 12: Scenario 1 supply chain

For *Scenario 1* as depicted in Figure 12, the inventory at Installation 1A consists of raw material for printing. The inventory at Installation 1B, 2 and 3 consists of printed spare parts. Therefore an additional formula has to be added before Equation (9) for the raw material storage and Equation (9) is adjusted for the scenario. In this scenario L_1 is replaced by L_{1A} and L_{1B}. L_{1A} is the lead time for raw materials from the supplier including delays. L_{1B} consists of the processing time of the spare part (also corrected for uncertainty) as described in Equation (4). Furthermore, the demand at Installation 1A is larger than the spare part demand since it also includes raw material demand for failed attempts. We use a Poisson distribution for both demands. We denote the regular demand rate as λ_B (which holds for all installations from 1B onward) and the demand rate for raw materials as λ_A (which holds for 1A). We denote the fixed probability of a print of a part on machine *m* in location *j* being successful as $q_{j,m}$. This probability is estimated by RNLA AM experts. The average number of attempts needed until a print is successful can be seen as the mean of a geometric distribution: $E(attempts) = \frac{1}{q_{j,m}}$. This formula is derived from the standard formula for the mean of a geometric distribution by van Berkum and Di Bucchianico (2016). Thus, $\lambda_A = \lambda_B * \frac{1}{q_{j,m}}$. So Equation (9) is replaced by the following two formulas:

$$\hat{C}_{1A}(\hat{y}_{1A}) = h_{1A}(\hat{y}_{1A} - \lambda_A L_{1A}) + \hat{C}_{1B} + \sum_{u=\hat{y}_{1A}-S_{1B}^e}^{\infty} [\hat{C}_{1B}(\hat{y}_{1A} - u) - \hat{C}_{1B}(S_{1B}^e)] \frac{(\lambda_A L_{1A})^u}{u!} e^{-\lambda_A L_{1A}} \tag{10}$$

$$\hat{C}_{1B}(\hat{y}_{1B}) = h_{1B}(\hat{y}_{1B} - \lambda_B L_{1B}) + \hat{C}_2(S_2^e) + \sum_{u=\hat{y}_{1B}-S_2^e}^{\infty} [\hat{C}_2(\hat{y}_{1B} - u) - \hat{C}_2(S_2^e)] \frac{(\lambda_B L_{1B})^u}{u!} e^{-\lambda_B L_{1B}} \tag{11}$$

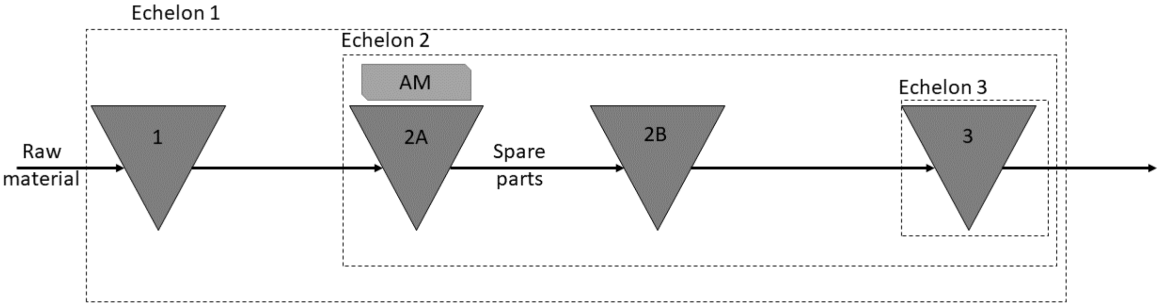


Figure 13: Scenario 2 supply chain

For *Scenario 2* as depicted in Figure 12, the inventory at Installation 1 and 2A consist of raw material for printing. The inventory at Installation 2B and 3 consists of printed spare parts. Therefore an additional formula has to be added before Equation (8) for the raw material storage and Equation (8) and (9) are adjusted for the scenario. In this scenario L_2 is replaced by L_{2A}, which is the lead time for raw materials from Installation 1 and L_{2B}, which consists of the printing time of the spare part (also corrected for uncertainty) as described in Equation (2) and Equation (4). In this scenario L_1 is the lead time for raw materials from the supplier. Furthermore, the demand at Installation 2A is larger than the spare part demand since it also includes raw material demand for failed attempts. Therefore with the same logic as for *Scenario 1*, $\lambda_A = \lambda_B * \frac{1}{q_{j,m}}$. The demand rate λ_A holds for Installation 2A and 1, λ_B holds for Installation 2B and 3. So Equation (8) and (9) are replaced by the following formulas:

$$\hat{C}_1(\hat{y}_1) = h_1(\hat{y}_1 - \lambda_A L_1) + \hat{C}_{2A}(S_{2A}^e) + \sum_{u=\hat{y}_1 - S_{2A}^e}^{\infty} [\hat{C}_{2A}(\hat{y}_1 - u) - \hat{C}_{2A}(S_{2A}^e)] \frac{(\lambda_A L_1)^u}{u!} e^{-\lambda_A L_1} \tag{12}$$

$$\hat{C}_{2A}(\hat{y}_{2A}) = h_{2A}(\hat{y}_{2A} - \lambda_A L_{2A}) + \hat{C}_{2B} + \sum_{u=\hat{y}_{2A} - S_{2B}^e}^{\infty} [\hat{C}_{2B}(\hat{y}_{2A} - u) - \hat{C}_{2B}(S_{2B}^e)] \frac{(\lambda_A L_{2A})^u}{u!} e^{-\lambda_A L_{2A}} \tag{13}$$

$$\hat{C}_{2B}(\hat{y}_{2B}) = h_{2B}(\hat{y}_{2B} - \lambda_B L_{2B}) + \hat{C}_3(S_3^e) + \sum_{u=\hat{y}_{2B} - S_3^e}^{\infty} [\hat{C}_3(\hat{y}_{2B} - u) - \hat{C}_3(S_3^e)] \frac{(\lambda_B L_{2B})^u}{u!} e^{-\lambda_B L_{2B}} \tag{14}$$

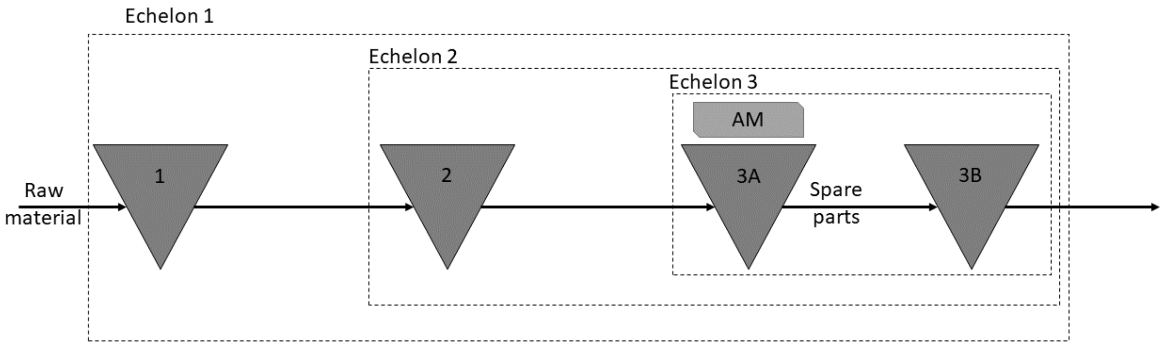


Figure 14: Scenario 3 supply chain

For *Scenario 3* as depicted in Figure 14, the inventory at Installation 1, 2 and 3A consist of raw material for printing. The inventory at Installation 3B consists of printed spare parts. Therefore an additional formula has to be added before Equation (7) for the raw material storage and Equation (7) and (8) are adjusted for the scenario. In this scenario L_3 is replaced by L_{3A}, which is the lead time for raw materials from Installation 2 and L_{3B}, which consists of the printing time of the spare part (also corrected for uncertainty) as described in Equation (2) and Equation (4).In this scenario L_1 is the lead time for raw materials from the supplier and L_2 denotes raw material lead time from Installation 1 to 2. Furthermore, the demand at Installation 3A is larger than the spare part demand since it also includes raw material demand for failed attempts. With the same logic as for *Scenario 1* and *3*, $\lambda_A = \lambda_B * \frac{1}{q_{j,m}}$. The demand rate λ_A holds for Installation 3A, 2 and 1, λ_B holds for Installation 3B. So Equation (7) and (8) are replaced by the following formulas:

$$\hat{C}_2(\hat{y}_2) = h_2(\hat{y}_2 - \lambda_A L_2) + \hat{C}_{3A}(S^e_{3A}) + \sum_{u=\hat{y}_2 - S^e_{3A}}^{\infty} [\hat{C}_{3A}(\hat{y}_2 - u) - \hat{C}_{3A}(S^e_{3A})] \frac{(\lambda_A L_2)^u}{u!} e^{-\lambda_A L_2} \tag{15}$$

$$\hat{C}_{3A}(\hat{y}_{3A}) = h_{3A}(\hat{y}_{3A} - \lambda_A L_{3A}) + \hat{C}_{3B}(S^e_{3B}) + \sum_{u=\hat{y}_{3A} - S^e_{3B}}^{\infty} [\hat{C}_{3B}(\hat{y}_{3A} - u) - \hat{C}_{3B}(S^e_{3B})] \frac{(\lambda_A L_{3A})^u}{u!} e^{-\lambda_A L_{3A}} \tag{16}$$

$$\begin{gathered}\hat{C}_{3B}(\hat{y}_{3B}) = e_{3B}\hat{y}_{3B} - h_{3B}\big(\lambda_B(L_{3B}+1)\big) \\ +(h_{3B}+b) \sum_{u=\max(\hat{y}_{3B},0)}^{\infty} (u - \hat{y}_{3B}) \frac{\big(\lambda_B(L_{3B}+1)\big)^u}{u!} e^{-\lambda_B(L_{3B}+1)}\end{gathered} \tag{17}$$

The solving method introduced in Section 5.6 also holds for the three scenarios described above. Note that the alteration made to Equation (8) for the optimization of Equation (9) holds for 2 installations in the four installation approach used for the AM scenarios. The second and third installation require the same adjustment for $\hat{y}_j < S^e_{j+1}$ in order to optimize the total costs. Also note that for this scenario we have to find the minimal value of S^e_{3B} through solving Equation (5) and find the subsequent costs through Equation (17).

6 Prototype Decision Support Tool

In this chapter we discuss the implementation, validation and verification of the model introduced in Chapter 5 in order to complete *Deliverable 4: Prototype decision support tool*. *RQ4.1: "How can the mathematic model be implemented in a prototype tool such that the RNLA can use it?"* is answered in Section 6.1. This computerized model uses data gathered from the RNLA in order to calculate KPI's for the selected scenarios in order to guide decisions on AM deployment. The goal is that this tool is built with current RNLA data, but is easily adjustable for future scenario's that might interest the RNLA. The validation of the model is described in Section 6.2 and the verification of the tool is described in Section 6.3. Sections 6.2 and 6.3 answer *RQ4.2: "How can the model be validated and the tool verified?"*.

6.1 Model implementation into tool

The implementation of the model is in the form of a computer program of the mathematical model in Python. Python is selected as this is a well-known programming language within the RNLA. One goal of the implementation step is to leave the input as easily adjustable as possible. Many of the parameters that we use are based on expert opinions and estimations. As it is possible that estimates and opinions change and since more data might be available in the future, the parameter values must be adjustable without making major changes to the tool itself. In order to make the tool user friendly the adjustable parameters are presented in an Excel datasheet, so it is easily adjustable even for people with no Python experience. A user manual is included in Appendix C.

The cost functions in Section 5.4 contain a summation to infinity. This not possible in practice, so after a certain number of terms, the sum is cut off. We do this after a decimal precision of 5 is reached. This means that as soon as the fifth number after the decimal point stops changing by increasing the number of terms, the sum is terminated. As the sum is used for the calculation of the expected backorder costs, a decimal precision of 5 should be sufficient. Testing a higher decimal precision of 15 on some calculation examples also reveals no changes in the output. Going lower than 5 on the decimal precision does influence the outcome in some examples and does not significantly decrease the calculation time.

6.2 Model validation

In order to validate the model, we base our approach on Sargent (2012). In order to justify the validity of the (computerized) mathematical model for our experimental conditions, we must show the answers are within the range of acceptable accuracy for the intended purposes. The most important thing is that the outcome validity is acceptable for the metrics and experiments we want to run. Sargent (2012) introduce a number of validation techniques. For this research we selected extreme condition testing and parameter variability and sensitivity testing. We believe these techniques fit best with our model since historical data is limited and many estimations have been made for the parameter values. We apply these techniques in a subjective, non-observable approach. This means we observe the model behavior and focus on the validity of the outcomes because the system itself cannot be observed and can only be judged based on estimates. We use our own subjective judgement and expert opinions to determine whether the results are satisfactory.

The extreme condition testing means to evaluate the behavior of the model under extreme parameter values such as zero demand or empty inventories. This way faulty model behavior can be identified. When the model behaves well under extreme conditions the outcomes are also more plausible for more likely scenarios. The parameters we want to use are the demand, fleet size, readiness, holding costs and (production) lead times as these are the variable parameters that influence the model output. We evaluate each parameter individually and keep all other parameters equal. Below we describe each test and discuss the model output. An overview of the specific parameter values used for each test is given in Appendix D. The model output for the tests is summarized in Appendix E.

For demand 250 parts per day would be impossible as it would require at least 2 breakdowns per vehicle per day, which would leave no time to actually replace the items in real life. With such large demand, costs and stocks would rise to extremely high levels. The other extreme is zero demand. One would expect no stock, production and costs when there is no demand. The model output for this test is summarized in Appendix E.1 From this output we can conclude that the model behaves as is expected. The model takes on high stocks and costs in a high demand scenario and no costs and stocks in a scenario without demand.

When the holding costs are the same for all installations, we see that the stock is moved as far downstream as possible. When holding costs are very high, the optimal policy is keeping very little stock. We also see that this causes the backordering costs to increase to an extremely high value. Alternatively when holding costs are zero, the total costs also decrease significantly. The backordering costs also decrease. The stock at Installation 3 is not affected significantly as it is mainly dictated by readiness. Therefore the model behaves as expected. A more detailed description of the model output is given in Appendix E.2.

Zero delivery lead time means that stock decreases significantly as lead time demand will also be very small. It means instant fulfillment of shipments and no stocks or costs should occur. When delivery lead time is very large the model also reacts with little stock as the total holding costs to cover demand are so high, no stock is a better option. This is explainable, but not entirely expected. We therefore need to be alert when using high lead times in the model. A more detailed description of the model output is given in Appendix E.3.

The production lead time is also investigated. This is done through making the print volume improbably large (1000 cubic centimeters) and zero. Print volume directly relates to print time. A volume of 1000 cubic centimeters is extreme as this would not fit on the print bed of most AM equipment. We also check the effect of zero and very large variance of the printing time. Zero variance and print time both lower total stock and decrease holding costs, which is expected. For extremely large variance and print time we see the same model behavior as for extremely large delivery lead time. We therefore attribute it to the same cause. A more detailed description of the model output is given in Appendix E.4.

We check the effect of a readiness of 0% and 100% and also the effect of 0 vehicles in the fleet and an improbably large number of vehicles in the fleet. 0% readiness and 0 vehicles should lead to no stock kept. A 100% readiness leads to 0 expected backorders. As the standard readiness is already 99.99%, the stock at echelon 3 does not change significantly. A very large fleet leads to a high allowed number of backorders, this is to be expected. For 0 fleet and positive demand we see the model still assumes stock is needed, which is understandable. However the user should be notified of the incorrect results in the software tool. A more detailed description of the model output is given in Appendix E.5 and Appendix E.6.

The other technique used for validation is parameter variability and sensitivity testing. We apply this technique to the same parameters used for the extreme scenario tests. With sensitivity testing the change in output values relative to the change in parameter values is evaluated. The technique used for the sensitivity analysis is the sensitivity index by Hoffman and Gardner (1983). This approach is fairly simple and calculates output percentage difference when varying parameters one by one from their minimum to their maximum values.

The sensitivity index (SI) is defined by:

$$SI = \frac{Output_{max} - Output_{min}}{Output_{max}}$$

(18)

The $Output_{min}$ and $Output_{max}$ represent the output values of the model for the minimum and maximum value of the parameter that is tested. As output we use the total costs given by the Clark and Scarf (1960) approach i.e. $\hat{C}_1(y_1^*)$. A low SI indicates low variability of the model outcome, whereas a higher SI indicates a high variability. The most sensitive parameters for which the exact values are unknown are focus points for improvement. When one parameter is tested, the others are set to the standard values also used for the extreme scenario tests. A detailed overview of the input data is given in Appendix D. The following SI values are found for the parameters tested:

1. For L_1; 0.9967
2. For L_2; 0.9897
3. For L_3; 0.9998
4. For $q_{j,m}$;0.8668
5. For λ; 0.999997
6. For v^p; 0.998
7. For e_1; 0.99992
8. For e_2; 0.9998
9. For e_3; 0.99994
10. For $VAR(Z_{j,n,m})$; 0.9879
11. For readiness; 0.9899
12. For fleet size; 0.7974

As the values for SI for many of the parameters are so large, it can be stated that they all have significant impact on the model output. However, it is hard to compare them in detail based on this metric and determine what the most important parameters are. We can see that $q_{j,m}$ and fleet size have a relatively low SI and are therefore relatively less impactful. The impact of holding cost can be nuanced by the fact that this parameter is less uncertain than others. The risk of parameter values that are not consistent with reality is higher for parameters such as demand, lead time and production time.

6.3 Tool verification

We combine the two main techniques for programming verification described by Sargent (2012), static and dynamic testing. With static testing the tool is verified without execution of the program. We do this with technical review and structured walkthrough. With technical review the elements of the program and model are discussed with the experts from the RNLA to find out if they are suitable for the research. For the structured walkthrough the program code is discussed with the RNLA experts to verify if the logic of the program is correct. These discussions do not raise concerns. Therefore the logic of the model is assumed to be correct.

With a dynamic test, the program output under different conditions is used to determine whether the program and implementation are correct. Sargent (2012) describes that input-output validation techniques are often used for dynamic testing. As we use such techniques (extreme conditions and sensitivity analysis) for the model validity we can use the outcomes of these validation techniques to also show the tool is verified. As the dynamic tests conducted do not raise concern, this also proves the implementation of the model is correct.

7 Scenario Analysis and Numerical Experiments

In this chapter we conduct a scenario analysis and do numerical experiments with the implemented model in order to complete *Deliverable 5: Scenario analysis and numerical experiments*. In Section 7.1 we answer *RQ5.1: "What are the optimal parameter values according to the tool when AM is introduced in an existing deployment scenario?"* by analyzing the optimal AM location and echelon stock policies for an example Main Task 1 scenario. We do this to show what would be the best possible AM setup for a potential Main Task 1 scenario. In Section 7.2, other numerical experiments are conducted in order to answer *RQ5.2: "What is the impact of the different parameter values on the model outcomes?".* These extra numerical experiments are used to find the best possible AM setup for potential situations that are not reflected in the example scenario but seem interesting to investigate.

7.1 Scenario analysis

A relevant scenario with relatively complete data is the mission in Lithuania also used by Zijlstra (2021). Note that this scenario is not an actual Main Task 1 deployment, as the RNLA has not actually been in a combat situation here. However, the deployment in Lithuania is referred to by RNLA experts as the closest representative with sufficient data for a potential Main Task 1 deployment. The deployment in Lithuania is aimed at an increased NATO presence against Russia. Installation 2 (the DCS) for this scenario is located in Warsaw, Installation 3 (the MOB) is located on the Lithuanian border with Poland. Shipments from Installation 1 to Installation 2 are done by air, all other shipments between the installations are done by truck. Shipments in a Main Task 1 situation are done every day. The conditions in the region are moist and muddy, with a high level of perceived threat from the opponent.

The items used in the research have already been introduced in Table 7 in Section 4.3. For the analysis items 1, 2, 10,11 and 12 are used since they have complete data and their characteristics are different enough such that they represent a broader set of parts. This selection contains both polymer and metal parts, both vital and essential parts, purchasing costs ranging from €2.18 to €6840, delivery lead times ranging from 3.19 days to 28 days and represent all three vehicles mentioned in Section 4.3. We give an overview of the parts and their characteristics in Table 9 and Table 10, the characteristics are discussed in detail below.

For a Main Task 1 deployment 125 Boxers are generally deployed by the 13th light brigade. So for this research we also assume that there are 125 deployed and operational Boxers. In such a deployment 143 Fenneks are deployed, so this Fennek fleet size is also used in this research. Part 10 is different since it is not from a vehicle operated by the RNLA. We therefore have to make some estimations for some the parameter values. Currently 20 NH90 helicopters are owned by the Air Force, so we choose the deployed NH90 fleet to be 15 for this research.

Standard lead times between installations are based on the distance and travel mode. For Installation 1 these are based on delivery data of the specific spare part and include delays. For parts 1, 2, 11 and 12: $\hat{L}_1 = 3.29\ days$, for part 10: $\hat{L}_1 = 28\ days$.

We also require the lead time for raw materials for the AM scenarios. The polymer printers require spools of filament, which are available at many suppliers. The RNLA delivery time for similar items is estimated at an average of 3.29 days, $\hat{L}_{polymer} = 3.29\ days$. The metal printers require titanium alloy powder, we do not have accurate data on this, as it is not stocked by the RNLA currently. An estimate is based on delivery information disclosed by suppliers of the titanium alloy. We estimate the delivery time to be 7 days, $\hat{L}_{metal} = 7\ days$. Note that for the outsourced metal printing at the depot level this does not hold, as the process of ordering raw material is outside the RNLA supply chain.

For the proposed Main Task 1 scenario $L_2 = 0.17\ days$, based on a 2 hour flight and a 2 hour transit to the airport. With a truck shipment this would take 1.59 days. $L_3 = 0.21\ days$ based on a truck shipment of around 5 hours. Then there is the uncertainty factor of the realized lead time Y_j. We assume uncertain delivery from a supplier is similar, regardless of the part. $\mathbb{E}[Y_j]$ is 0.31 days (see Appendix B.1).

For the holding costs we make the same estimation as Westerweel et al. (2020) and Zijlstra (2021 that the echelon holding costs are 100% of the spare part purchase value for echelon 1 and 2 and 150% for echelon 3. This reflects the more limited space in the most downstream location. The part purchase value can be found in Table 9 and Table 10. Installation holding costs are also derived from this. Furthermore we use that holding cost for the material required to make a spare part is equal to that of the produced spare part. Based on purchasing value the cost would be lower, but since these printing materials require the same amount of space and handling the increased holding costs are justified.

The demand rate for the spare parts is based on the yearly demand data the RNLA has on the specific parts. This is converted to daily demand for the scenario. This data is based on peacetime and Main Task 2 and 3 records. Therefore the intensity of demand is too low for a Main Task 1 scenario. RNLA experts currently estimate the demand intensity of a Main Task 1 scenario to 5 times higher than for the other scenarios. For parts 1 and 2 the adjusted demand rate is 0.028 parts/day. Part 11 has an adjusted demand rate of 0.322 parts/day and for part 12 this is 0.119. For part 10 this is more difficult to determine as the NH90 is not managed by the RNLA. We estimate a demand of 0.021 parts/day based on that the part is vital and that the fleet size of the NH90 is approximately 1/6th that of the other two vehicles. The demand for printed spare parts is assumed to be 10 times higher for polymer printed parts based on Westerweel et al. (2020) and RNLA expert opinions. The demand intensity is equal for metal parts based on expert opinions within the RNLA.

The base printing time is calculated based on the printing volume v_p of the part divided by the build speed S_i of printer *i*. Then there is the realized printing time $W_{j,n,m}$ that is influenced by the distribution of delay $Z_{j,n,m}$ and the printing time of the part. Due to the limited data on metal parts, we only apply this method to the polymer parts. The values for each part are calculated for the UltiMaker, Markforged, Fieldmade and depot printers. The calculation is based on Equation (4).

For metal parts such as part 10 a printing lead time of 1 to 2 days is standard regardless of the part according to Fieldmade experts. This includes post processing and potential delays. At the depot level outsourcing is currently the only option for metal printing, using this to produce a single unit of part 10 would take 2 weeks. This includes extra time for potential failures calculated by the outsourcing party. Note that this excludes modeling, IP contracting and part qualification as these are outside of the research scope (these are also excluded for other lead times and print times). We use the maximum time here as described by the experts to get the most reliable estimate. In reality this will lead to somewhat longer waiting times and therefore more backorders. The real situation will therefore be more favorable.

The printing costs $c^p_{n,m}$ are calculated based on the print volume v^p and raw material costs c^{rm}_m:

$$c^p_{n,m} = v^p c^{rm}_m \tag{19}$$

For metal AM it is better to specifically relate costs to part 10, as the more complex production process is not fit for a general calculation used on the polymer parts. Part 10 is made out of titanium alloy. Production through outsourced AM would cost € 7,594.00, this excludes modeling, IP contracting and part qualification as these are outside of the research scope (these are also excluded for other print costs). Note that 't Hoen-Velterop and Kool (2020) calculated this cost based on outsourcing to the NLR in the year 2020. Current contracts at the RNLA will probably lead to lower costs as they are based on higher volume orders, however this is the only reliable cost estimation we have for now.

An additional cost factor not included in the optimization is the holding costs for in transit stock. Holding costs for in transit stock from installation *j* to *j+1* are given by $h_j \lambda L_{j+1}$. We denote this by $c^{IT}_{j,j+1}$. The total costs for in transit stock, C^{IT} is given by $C^{IT} = \sum c^{IT}_{j,j+1}\ \forall j \in J$. This calculation is made for every part and added up.

We can calculate the cost of spare parts based on the AM scenario from Section 5.4 that is applied. For *Scenario 0* we can calculate the CM cost of the spare parts in the system by $S^e_1 * c^{cm}$. For *Scenario 1, 2* and *3* we want to know the AM spare part production costs for all parts in stock and the purchasing cost for all raw material in stock. We denote the total raw material stock as S^e_{rm}. For *Scenario 1,* $S^e_{rm} = S^e_{1A} - S^e_{1B}$. For *Scenario 2,* $S^e_{rm} = S^e_1 - S^e_{2B}$. For *Scenario 3,* $S^e_{rm} = S^e_1 - S^e_{3B}$. The raw material cost for these 3 scenarios can be calculated by $S^e_{rm} * c^{rm}_m * v^p$. The printed part costs for *Scenario 1* is $S^e_{1B} * c^p_{n,m}$, for *Scenario 2* it is $S^e_{2B} * c^p_{n,m}$ and for *Scenario 3* it is $S^e_{3B} * c^p_{n,m}$. Adding these costs together for each scenario gives us the total spare part costs. We can add them to the total holding costs and in transit costs to calculate to total costs for the scenario under to optimal policy.

Table 9: Polymer part specific parameters

Part	L_1 (days)	v^p (cm^3)	c^{cm} (€/part)	λ_n (parts/day)	$c^p_{n,m}$ (€/part)		$\mathbb{E}[\hat{P}_{j,n,m}]$ (days/part)			
					U	**M,F,D**	**U**	**M**	**F**	**D**
1	3.29	2.0	2.18	0.028	0,25	0,51	0.010	0.017	0.016	0.015
2	3.29	3.0	525.38	0.028	0,17	0,34	0.007	0.012	0.011	0.010
11	3.29	2.0	32.84	0.322	0.17	0.34	0.007	0.012	0.011	0.010
12	3.29	10.0	31.24	0.119	0.84	1.70	0.043	0.058	0.054	0.052

Table 10: Metal part specific parameters

Part	L_1 (days)	v^p (cm^3)	c^{cm} (€/part)	λ_n (parts/day)	$c^p_{n,m}$ (€/part)		$\hat{P}_{j,n,m}$ (days/part)	
					F	**D**	**F**	**D**
10	28	99.0	6840	0.021	7594	7594	2	14

For this test case the three AM scenarios are the results are gathered and summarized in Table 11 and Table 12.

Table 11: Scenario results for parts 1, 2, 11 and 12

	S^e_j *Parts: (1,2,11,12)*	$\hat{C}_1(y^*_1)$	C^{IT}	*Total spare part costs*	*Total costs for policy*
Scenario 0 (No AM)	$S^e_1 = (1,1,3,2)$ $S^e_2 = (1,1,1,1)$ $S^e_3 = (1,1,1,1)$	*€2986.24*	*€43.36*	*€688.56*	*€3718.16*
Scenario 1 (Printer at Depot)	$S^e_{1A} = (3,3,9,6)$ $S^e_{1B} = (1,1,4,2)$ $S^e_2 = (1,1,4,2)$ $S^e_3 = (1,1,2,1)$	*€5010.03*	*€446.30*	*€15.30*	*€5471.63*
Scenario 2	$S^e_1 = (3,3,9,4)$				

(Printer at DCS)	$S_{2A}^e = (1,1,3,1)$ $S_{2B}^e = (1,1,2,1)$ $S_3^e = (1,1,2,1)$	*€5502.66*	*€467.77*	*€11.90*	*€5982.33*
Scenario 3A (UltiMaker at MOB)	$S_1^e = (1,2,26,11)$ $S_2^e = (1,0,6,3)$ $S_{3A}^e = (0,0,6,3)$ $S_{3B}^e = (0,0,1,1)$	*€7542.88*	*€457.07*	*€15.28*	*€8015.23*
Scenario 3B (Markforged at MOB)	$S_1^e = (1,1,22,10)$ $S_2^e = (0,0,5,3)$ $S_{3A}^e = (0,0,5,2)$ $S_{3B}^e = (0,0,1,1)$	*€5055.57*	*€463.95*	*€25.33*	*€5544.85*

Table 12: Scenario results for part 10

	S_j^e *Part: (10)*	$\hat{C}_1(y_1^*)$	C^{IT}	*Total spare part costs*	*Total costs for policy*
Scenario 0 (No AM)	$S_1^e = (3)$ $S_2^e = (1)$ $S_3^e = (1)$	*€43,775.46*	*€213.13*	*€20,520.00*	*€64,508.59*
Scenario 1 (Printer at Depot)	$S_{1A}^e = (2)$ $S_{1B}^e = (2)$ $S_2^e = (1)$ $S_3^e = (1)$	*€58,836.83*	*€2196.04*	*€15,188.00*	*€76,220.87*

For Table 11 and Table 12 the following notation is used: S_j^e denotes the optimal echelon stock for echelon j denoted for all parts separately; $\hat{C}_1(y_1^*)$ denotes the cost output by the Clark and Scarf approach; C^{IT} denotes the costs for in transit stock. *Total spare part costs* denotes the costs of purchasing or producing the required spare parts. *Total costs for policy* denotes the sum of all other cost columns for the optimal scenario policy.

From the results shown in Table 11 we can see that *Scenario 0*, without AM, has the lowest total costs for polymer parts under a chosen readiness of 99.99%, therefore this is the optimal for this set of parameter values. This is an understandable outcome, as the quality of printed polymer parts causes the demand rate to increase by a factor 10 according to experts. With such an increase in demand it is not surprising that *Scenario 0* has the lowest total costs and stock.

We do see that *Scenario 1,* printing at the depot, is the best performing AM scenario from a cost perspective. The scenario has a cost increase of 47.2% and 3 times the stock of Scenario 0. *Scenario 2,* printing at the DCS, is the best performing AM scenario from a stock perspective. The scenario has a cost increase of 60.9% and 1.71 times the stock of Scenario 0. *Scenario 3B*, a Markforged printer at the MOB comes close, but requires significantly more stock throughout the supply chain. As we can see from the echelon stock in Scenario 1 and 3, the required stocks are not 10 times larger than for Scenario 0. This means with more favorable quality for AM parts, AM scenarios might outperform Scenario 0. We also see that the costs required to produce the spare parts is lower than the costs to purchase the spare parts. This is also understandable as the costs to purchase a spare part are often higher than the cost of the raw materials required to print it. Note that the print costs only include raw material costs and that the costs for operating the machinery are not included. Total spare part costs for Scenario 0 are *€688.56*, *€15.30* for Scenario 1 and *€11.90* for Scenario 2. The results lead us to believe there is potential for using printed polymer parts as full replacements, but that the quality of the printed parts is a limiting factor in this example deployment.

For metal parts *Scenario 0* also performs best. However, the total stock that has to be kept is less under *Scenario 1*. We see that spare part costs is significantly less for Scenario 1. However, due to the occurrence of print failures, the realized demand at the printer is higher. This in turn also causes C^{IT} to increase slightly, as more raw material needs to be shipped. Purely based on costs AM is still not the best option, but the decrease in required stock is also beneficial for the RNLA. These results lead us to believe that there is serious potential for using printed metal parts as full replacements. The stock can be decreased by about 33.3%. Also we see that the total cost recorded through the model for *Scenario 0* is *€64,508.59.* For *Scenario 1* the costs are *€76,220.87.* This is a price difference of 18.2%.

As can be seen from the results in Table 11 and Table 12, the total stock required is relatively low for most scenarios. This is mainly due to the total average demand of all parts being around 37 parts per year. This value is based on the data we have retrieved from the RNLA parts database adjusted for Main Task 1 intensity.

Based on the results we see some interesting phenomena that require further investigation. We have seen that the quality of the printed parts is a limiting factor. We therefore want to investigate the effect of altering the quality difference on the output. We also see that the total stock required is relatively low due to the total average demand also being relatively low. We therefore want to investigate the effect of altering the demand rate on the output. These numerical experiments are described in detail in Section 7.2.

7.2 Other numerical experiments

Besides the scenario analysis and the validation cases, we also want to run some other numerical experiments. These numerical experiments are sets of adjusted parameter values in order to evaluate (potential) scenarios for which we have no example data. Here we describe the experiments and discuss the most interesting outcomes. For the exact input parameter values, refer to Appendix F. A more detailed description of the output is given in Appendix G. The main takeaways from the numerical experiments in this section are summarized at the end of the section.

The first experiment is an inflated demand rate for spare parts. We individually assess each spare part, while the AM machinery will be used for multiple spare parts. This will lead to more demand for printed parts and the waiting time for print orders will therefore be higher. Therefore we want to estimate what would happen in such a high demand scenario by increasing the demand rate of the evaluated part. We do this to get an indication on the required stocks and the cost increase under high demand. Actual costs will be different as the approximation is made with one part. In reality there will be demand for multiple parts simultaneously, these all have slightly different holding and material costs. We see that for the combined demand Scenario 0 performs better than for the individual parts. A stock of 3 parts for the combined scenario as opposed to 6 parts. So a larger combined demand leads to less stock. The small individual demand causes stock to be required for all parts to reach the desired readiness. For the combined demand, the demand for parts 1 and 2 will probably have little effect on the total stock since it is so small. This same effect is seen for Scenario, total $S_{1A}^{e} = (19)$ against $S_{1A}^{e} = (21)$. Since demand for printed parts is 10 times higher than for conventional parts the relatively smaller difference for Scenario 1 is understandable. The stabilizing effect of a combined demand rate is less noticeable for AM scenarios, meaning the stock is for a large part dictated by lead time in the case AM is applied. The full output is summarized in Appendix G.1.

Based on the previous test we also test the summed demand, but assume printed parts are not 10 times as likely to fail but only 5 times as likely. This represents a scenario where there is more trust in AM technology and the certification of AM parts is better established. It still considers that printed parts are not as strong as injection molded parts. This test is run since the current multiplier for AM seems very conservative. We see that for this lower demand multiplier AM performs better, which is to be expected. But the improvement is not so large that an AM scenario outperforms Scenario 0 based on costs or stock. We do see that Scenario 2 performs closer to Scenario 1 on costs and even better based on total stock required. The same effect is noticeable for individual parts such as part 11. Based on this we can say that downstream production is affected more by increased demand. We can also see that even for a lower demand multiplier, AM production is more costly and requires more stock. Only for cases where there is no multiplier, for instance part 10, we can see that AM can lower total required stock. This proves the quality difference of AM produced parts has a very significant influence on the performance of AM in the RNLA supply chain. The full output is summarized in Appendix G.1.

The first test pointed to the importance of lead time for the model output. Therefore, we experiment with an inflated lead time delay in the deployment country. When the threat levels increase, the chance that shipments are disrupted becomes higher. The current estimations for the delay distribution as described in Appendix B leads to fairly low delays. Because actual data on Main Task 1 deployments is limited we cannot say with certainty that the actual delays will not be much longer. Therefore we want to estimate what would happen in such a longer delay scenario by increasing the expected delay for shipments to Installation 2 and Installation 3. This is again an approximation to get an indication on the required stocks and the cost increase under high lead times. We test the effect of an increased delay for lead times to Installation 2 and 3 for Scenario 0 and Scenario 1, as these scenarios perform best. The costs and stock for the optimal policy scale with the increase in lead time, which is to be expected. For Scenario 0 we see that an increase in L_2 has more effect than an increase in L_3. This might be explained by the fact that the lead time for Installation 2 is longer and is therefore affected more by the increase in delay. For Scenario 1 and increase in L_3 has more effect. This can be explained the increased demand for AM parts having an effect on the stock kept at the most downstream installation. Another interesting effect is that increasing both lead times for Installation 2 and 3 is less impactful for total stock than increasing only one. This leads us to believe that a larger difference in lead times between installations is more impactful than a total increase. For larger multipliers of the lead times this effect is not as noticeable. This leads us to believe that placing stock points on equal lead time intervals, leads to a lower total stock required. Again proving the importance of lead times for system performance. The full output is summarized in 0.

The third experiment is a material shortage for the AM input materials. We implemented raw material supply into the model, however the data used for the scenario analysis describes a quite steady supply of raw materials. When this supply is disrupted due to increased threat levels or material shortages at the supplier this could have significant impact on the optimal AM placement. To estimate what would happen under such a raw material shortage we increase the expected delay for shipments to Installation 1 in for scenarios where AM is applied. We see that an increase in L_1, even of only 7 days, has a very significant effect on the total costs and stock in all AM scenarios. If we compare the three AM scenarios, we see that Scenario 3 performs the worst under these conditions. This is understandable as the lead time demand at echelon 1 is increased the most by reprints and quality problems. So this tells us that for all AM scenarios it is very important to keep a steady supply of raw materials, since delays have significant impact. It again shows the importance of the lead time for the performance of the supply chain.

Based on the results from the other numerical experiments we see some interesting phenomena. The main takeaways from the findings discussed in this section are:

- The effect of the increased demand intensity caused by the higher failure probability for polymer AM parts is shown to indeed be significant. However, even for a decreased demand intensity the configuration without AM still performs better based on costs and the required spare part stocks. The demand intensity was halved for the test to simulate a situation where the quality of AM produced parts was significantly better than expected. This leads us to believe that printed polymer spare parts can only function as full replacements when the failure probability of these parts is equal to the failure probability of conventional spare parts. From the interviews we know this will not be the case (at least with current technology). Which therefore makes it currently impossible to use these printed polymer parts as more than temporary replacements.
- The shipment lead time seems to have significant effect on the model output. Specifically in the case where the shipment lead time to one installation is much higher than all other shipment lead times in the supply chain. This means that delays at any installation have significant impact on the required spare part stocks and the total costs. This also leads us to believe that placing stock points on equal lead time intervals, leads to a lower total stock required.
- The effect of a material shortage for the production of AM is detrimental for the overall performance of any of the AM scenarios evaluated. We see that an increase in L_1, even of only 7 days, has a very significant effect on the total costs and stock in all AM scenarios. We also see that Scenario 3 performs the worst under these conditions. This leads us to believe that for all AM scenarios it is very important to keep a steady supply of raw materials.

Based on the main takeaways from this section and the takeaways from the Main Task 1 scenario analysis we can formulate the full conclusions and recommendations for the RNLA. These conclusions and recommendations are discussed in Chapter 8.

8 Conclusion and Discussion

In this chapter we conclude this research by answering the main research question. This answer is formulated in Section 8.1. In Section 8.2 we discuss the limitations of this research and how they impact the findings. We also use the findings and the limitations to formulate concrete recommendations for future research.

8.1 Conclusion

In this research a mathematical model has been formulated and processed into a software tool that can evaluate optimal stock policies and costs for multiple supply scenarios during RNLA deployment. This allows us to answer the main research question:

"How can AM be used in the RNLA mission supply chain to reduce the logistical footprint?"

We evaluate multiple AM technologies in different locations along the RNLA mission supply chain by modeling it based on the Clark and Scarf (1960) approach. We incorporate multiple uncertainties into our model identified through interviews and literature. We evaluate costs under a given material readiness in order to compare the technologies and locations with one another. The evaluation is done by executing the model for a current scenario and a number of numerical experiments.

We see that in many of the test cases done in this research the scenario where no AM is applied performs better. The required spare part stock as a buffer for lead times in this scenario is generally lower and the total costs for the optimized policy are also lower. We acknowledge that these findings are not in line with the findings by Zijlstra (2022) and Westerweel et al. (2021). They find that the application of AM is beneficial in many scenarios. We attribute this to the fact that we do not use AM parts as temporary fixes and investigate the effect of using AM as an alternative to conventional parts. This attribution can be deduced from the significant effect of the increased failure probability of printed polymer parts on the costs and required spare part stocks for all AM scenarios and the fact that this effect is not seen for the printed metal part (which has the same quality as a conventional metal part). Due to the lower quality of polymer AM parts, demand in AM scenarios is 10 times higher than for other scenarios. This is based on the lower quality of polymer AM parts described by experts and the increased failure rate suggested by Westerweel et al. (2021). Combined with the potential failures in the printing process, this leads to significantly more demand. For Zijlstra (2022) using a higher quality printer at an MOB was the most beneficial. We see that without the temporary fix assumption, this is not the case for our tests. The tests are based on a similar scenario as used by Zijlstra (2022). This shows the quality difference of AM produced parts has a very significant influence on the total costs and the required spare part for AM scenarios in the RNLA supply chain. This leads us to believe that printed polymer spare parts can only function as full replacements when the quality of these parts is equal to the quality of conventional spare parts. From the interviews we know this is not the case with current technology. Therefore using printed polymer parts as full replacements is currently not a viable option.

If we only look at the AM scenarios, based on the Main Task 1 deployment analysis we can state that Scenario 1 performs best. Scenario 1 means printing at the depot level where quality control is best and the print output can be maximized. When we change the effect of quality from a 10-time multiplication of spare part demand to a 5 time multiplication of spare part demand, the results change. From the numerical experiments conducted on spare part quality we can see that Scenario 2 starts outperforming Scenario 1. Scenario 2 means printing at a deployed central stock with an integrated solution such as the Fieldmade print container. This further justifies the notion that the quality of printed parts is of great influence. When the quality of the polymer parts can be improved results closer to the findings by Zijlstra (2022) and Westerweel et al. (2021) might be found. In the interviews RNLA AM experts mention the 10 times increase in demand might be a bit high. They cannot accurately say what the actual difference in quality is based on the current data available.

However, that there is a difference in quality for polymer parts is clear based on the discussions. Improving the quality estimate is therefore important in order to see the real effect it has on AM efficiency. We also see that although the demand for printed polymer parts is 10 times higher, the stock required for the AM scenarios at the depot and DCS is not 10 times higher. This again shows that AM has potential to reduce overall stock, but is currently limited by the quality difference for the polymer printed parts.

The quality of metal parts produced through AM has been proven to be as good or even better than with conventional methods. Therefore no increase in demand is used for the experiments with metal spare parts. From the results we can see that using AM to produce metal parts is more costly, but requires less stock. The stock can be decreased by about 33.3%. This is a serious benefit for the RNLA as it decreases the logistical footprint. Also we see that the total cost recorded through the model for the scenario without AM is *€64,508.59.* For the scenario with AM the costs are *€76,220.87.* This is a price difference of 18.2%, which is also much less than the 47.2% increase we see for the polymer parts. We can therefore conclude that printing metal parts can be a very effective way of decreasing spare part stock for the RNLA for a relatively small increase in costs.

Another finding from the numerical experiments is that lead time has a significant effect on the required spare part stocks, especially in AM scenarios. We see large increases in spare parts stocks for Scenarios 2, 3 and 4 when lead time is increased. We see in scenarios where raw material supply is disrupted, the cost for AM scenarios increases much more than for increases in lead times between installations. So this tells us that for all AM scenarios it is very important to prevent disruptions in the supply of raw materials. This leads us to believe that when raw material supply is very uncertain, AM will quickly lose its advantages and the stockpiling of raw materials will be required to keep equipment operational. Another finding is that an increase of one lead time in the supply chain, leads to more stock, relative to the increase. Even small increases in lead times can increase the required stocks and the subsequent total costs. Whereas a small, but equal increase to all lead times, has little to no effect on the total stock required. The case where the shipment lead time to one installation is much higher than all other shipment lead times in the supply chain has more impact on costs and stocks than cases where all lead times are increased. This effect is noticed for scenarios with AM as well as the base scenario without AM. This leads us to believe that placing stock points on equal lead time intervals, leads to a lower total stock required. A potential solution for this could be to further decouple the supply chain and ad more stock points along the deployment supply chain. We do admit that this is very costly and the benefits hereof might therefore not outweigh the costs. To further identify the effect of further decoupling the supply chain, more research is necessary. This also further justifies the notion that lead times are a significant parameter within the RNLA supply chain. Improving the estimations for shipment delays is therefore also something that is important to further investigate the effectiveness of AM for the RNLA.

We extend the research of Westerweel et al. (2021), Zijlstra (2022) and contribute to literature by proposing a model to not only evaluate different ways of integrating AM in a remote spare part supply chain, but also incorporate new AM technology such as SLM for metal parts. We include a number of uncertainties and take raw material supply into account. Furthermore, we contribute to literature by evaluating a scenario based on field research and a number of numerical experiments.

Next to the conclusions and corresponding recommendations discussed in this section it is also important to discuss the limitations of the research. These limitations are connected to the conclusions drawn, but we discuss them separately as they are also related to the overall methodology used in this research. These conclusions and limitations also lead to directions for future research. Both the limitations and directions for future research are discussed in Section 8.2.

8.2 Limitations and directions for future research

We acknowledge that this research has a number of limitations. The first limitation is that the mathematical model parameters are all based on static values. Therefore all calculations are done with the expected values of the uncertain variables. In this research we can give an indication of how the uncertainties affect the model outcomes. We can however not entirely predict variables such as lead time, printing time and demand. As can be seen from the sensitivity analysis and numerical experiments, changes in these parameter values can lead to significant changes to the output. Therefore future research should work on a dynamic model such as a discrete event simulation based on the model and uncertainties introduced in this research. For such a dynamic model transitions between events should be based on well fitted distributions or transition probabilities.

Another limitation is lack of historical data for AM usage during deployment and Main Task 1 deployment altogether. For the evaluation done in this research estimates based on expert opinions are widely used. As these estimates are based on limited data, it would be preferred to improve the estimations in the future when more data is available. Specifically data on the AM printing process and shipment delays could improve the current estimates and potentially lead to different results. When further research incorporates a more dynamic model, also more data should be available to base the probability distributions of stochastic variables on. As can be seen from the sensitivity analysis and numerical experiments, changes in lead time, printing time and demand can lead to significant changes to the output. These are therefore focus points for future research to improve. We also base the lead time from the OEM for conventional spare parts on historical data. However, from discussions with RNLA experts we learn that actual lead times can sometimes be much longer. This is not evident from current data on printable spare parts and therefore requires further data and research to investigate the effect of these potentially longer lead times on the implementation of AM.

A further limitation is that the mathematical model is written for single sourcing and a single item at a time. The single sourcing means that we regard AM as a replacement for ordered spare parts in our model. This is done to evaluate the effect of no longer seeing AM parts as temporary fixes. Future research should use this notion of AM parts being a full replacement and also incorporate ordered spare parts. This would create a dual sourcing situation in future research, which we believe could be an even more effective use of AM. We also only review one item at a time due to the limitations of the mathematical model introduced in this research. Some workarounds have been introduced, however it still remains a point where our model can be improved. The demand for spare parts has an effect on the raw materials needed and the printer utilization. The question also remains how to prioritize spare part and raw material demand for a limited printer and storage capacity. These are all points future research should incorporate to expand and improve upon the model introduced in this research.

We assume that shipment capacity is always sufficient. This means that we do not incorporate the logistics capacity allocation in our research scope. This would be a good expansion to this research for future research. Especially when the model is written for multiple sourcing options this capacity allocation will also play a big role. The question then arises on how much transport capacity to allocate to what spare parts. Also how much transport capacity should be allocated to AM raw materials and how should these raw materials than be allocated to spare part demand.

We also neglect the time required to repair the damaged vehicle as it is not specifically influenced by the AM scenario. This is a somewhat blunt approach as the down time to repair the vehicle is not directly influenced by AM, but it is influenced by demand. Since more demand also leads to more repair time and therefore also to a lower readiness. We can give an indication of the time needed to repair the vehicles by λ*Mean time to repair (MTTR). As we assume that the demand rate for polymer printed parts is 10 times more than their CM counterparts, the total repair time is also about 10 times as high. The impact of this is highly dependent on the MTTR of the specific spare part. This would be something to incorporate in a dynamic model. This MTTR should then also account for retrieval time of the vehicle and waiting time until a maintenance crew is available.

In our research we do not account for the purchasing costs and operating costs of AM machinery besides the raw materials used. We have not incorporated purchasing costs for machinery since we assume a steady state scenario where we are only interested in the performance of different AM setups relative to each other and a base scenario without AM. We also do not include operating costs such as power consumption. As power might be limited during a deployment this might lead to a tradeoff between utilization of the AM machinery and using power for other crucial operations. As we know from AM literature such as Savastano et al. (2016), Sobota et al. (2020) and Verboeket and Krikke (2019), the cost of purchasing and operating AM machinery is often a barrier. We therefore think that a more in-depth analysis of the costs of operating the machinery (including tradeoff costs for power consumption) and an investment analysis that evaluates the identified benefits against the purchasing costs are both good additions for future research at the RNLA.

The capacity of energy supply, manpower and space in the area behind the frontline are currently fairly limited. We assume there is enough capacity to operate AM machinery, however in reality this might not be possible. Future research should also focus more on the capacity constraints that hold in the backfield. This can be done through investigations of how AM power consumption affects other operations. Also investigations of the physical space required for AM equipment and raw material to see if it is viable to keep the amount of raw material stock proposed by our tests.

The limited data on printable parts, the printing of parts and the quality of the parts has also limited the results that could be gathered in this research. The lack of data on metal parts is an area where a lot more research at the RNLA is necessary in order to expand on the findings of this research. We suggest therefore more in-depth research into what metal parts for RNLA equipment could potentially be printed. As seen in our results the printing of metal parts can lead to advantages in stock keeping. Therefore this is a good avenue for future research. We have also used very rough estimates for the quality of printed parts. We found that the effect of part quality is very significant on the model output. Future research at the RNLA should therefore also focus on improving these estimates.

Similar to the recommendation made by Zijlstra (2022), we recommend further efforts to collaborate with OEMs in order to help with certification and licensing of printed spare parts. From the interviews we see that the lack of integration of printed spare parts into the RNLA standards currently raises some cautiousness around the application of AM within the RNLA. Proving the quality of printed spare parts and working together with OEMs to establish licensing arrangements will resolve some of the skepticism and boost the use of AM withing the RNLA. As we can see from our research, expanding on this topic with new research is crucial to the success of AM within the RNLA.

Such a combined effort with OEMs can also be a good way to improve the quality of printed polymer parts by identifying ideal printing methods and conditions for each part. As we have identified already, increasing the quality of polymer printed parts can enable them to eventually be used as full replacements for conventional spare parts. How much the quality needs to improve to enable the use as full replacements is something which requires further research. It also requires more research and data to identify if the necessary quality improvements are feasible with current or future AM technology.

References

Axsäter, S. (2015). *Inventory Control.* Switzerland: Springer.

Bastiaans, M., Blankers, I., van Scheepstal, P., & Veraar, R. (2015). *De impact van 3D-printen op Defensie.* Den Haag: TNO.

Bender, C. M., & Orszag, S. A. (1999). *Improvement of convergence.* Berlin: Springer.

Blumberg, B. (2014). *Business Research Methods.* New York: McGraw-Hill Education.

Calimo. (2010). Weibull PDF. *Weibull distribution.* Wikipedia. Retrieved from https://commons.wikimedia.org/wiki/File:Weibull_PDF.svg

Choudhary, N., Kumar, A., Sharma, V., & Kumar, P. (2021). Barries in adoption of additive manufacturing in medical sector supply chain. *Journal of Advances in Management Research, 18*, 637-660.

Clark, A., & Scarf, H. (1960). Optimal Policies for a Multi-Echelon Inventory Problem. *Management Science, 6*, 475-490.

den Boer, J., Lambrechts, W., & Krikke, H. (2020). Additive manufacturing in military and humanitarian missions: Advantages and challenges in the spare parts supply chain. *Journal of Cleaner production, 257*, Article 120301.

Dijkstra, J. (2013). Optimizing maintenance of weapon systems used under different loads and/or maintained at different locations. *Mater Thesis*. Eindhoven: Eindhoven University of Technology.

Dutch Ministry of Defence. (2022). *Wat doet defensie*. Retrieved from Defensie.nl: https://www.defensie.nl/onderwerpen/overdefensie/het-verhaal-van-defensie/wat-doet-defensie

EvgSkv. (2023). Exponential distribution pdf. *Exponential distribution.* Wikipedia. Retrieved from https://commons.wikimedia.org/wiki/File:Exponential_distribution_pdf_-_public_domain.svg

Gass, S., & Fu, M. (2016). Pollaczek-Khintchine Formula. In S. Gass, & M. Fu, *Encyclopedia of Operations Research and Management Science* (p. 1141). Boston: Springer. doi:10.1007/978

Hartig, S., & Wulfsberg, J. P. (2021). Konzept zur Integration Additiver Fertigung zur Unterstützung zeitweise autark operierender Systeme am Beispiel der Deutschen Marine. *CPM-Forum, 5*, 72-76.

Hoffman, F., & Gardner, R. (1983). Evaluation of uncertainties in radiological assessment models. In J. Till, & R. Meyer, *Radiological Assessment: A Textbook on Environmental Dose Analysis* (pp. 11.1-11.51). Washington: U.S. Government Printing Office.

IkamusumeFan. (2013). Uniform Distribution PDF SVG. *Continuous uniform distribution.* Wikipedia. Retrieved from https://commons.wikimedia.org/wiki/File:Uniform_Distribution_PDF_SVG.svg

ISO Central Secretary. (2021). *Additive manufacturing — General principles — Fundamentals and vocabulary.* Geneva, CH. Retrieved from https://www.iso.org/obp/ui/#iso:std:iso-astm:52900:ed-2:v1:en

ISO Central Secretary. (2022). *Mass customization value chain management — Part 1: Framework) – Part 1: Overview.* Geneva, CH. Retrieved from https://www.iso.org/obp/ui/fr/#iso:std:iso:24644:-1:dis:ed-1:v1:en

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

Knofius, N., van der Heijden, M. C., Sleptchenko, A., & Zijm, W. H. (2021). Improving effectiveness of spare parts supply by additive manufacturing as dual sourcing option. *OR spectrum, 43*, 189-221.

Knowledge Center for Logistics. (2022). *Potential of Additive Manufacturing according to the Knowledge Center.* Soesterberg.

Knowledge Center Logistics. (2022). *Potential of Additive Manufacturing according to the Knowledge Center .* Soesterberg.

Kraft, D. (1988). *A software package for sequential quadratic programming.* Köln: DLR German Aerospace Center — Institute for Flight Mechanics.

Langenhoff, L., & Zijm, W. (1989). An analytical theory of multi-echelon production/distribution systems. *Memorandum COSOR*(8910).

Little, J. (1961). A Proof for the Queuing Formula: L = λW. *Operations Research, 9*(3), 383-387.

Markforged. (2022, November 29). *17-4PH Stainless Steel*. Retrieved from Markforged: https://markforged.com/materials/metals/17-4-ph-stainless-steel

Ministerie van Defensie. (2022). *Royal Netherlands Army*. Retrieved from Defensie: https://english.defensie.nl/organisation/army

Sargent, R. (2012, December 7). Verification and validation of simulation models. *Journal of Simulation*(7), 12-24.

Sate-Dependent Systems. (1997). In C. E. Ebeling, *An introduction to reliability and maintainability engineering* (pp. 108-121). Boston: McGraw-Hill.

Savastano, M., Amendola, C., Massaroni, E., & D'Ascenzo, F. (2016). 3-D printing in the spare parts supply chain: an explorative study in the automotive industry. *Digitally supported innovation, 18*, 153-170.

SciPy. (2008). *Optimization and root finding*. Retrieved from SciPy: https://docs.scipy.org/doc/scipy/reference/optimize.html

Sgarbossa, F., Peron, M., Lolli, F., & Balugani, E. (2021). Conventional or additive manufacturing for spare parts management: An extensive comparison for Poisson demand. *International Journal of Production Economics, 233*, Article 107993.

Shang, K. H., & Song, J.-S. (2003). Newsvendor bounds and heuristic for optimal policies in serial supply chains. *Management Science, 49*, 618-638.

Shanks, D. (1955). Non-linear Transformations of Divergent and Slowly Convergent Sequences. *Journal of Mathematics and Physics, 34*(1-4), 1-42.

Skbkekas. (2010). Geometric pmf. *Geometric distribution.* Wikipedia. Retrieved from https://commons.wikimedia.org/wiki/File:Geometric_pmf.svg

Sobota, V., van de Kaag, G., Luomaranta, T., Martinsuo, M., & Ortt, J. (2020). Facotrs for metal additive manufacturing technology selection. *Journal of Manufactruing Technology Management, 32*, 26-47.

Springer, M. (1979). The Distribution of products and quotients of nonnegative random variables. In *The algebra of random variables* (pp. 97-100). New York: John Wiley & Sons.

't Hoen-Velterop, L., & Kool, G. (2020). *Metals additive manufacturing for military operations.* Amsterdam: NLR.

Tromp, I. (2022, December 4). VEDN indicator. Leusden: Koninklijke Landmacht.

van Berkum, E., & Di Bucchianico, A. (2016). *Statistical Compendium [Lecture notes].* Eindhoven: Eindhoven University of Technology.

van Houtum, G. (2006). Multi-echelon production/inventory systems : optimal policies, heuristics, and algortihms. *BETA publication: working papers*(177).

van Oers, J. (2022). *Risk analysis of high speed additive manufacturing.* Eindhoven: Eindhoven University of Technology.

van Veen, D. (2021). *Implementatie van AM binnen CLAS naar DOTMLPFI-LPFIA factoren.* Rijswijk: TNO.

Weiss, N., Holmes, P., & Hardy, M. (2002). *A course in probability.* Pearson Addison Wesley.

Westerweel, B., Basten, R., den Boer, J., & van Houtum, G.-J. (2021). Printing spare parts at remote locations: Fulfilling the promise of additive manufacturing. *Production and Operations Management, 30*, 1615-1632.

Xenonoxid. (2022). Log-normal-pdfs. *Log-normal distribution.* Wikipedia. Retrieved from https://commons.wikimedia.org/wiki/File:Log-normal-pdfs.png

Xu, X., Rodgers, M. D., & Guo, W. (2021). Hybrid simulation models for spare parts supply chain considering 3D printing capabilities. *Journal of Manufacturing Systems, 59*, 272-282.

Zijlstra, V. (2022). Printing in the Army: Where to locate additive manufacturing capabilities in a remote spare parts supply chain? *Master Thesis*. Eindhoven: Eindhoven University of Technology.

Appendix A. Interview Procedure

In Chapters 3 and 4 interviews are used to identify the answers to the related research questions. In this appendix the interview procedure and interviewees are introduced.

The goal of the interviews is to gather information about multiple aspects that revolve around AM in the RNLA. Based on the findings of Blumberg et al. (2014), for such an explorative research, an open-ended, structured interview is most fitting. The structured interview uses multiple interviewing techniques and question types. These questions dictate the topics discussed, keeping them equal along all interviews so that they can be more easily compared. The interview is open-ended by encouraging interviewees to interpret the questions in their own way and give their own thoughts and insights around the topics without being guided towards a specific answer. During the interviews the respondents are asked about the operating environments of the RNLA, the supply chain of the RNLA, the current state of AM within the RNLA, the factors and uncertainties influencing AM in the RNLA and their personal vision for AM within the RNLA. First, the goal of the research is introduced to the interviewee:

"Through this research we try to further investigate the application of AM within the RNLA supply chain. To expand upon previous research we are interested in the specific uncertainties that play a role when applying AM in the RNLA supply chain. Furthermore we are looking for more insights in possible AM technologies and their impact on the supply chain."

Three types of questions are used: Introductory questions, indirect questions and direct questions. The questions are sorted based on the research question. This way the conversation will remain on topic, as opposed to when the questions are sorted based on type. Other methodology from the same authors is used to learn more from the answers given by the interviewees. Follow-up questions are used to make the interviewee elaborate more on their answer to a specific question. Probing questions are used to make the interviewee explain more about a specific part of the answer they give. Finally, Interpreting questions are used to test whether or not the answer was understood correctly. This additional methodology is applied where necessary, this is therefore not structured beforehand. The questions used in the interviews are the following:

General questions

1. Could you shortly tell me about your function and your relation to AM in the armed forces?
2. What does the (remote) supply chain look like for the armed forces?
3. What challenges do you see with the armed forces supply chain at the moment?
4. What challenges do you see with AM in the armed forces at the moment?
5. What opportunities do you see for AM in the armed forces supply chain?

Deliverable 1 RQ 1.1: What are the differences interesting for AM between operating environments?

1. What are the specific different characteristics of Main Task 1, 2 and 3 respectively?
2. Which of these differences does in your eyes affect the application of AM and how?
3. Based on the specific characteristics identified in question 1 and 2, for what main tasks do you think AM would fit, in what form and why?
4. If we look at the supply chain of the RNLA, in which location(s) do you think a specific AM technology could fit and why?
5. For what repairs is AM applied in such an ideal location in your eyes?
6. Are there any locations where you do not see a good enough use-case to justify the application of AM and why?

Deliverable 1 RQ 1.2: What uncertainties play a role when applying AM in the RNLA mission supply chain?

1. What factors influence the application of AM in any context and how?
2. Which of these factors are uncertain in your eyes, so they are not exactly known prior to the deployment of AM?
3. Which of these factors are important to incorporate in the model and why?

Deliverable 2 RQ 2.1: What are the relevant differences between AM technologies interesting for the RNLA? & 2.2: Where are the different technologies applicable in the RNLA supply chain? (SME AM military)

1. What AM technologies does the army already use and what are they used for?
2. What (other) AM technologies do you deem useful for the armed forces and why?
3. Are there specific types of machines within these technologies that you deem best and why?
4. What are the different characteristics of these technologies/machines you deem important in the remote application of AM?
5. Due to these characteristics, do you see an ideal application environment and why?

Deliverable 2 RQ 2.3: What are the characteristics of spare parts produced by the different technologies in The RNLA context? (SME AM military)

1. What is the difference between spare parts produced by AM and conventional spare parts? (quality: failure rate, failure mode, performance against original)
2. How are these differences affected by the different machinery discussed under the previous set of questions?
3. Do you think AM is fit to produce spare parts that fully replace conventional parts?
4. In what cases do you think AM is capable to do this?
5. What parts do you deem best fit to be replaced by AM parts and why?
6. How would this affect the failure rate and modes of the specific spare parts?

Adjusted questions for certain topical experts

Logistics expert

1. How are spare parts inventory levels currently set and why?
2. How is spare part order replenishment handled in remote locations?
3. Could you give a detailed description of the remote RNLA spare part supply chain?

AMMAn/ external AM questions

1. Could you shortly tell me about your function and your relation to AM (possibly in the armed forces)?
2. What challenges do you see with AM in the armed forces at the moment?
3. What opportunities do you see for AM in the armed forces supply chain?
4. What is the difference between spare parts produced by AM and conventional spare parts? (quality: failure rate, failure mode, performance against original)
5. How are these differences affected by the different machinery discussed under the previous set of questions?
6. Do you think AM is fit to produce spare parts that fully replace conventional parts?
7. In what cases do you think AM is capable to do this?
8. What parts do you deem best fit for this application?
9. How would this affect the failure rate and modes of the specific spare parts?

10. What technologies does the army already use that you have worked with and what are they used for?
11. What (other) AM technologies do you deem useful for the armed forces and why?
12. Are there specific types of machines within these technologies that you deem best and why?
13. What are the different characteristics of these technologies/machines you deem important in the remote application of AM?
14. Due to these characteristics, do you see an ideal application environment?
15. What factors influence the application of AM in any context and how?
16. Which of these factors are uncertain in your eyes, so they are not exactly known prior to the deployment of AM?
17. Which of these factors are important to incorporate in the model?

A number of experts are important to interview. Some are active in the field with AM, some are AM experts for the entire RNLA, some have knowledge of AM and the logistical field, some are very knowledgeable on the supply chain of the RNLA and some are external experts who have a broad knowledge of AM technology. This leads to ten respondents. A short overview of the respondents is given in Table 13. Their functions and importance for the research are described below the table. Columns 3 and 4 show whether or not the respondent has expertise in the RNLA supply chain (SC) and additive manufacturing (AM). Respondents 1 through 8 are internal interviewees, respondents 9 and 10 are external experts.

Table 13: Interview respondent overview

Respondent	**Function**	**SC**	**AM**
1	Project Manager for the Innovation Department of the RNLA	X	X
2	Head of Engineering Advice for the RNLA		X
3	Head of the Production Unit Technology for CLAS		X
4	Major within the Knowledge Center for Logistics	X	
5	Officer of the 13th maintenance platoon		X
6	Member of the Innovation cell for the Knowledge Center for Logistics and chairman of the AM Knowledge Network within the Ministry of Defence	X	X
7	Member of the Innovation cell for the Knowledge Center for Logistics	X	X
8	AM technical specialist and project leader for CLAS		X
9	Senior R&D engineer NLR		X
10	Brightlands liaison for the Ministry of Defence		X

Respondent 1: Works as a program counselor for the innovation department of the RNLA. This department focusses on concept development and experiments with new technologies or methods to use within the RNLA. The respondent also has the role of Program manager, meaning responsibility for funding and planning. Whereas counselor the focus is more on the contents of the innovation. AM is one of the innovations the respondents is involved in.

Respondent 2: Head of the cluster Engineering and Advice within the technology department of CLAS in Leusden. Within this department four people are actively working with and on AM for the RNLA. The respondent manages these people and is therefore knowledgeable on the subject.

Respondent 3: Head of the different clusters within the technology department. The respondent therefore has a managing role when it comes to AM and represents the higher up goals of CLAS when it comes to the innovation. This is more aimed at policy than the technology itself.

Respondent 4: Expert on the RNLA supply chain within the Knowledge Center for Logistics, which is responsible for the logistics doctrine and logistical strategy. Also with regards to new innovations such as AM. Therefore knowledgeable on the subject but for the majority on the supply chain side.

Respondent 5: Officer with the 13th maintenance platoon in Oirschot, which is part of the 13th light brigade. They are responsible for the operational material services for the brigade. There are four of such platoons within the brigade. The specific function is business operations, which also entails the innovation side of the business operations for the platoon. This also includes the facilitating of 3D-printing activities.

Respondent 6: Part of the future cell of the knowledge center for logistics. This future cell is aimed at technologies and innovations that are interesting for the RNLA. This includes AM. The respondent is furthermore chairman of the AM knowledge network including experts on AM from all branches of the military. This network is also part of an international AM community with NATO partners.

Respondent 7: Part of the future cell of the knowledge center for logistics. This future cell is aimed at technologies and innovations that are interesting for the RNLA. This includes AM.

Respondent 8: AM Technical specialist for the RNLA within CLAS. Heavily involved in all things AM related within the RNLA and part of the RNLA expertise team for AM.

Respondent 9: Senior R&D engineer for NLR. Main focus of R&D towards metal AM. This also includes multiple research projects for various Dutch military branches.

Respondent 10: New business development for the Brightlands Chemelot campus. This means the acquisition of companies and real estate for the campus. The also means making the connection between the campus ecosystem and the industry. The liaison is the account manager for the connection between the Dutch military and Brightlands, including for AM.

Appendix B. Distribution fitting

In Section 5.3 two input variables are described, the lead time between installations and the printing time of a spare part. There we discussed that these variables are based (partly) on distributions of their respective delay values. In Appendix B.1 we discuss the fitting of the lead time delay distribution. In Appendix B.2 we show the print time delay distribution. The estimation of these distributions has been done based on expert estimations. As there is no historical data available on these variables we opt to use an estimation of the distribution based on expert insights. RNLA supply chain experts are consulted in order to form an estimate of the delay that might take place and the respective chance of such a delay occurring. We show for both delay variables how we evaluate what distribution fits the data.

Appendix B.1 Lead time delay distribution

Equation (1) describes the general way we incorporate uncertainty into the delivery lead time in between installations. Here we describe how we determine the distribution of Y_j and determine $\mathbb{E}[Y_j]$ based on that. Several experts were asked to estimate the probability of different delays occurring. This estimation is done by first discussing the delay behavior of shipment lead times with individual experts. Based on the collected stories some example sketches of the delay probability distribution are made and discussed with the same experts. Figure 15 gives the estimate of the probability of different delays occurring that came closest to reality according to experts.

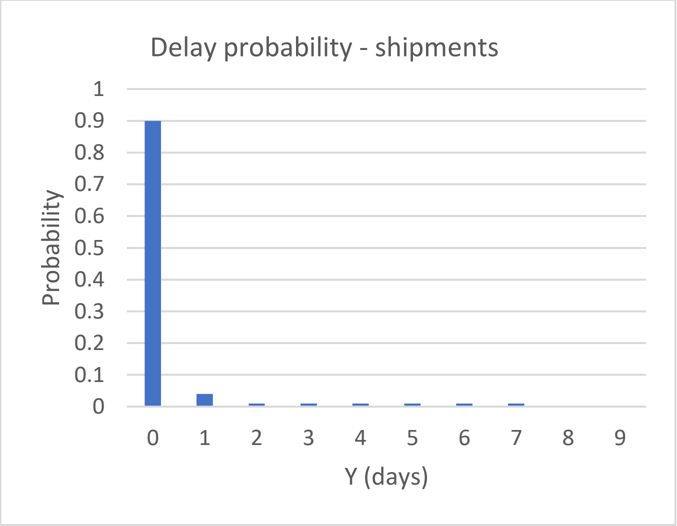


Figure 15: Estimated shipment delay probability

The horizontal axis displays the days the shipment is delayed and the vertical axis the corresponding probability. Since Y_j denotes time and is therefore continuous, we review a number of continuous probability distribution. Note that the bars relate to the probability of the delay being between Y and Y+1 days. We review a number of distributions that, under certain parameter values, have a comparable probability density function (PDF) graph to the estimated distribution in Figure 15. We review the log-normal distribution, exponential and Weibull (an overview of these distributions is given in Appendix B.1.1). The distributions are fitted to Figure 15 and the following are rated based on the sum of squared errors. An exponential distribution with rate 3.2258 has the best fit based on sum of squared estimate errors. Figure 16 shows the exponential distribution fitted to the estimated data.

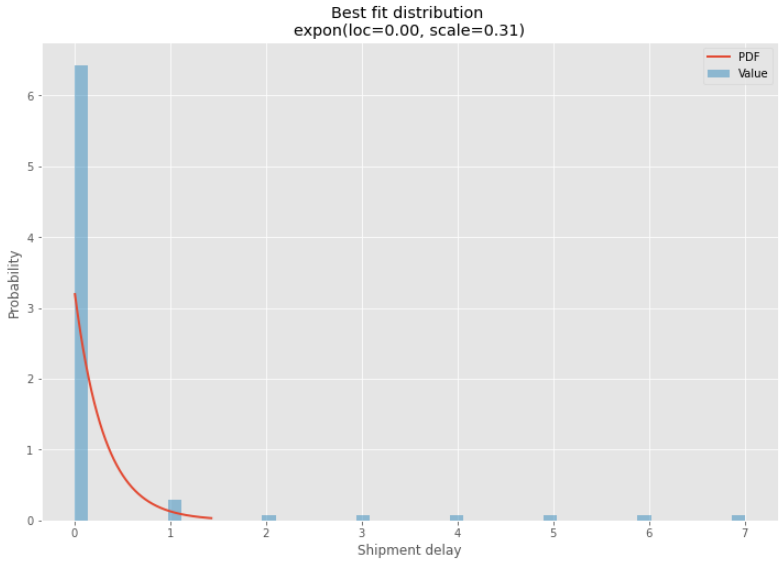


Figure 16: Estimated PDF and Exponential comparison

The means for the distribution and the data are the same. Based on the fitted distribution the mean of the delay $\mathbb{E}[Y_j]$ is 0.31 days. This is an estimate made by the RNLA experts that holds for all shipment delays in a Main Task 1 scenario, therefore we apply this delay estimate to all delivery lead times.

Appendix B.1.1 Fitted shipment delay distribution overview

The overview of the distributions is based on van Berkum and Di Bucchianico (2016).

Log-normal distribution:

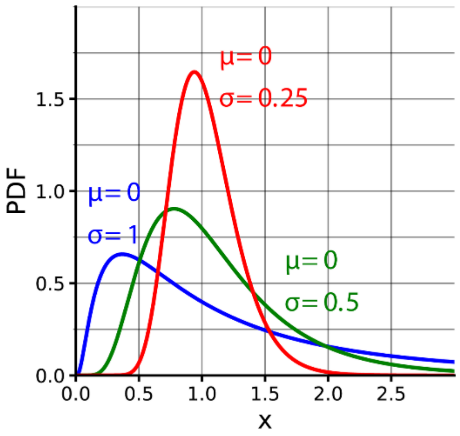


Figure 17: Log-normal distribution PDF by Xenonoxid (2022)

Parameters	$\mu = mean, \sigma = standard\ deviation$
PDF	$\frac{1}{x\sigma\sqrt{2\pi}}\ \exp\left(-\frac{(\ln x-\mu)^2}{2\sigma^2}\right)$
CDF	$\frac{1}{2}1 + erf\left[\left(\frac{\ln x - \mu}{\sigma\sqrt{2}}\right)\right]$ $erf[z] = \frac{2}{\sqrt{\pi}}\int_0^z e^{-t^2}\ \mathrm{dt}.$

Mean	$\exp\left(\mu + \frac{\sigma^2}{2}\right)$
Variance	$[\exp(\sigma^2) - 1]\exp(2\mu + \sigma^2)$

Exponential distribution:

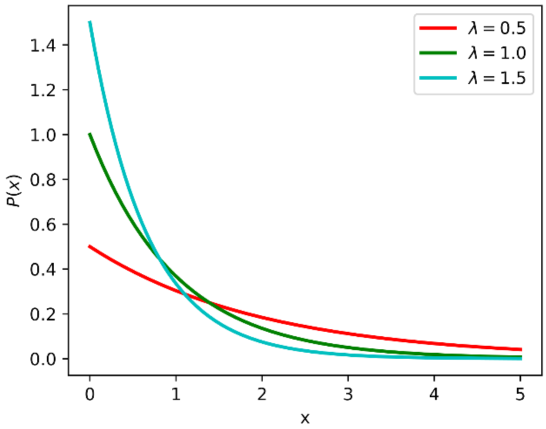


Figure 18: Exponential distribution PDF by EgvSkv (2023)

Parameters	$\lambda \in (0, \infty)$ (rate)
PDF	$\lambda e^{-\lambda x}$
CDF	$1 - e^{-\lambda x}$
Mean	$\frac{1}{\lambda}$
Variance	$\frac{1}{\lambda^2}$

Weibull distribution:

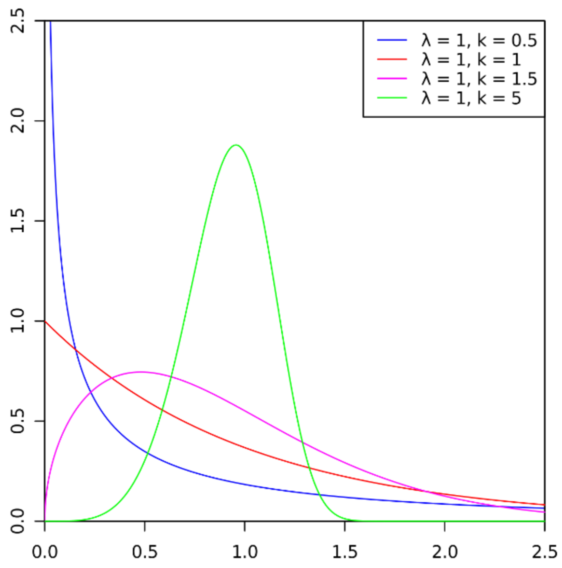


Figure 19: Weibull distribution PDF by Calimo (2010)

Parameters	$\lambda \in (0, \infty)$ (rate), $k \in (0, \infty)$(shape)
PDF	$f(x) = \begin{cases} \frac{\lambda}{k}\left(\frac{x}{\lambda}\right)^{k-1} e^{-(x/\lambda)^k}, & x \geq 0 \\ 0\,, & x < 0 \end{cases}$
CDF	$\begin{cases} 1 - e^{-(x/\lambda)^k}, & x \geq 0 \\ 0, & x < 0 \end{cases}$
Mean	$\lambda\Gamma(1 + 1/k)$ where $\Gamma(n) = (n-1)!$
Variance	$\lambda^2\left[\Gamma\left(1+\frac{2}{k}\right) - \left(\Gamma\left(1+\frac{1}{k}\right)\right)^2\right]$

Appendix B.2 Print time distribution

Equation (2) and Equation (4) describe the general way we incorporate uncertainty into the print time of a spare part. Here we describe how we determine the distribution of $Z_{j,n,m}$ and determine $\mathbb{E}\left[Z_{j,n,m}\right]$ and $VAR\left(Z_{j,n,m}\right)$ based on that. For the print time of a spare part *n* on machine *m* in location *j* we have very little data available. Therefore we opt to use an estimation of the distribution based on expert insights and the expert insights used by Zijlstra (2021). We only have indications on the chance that a print is successful on a certain machine. We use this to base the delay distribution on. The successful print chance is a good thing to base the distribution on as the delay is mainly caused by failed prints.

Based on expert opinions Zijlstra (2021) assumes the percentage of prints that are successful to be 70% for the UltiMaker S5 and for the Markforged mark 2 to be 90%. Based on the current opinions of RNLA experts, we assume that there is less difference between these two printers. We take the percentage of successful prints for the UltiMaker S5 to be 70% and for the Markforged mark 2 to be 80%. The Fieldmade installation is more stable due the controlled environment of the printing container. We choose a successful print chance of 90%. The depot-based printing is also in a controlled environment, subject to even less uncertainty. Here we choose a successful print chance of 99% is estimated. This gives us the following values for $q_{j,m}$: $q_U = 0.7$, $q_M = 0.8$, $q_F = 0.9$, $q_D = 0.99$.

The delay $z_{j,n,m}$ is determined by how many failed attempts there are and how long each failed attempt takes. This makes the distribution of $z_{j,n,m}$ the product of two independent random variables. We denote the distribution of the number of failed attempts by $Q_{j,m}$ and the distribution of the time in the printing process where the defect is detected and the print is terminated is denoted by $T_{j,n,m}$, so $Z_{j,n,m} = Q_{j,m} \cdot T_{j,n,m}$.

The expected number of failed attempts before the print is successful and the variance thereof can be described by a geometric distribution,

$$E(Q_{j,m}) = E(attempts) - 1 = \frac{1}{q_{j,m}} - 1 = \frac{1 - q_{j,m}}{q_{j,m}}$$

$$VAR(Q_{j,m}) = VAR(attempts) = \frac{1 - q_{j,m}}{q_{j,m}^2}$$

(B. 1)

After discussion with RNLA experts and consulting the research of van Oers (2022) we find that a failure can occur anywhere in the printing process with equal likelihood. Therefore $T_{j,n,m}$ can be described by a continuous uniform distribution with a minimum of 0 and a maximum equal to the print time of one part without delays i.e. $P_{j,n,m}$. Therefore,

$$E(T_{j,n,m}) = \frac{1}{2} P_{j,n,m}$$

$$VAR(T_{j,n,m}) = \frac{1}{12} P_{j,n,m}^2$$

(B. 2)

Based on the Law of total expectation introduced by Weis, Holmes and Hardy (2002), we know that the mean of the product of two independent random variables (let us call them X and Y) is given by:

$$E(XY) = E(X) \cdot E(Y)$$

Based on this, for $z_{j,n,m}$ we have:

$$E(z_{j,n,m}) = E(Q_{j,m}) \cdot E(T_{j,n,m}) = \frac{1 - q_{j,m}}{q_{j,m}} \cdot \frac{1}{2} P_{j,n,m} = \frac{0.5(1 - q_{j,m}) P_{j,n,m}}{q_{j,m}}$$

(B. 3)

Based on Springer (1979) we know the variance of two independent random variables (X and Y), for which the squared counterparts are also independent (X^2 and Y^2) is given by:

$$VAR(XY) = (VAR(X) + E(X)^2)(VAR(Y) + E(Y)^2) - (E(X)^2 \cdot E(Y)^2)$$

Based on this, for Z_m we have:

$$VAR(z_{j,n,m}) = \left(VAR(Q_{j,m}) + E(Q_{j,m})^2\right)\left(VAR(T_{j,n,m}) + E(T_{j,n,m})^2\right) - \left(E(Q_{j,m})^2 \cdot E(T_{j,n,m})^2\right)$$

$$= \left(\frac{(q_{j,m} - 1)(q_{j,m} - 2)}{q_{j,m}^2}\right) \frac{1}{3} P_{j,n,m}^2 - \left(\frac{\left(1 - q_{j,m}\right)^2 P_{j,n,m}^2}{4 q_{j,m}^2}\right)$$

(B. 4)

This mean and variance can be used in Equation (2) and subsequently in Equation (4) in Section 5.3 to estimate the total time it takes to complete a print. An overview of the distributions used is given in Appendix B.2.1.

Appendix B.2.1 Fitted print time delay distribution overview

The overview of the distributions is based on van Berkum and Di Bucchianico (2016).

Geometric distribution:

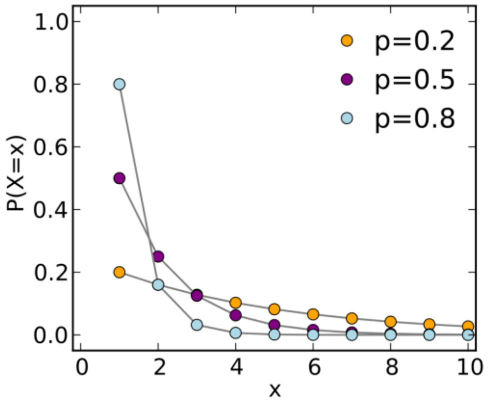


Figure 20: Geometric distribution PDF by Skbkekas (2010)

Parameters	$0 < p \leq 1$ success probability
Probability mass function (PMF)	$Pr(X = k) = (1 - p)^{k-1}p$
CDF	$Pr(X \leq k) = 1 - (1 - p)^k$
Mean	$\frac{1}{p}$
Variance	$\frac{1 - p}{p^2}$

Uniform distribution:

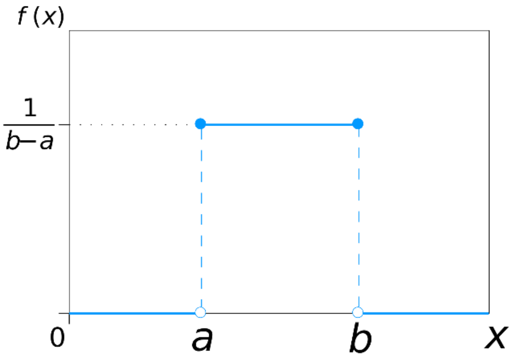


Figure 21: Uniform distribution PDF by IkamusumeFan (2013)

Parameters	$-\infty < a < b < \infty$
PDF	$\begin{cases} \frac{1}{b-a} & for\ \ x \in [a,b] \\ 0 & otherwise \end{cases}$
CDF	$\begin{cases} 0 & for\ x\ < a \\ \frac{x-a}{b-a} & for\ \ x \in [a,b] \\ 1 & for\ x\ > a \end{cases}$
Mean	$\frac{1}{2}(a+b)$
Variance	$\frac{1}{12}(b-a)^2$

Appendix C. Software tool manual

Here we give a short manual for the software tool aimed at the RNLA user where input and output are explained. First some general instructions are given on how to use the tool. Then the input excel file and data entry are explained. Then example output is given to show how the RNLA can read results from the tool.

Prerequisites and disclaimers

The tool is written in Python 3.8. Other versions of Python can lead to problems with the execution of the file. Use an Integrated Development Environment, we suggest using Spyder: https://www.anaconda.com/products/distribution

Make sure the Python file and data files remain in the original folders. Moving the files to other locations will lead to errors in the initialization of the code.

Required additional Python packages are:

- Pandas: https://pandas.pydata.org/
- MpMath: https://mpmath.org/
- Numpy: https://numpy.org/

Initialization and data entry

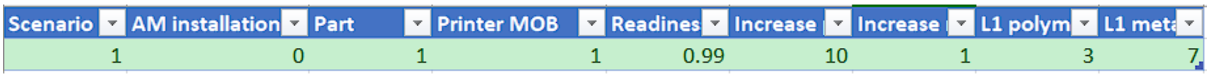
Refer to the legends in the specific datasheets described in Appendix C.1 for detailed explanation of what all cells and values mean.

Execution and data retrieval

To execute the tool, loading and running the python file is required. The tool can be used to run different scenarios and parameter values without altering the code itself. All adjustments are made through the datasheets. Refer to Appendix C.2 for a representation and description of the tool output.

Appendix C.1 Input explanation

The **INIT datasheet** is where you can easily switch between parts, scenarios and other settings in order to evaluate different scenarios. The legend alongside the table gives an extensive explanation of what all cells and values do. The **INIT datasheet** is structured as follows:



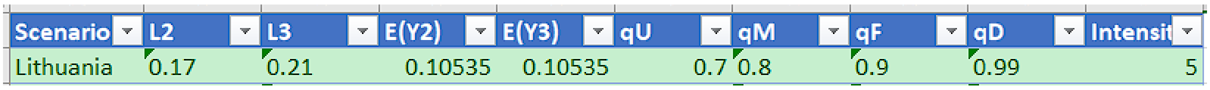
Scenario	AM installation	Part	Printer MOB	Readines	Increase	Increase	L1 polym	L1 meta
1	0	1	1	0.99	10	1	3	7

Figure 22: Initialization datasheet

- **Scenario** denotes the scenario chosen from the list of scenarios, this should be a number not a name.
- **AM installation** denotes the location where the AM machinery is located. 0 denotes no AM, 1, 2 and 3 denote their respective installations i.e. one of the four model scenarios introduced in Section 5.4.
- **Part** denotes the part chosen from the list of parts.
- **Printer MOB** means the type of printer used at the most downstream location. 1 = UltiMaker, 2 = Markforged, 3 = Fieldmade.
- **Readiness** means the readiness required for the part selected or the vehicle corresponding to that part.
- **Increase demand** is the factor with which demand is multiplied for AM produced parts. This is a separate parameter for polymer and metal parts.
- **L1 polymer/ metal** is the lead time for the two raw material types in days.

If you want to make more significant changes to the data evaluated you can make alterations to the other datasheets.

The **Scenario datasheet** holds the specific Main Task 1 scenarios that can be played out. Note that the scenarios are based on the three-tiered supply chain elaborated in this research. Scenarios that do not fit this description are not advised, as the tool will yield inaccurate results. Do not alter the example scenarios, add new ones and select them in the INIT datasheet. Note that missing data from the required cells will lead to incomplete calculations and errors. The **Scenario datasheet** is structured as follows:

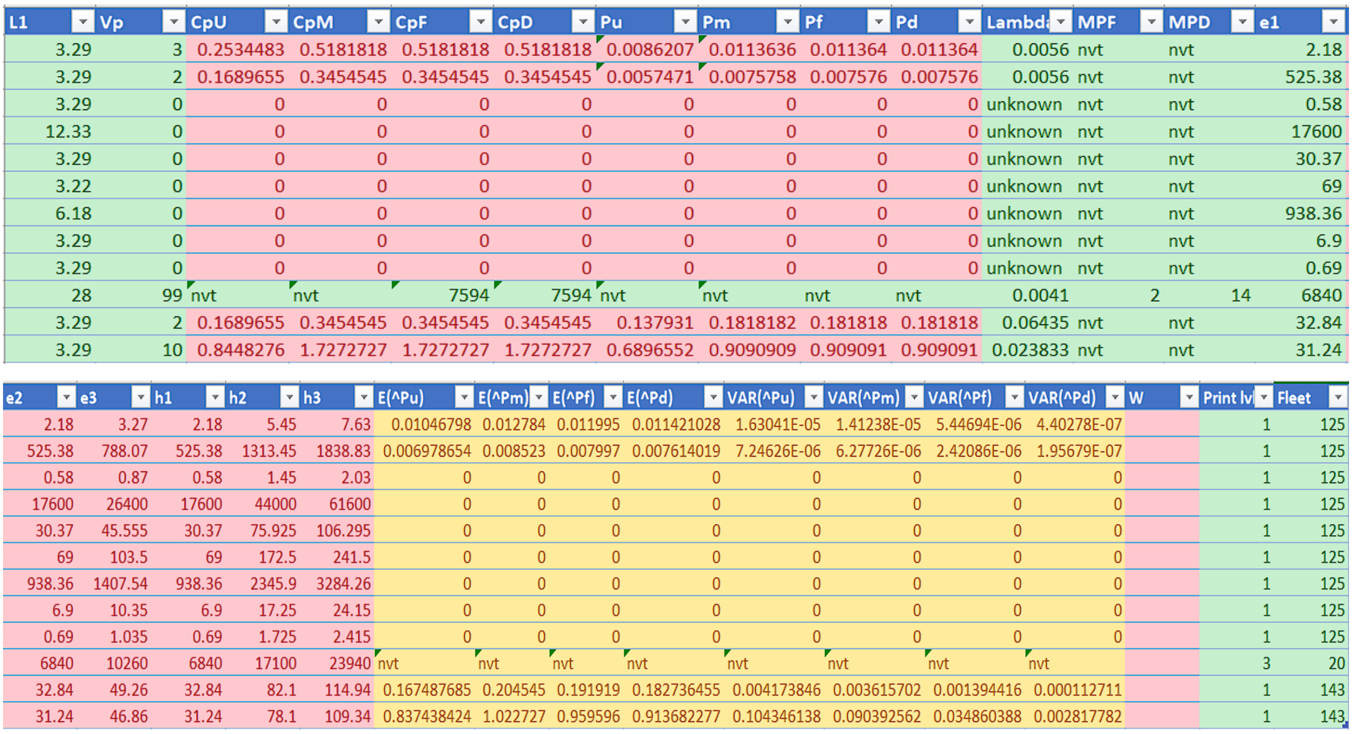


Scenario	L2	L3	E(Y2)	E(Y3)	qU	qM	qF	qD	Intensit
Lithuania	0.17	0.21	0.10535	0.10535	0.7	0.8	0.9	0.99	5

Figure 23: Scenario datasheet

- The **Scenario** name is unimportant for the tool, it only functions as an indicator for the user.
- **L2** and **L3** are the lead times between Installation 1 and 2, and Installation 2 and 3 respectively.
- **E(Y2)** and **E(Y3)** are the average delays in the lead time between installations, Y2 is the delay to Installation 2 and Y3 the delay to Installation 3.
- **qU, qM, qF, qD** denote the probability of a print to be successful on respectively the UltiMaker, Markforged, Fieldmade and Depot printer. Where Depot means any printing solution in the Netherlands. Note that this chance should be adjusted for your proposed location of the printer.
- **Intensity** denotes the multiplier of demand rate for the specific scenario.

The **Parts datasheet** holds the parts that can be used in the evaluation. Note that in this datasheet some cells are automatically calculated based on the given part data. We advise you not to alter this. Note that missing data from the required cells will lead to incomplete calculations and errors. It is again advised to leave the example data as is. The **Parts datasheet** is structured as follows:



L1	Vp	CpU	CpM	CpF	CpD	Pu	Pm	Pf	Pd	Lambd	MPF	MPD	e1
3.29	3	0.2534483	0.5181818	0.5181818	0.5181818	0.0086207	0.0113636	0.011364	0.011364	0.0056	nvt	nvt	2.18
3.29	2	0.1689655	0.3454545	0.3454545	0.3454545	0.0057471	0.0075758	0.007576	0.007576	0.0056	nvt	nvt	525.38
3.29	0	0	0	0	0	0	0	0	0	unknown	nvt	nvt	0.58
12.33	0	0	0	0	0	0	0	0	0	unknown	nvt	nvt	17600
3.29	0	0	0	0	0	0	0	0	0	unknown	nvt	nvt	30.37
3.22	0	0	0	0	0	0	0	0	0	unknown	nvt	nvt	69
6.18	0	0	0	0	0	0	0	0	0	unknown	nvt	nvt	938.36
3.29	0	0	0	0	0	0	0	0	0	unknown	nvt	nvt	6.9
3.29	0	0	0	0	0	0	0	0	0	unknown	nvt	nvt	0.69
28	99	nvt	nvt	7594	7594	nvt	nvt	nvt	nvt	0.0041	2	14	6840
3.29	2	0.1689655	0.3454545	0.3454545	0.3454545	0.137931	0.1818182	0.181818	0.181818	0.06435	nvt	nvt	32.84
3.29	10	0.8448276	1.7272727	1.7272727	1.7272727	0.6896552	0.9090909	0.909091	0.909091	0.023833	nvt	nvt	31.24

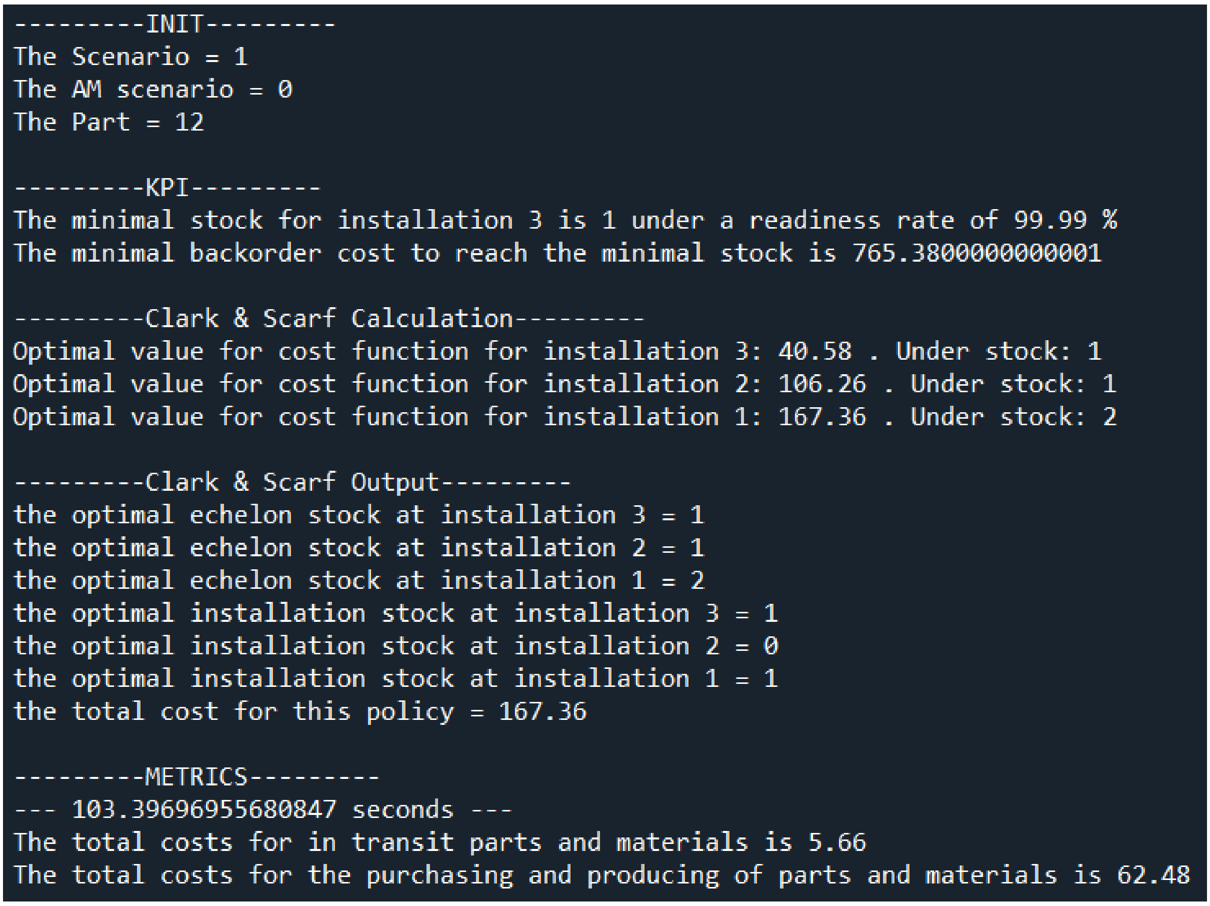
e2	e3	h1	h2	h3	E(^Pu)	E(^Pm)	E(^Pf)	E(^Pd)	VAR(^Pu)	VAR(^Pm)	VAR(^Pf)	VAR(^Pd)	W	Print lv	Fleet
2.18	3.27	2.18	5.45	7.63	0.01046798	0.012784	0.011995	0.011421028	1.63041E-05	1.41238E-05	5.44694E-06	4.40278E-07		1	125
525.38	788.07	525.38	1313.45	1838.83	0.006978654	0.008523	0.007997	0.007614019	7.24626E-06	6.27726E-06	2.42086E-06	1.95679E-07		1	125
0.58	0.87	0.58	1.45	2.03	0	0	0	0	0	0	0	0		1	125
17600	26400	17600	44000	61600	0	0	0	0	0	0	0	0		1	125
30.37	45.555	30.37	75.925	106.295	0	0	0	0	0	0	0	0		1	125
69	103.5	69	172.5	241.5	0	0	0	0	0	0	0	0		1	125
938.36	1407.54	938.36	2345.9	3284.26	0	0	0	0	0	0	0	0		1	125
6.9	10.35	6.9	17.25	24.15	0	0	0	0	0	0	0	0		1	125
0.69	1.035	0.69	1.725	2.415	0	0	0	0	0	0	0	0		1	125
6840	10260	6840	17100	23940	nvt	nvt	nvt	nvt	nvt	nvt	nvt	nvt		3	20
32.84	49.26	32.84	82.1	114.94	0.167487685	0.204545	0.191919	0.182736455	0.004173846	0.003615702	0.001394416	0.000112711		1	143
31.24	46.86	31.24	78.1	109.34	0.837438424	1.022727	0.959596	0.913682277	0.104346138	0.090392562	0.034860388	0.002817782		1	143

Figure 24: Parts datasheet

For all the datasheets **green cells** represent parameters that you should fill in. **Yellow cells** indicate parameters for the print time distribution. These are calculated based on Appendix B.2. These should only be changed if you want to change the print time distribution. **Red cells** represent parameters that are calculated automatically (an explanation of these calculations is given in the text of Section 7.1). They should not be changed unless you are certain you want to deviate from the calculations behind these cells.

- **L1** is the lead time from the supplier to the depot including average delays.
- **Vp** is print volume.
- **CpX** is the print costs on machine X for raw material these cells are based on the print volume and printer and calculated automatically for the given polymer parts. For the Metal parts they have to be filled in by hand.
- **Px** is the minimum print time of the part on machine x, not including delays.
- **Lambda** is the amount ordered of the part per day.
- **MPF** is mean time to print metal part with Fieldmade.
- **MPD** is mean time to print metal part at depot, currently based on expediting.
- **e1** is the local holding costs at Installation 1, should be equal to the purchasing costs. All other e and h values are calculated automatically.
- **E(^Px)** is the expected print time of the part including delays on machine x.
- **VAR(^Px)** is the variance of the print time including delays on machine x.
- **W** is calculated automatically according to Equation (4), for metal parts the relevant print time is currently based on the **MPF** and **MPD**.
- **Print lvl** represents the level where the part can be printed according to the description given in Section 4.2.
- **Fleet** represents the number of vehicles deployed for the specific part.

Appendix C.2 Tool output visualization



```
---------INIT---------
The Scenario = 1
The AM scenario = 0
The Part = 12

---------KPI---------
The minimal stock for installation 3 is 1 under a readiness rate of 99.99 %
The minimal backorder cost to reach the minimal stock is 765.3800000000001

---------Clark & Scarf Calculation---------
Optimal value for cost function for installation 3: 40.58 . Under stock: 1
Optimal value for cost function for installation 2: 106.26 . Under stock: 1
Optimal value for cost function for installation 1: 167.36 . Under stock: 2

---------Clark & Scarf Output---------
the optimal echelon stock at installation 3 = 1
the optimal echelon stock at installation 2 = 1
the optimal echelon stock at installation 1 = 2
the optimal installation stock at installation 3 = 1
the optimal installation stock at installation 2 = 0
the optimal installation stock at installation 1 = 1
the total cost for this policy = 167.36

---------METRICS---------
--- 103.39696955680847 seconds ---
The total costs for in transit parts and materials is 5.66
The total costs for the purchasing and producing of parts and materials is 62.48
```

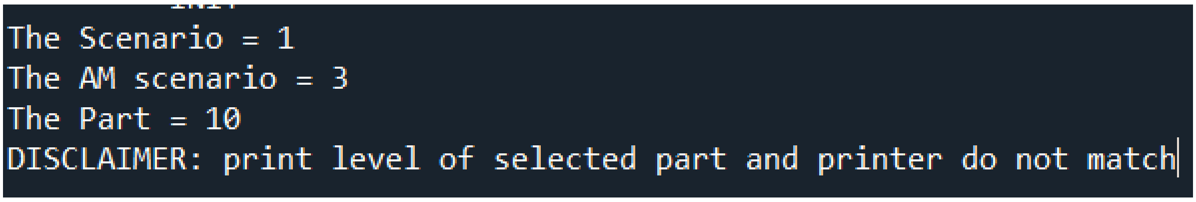
Figure 25: Example output

Figure 25 shows how Python presents the user with the tool output. This is example output for *Scenario 0* in an example Main Task 1 deployment. **The Scenario** indicates the Main Task 1 deployment scenario form the **scenario datasheet** that has been executed. **The AM scenario** refers to the selected AM installation and **The Part** refers to the spare part for which the tool is executed. Both are selected in the **INIT datasheet.**

All output is printed with an explanation so the user can easily know what they are dealing with. Cost output is given in euros.

Under **METRICS** some metrics are recorded that are not used in the optimization. The **seconds** indicate the number of seconds it required to complete the calculations. For the example used it was a little more than 103 seconds. The **in transit costs** and **spare part costs** calculations are described in detail in Section 7.1.

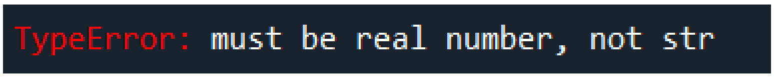
The program also displays intentional errors in some cases. If an **AM scenario** is chosen that does not match the part print level as described in Table 7 the following message is displayed:



```
The Scenario = 1
The AM scenario = 3
The Part = 10
DISCLAIMER: print level of selected part and printer do not match
```

Figure 26: Disclaimer for print level

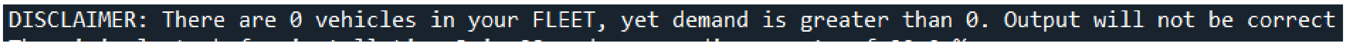
If a parameter value is “unknown” the following error message is prompted:



```
TypeError: must be real number, not str
```

Figure 27: Error for "unknown" value in input

If the fleet size is set to 0 and demand is greater than 0 the following message is prompted:



```
DISCLAIMER: There are 0 vehicles in your FLEET, yet demand is greater than 0. Output will not be correct
```

Figure 28: Dsiclaimer for empty fleet

If the print success rate is set to zero, the following warning is issued by the tool. The code will still execute but the total costs will be displayed as nan (not a number).

```
RuntimeWarning: divide by zero encountered in scalar divide
```

Figure 29: Warning for a print success rate of 0

Appendix D. Validation data

Here we give an overview of the parameters we use for the validation of the software tool. All parameters are summarized in excel tables that are used for the tool execution.

Appendix D.1 Extreme scenario data

The parameters tested are the demand, intermediate stocks, holding costs and (production) lead times, as described in Section 6.2. We evaluate each parameter individually and keep all other parameters equal. The following set of parameter values is used as a starting point:

Part	L1	Vp	Lambda	Cost	Print lvl	Fleet
11	3.29	2	0.06435	32.84	1	143

Scenario	L2	L3	E(Y2)	E(Y3)	qU	qM	qF	qD	Intensity
Lithuania	0.17	0.21	0.31	0.31	0.7	0.8	0.9	0.99	5

Readiness	Increase polymer demand	Increase metal demand	L1 polymer	L1 metal
0.9999	10	1	3	7

Below we describe each test and the model output. We also evaluate combinations of the data. The excel sheets below show all the different input parameter sets used. The green cells indicate the extreme values for the specific extreme case.

The following extreme parameters sets are tested trough the scenario datasheet.

Table 14: Extreme scenario parameter values

Scenario	L2	L3	E(Y2)	E(Y3)	qU	qM	qF	qD
Extreme1	0	0.22	0	0.31	0.7	0.8	0.9	0.99
Extreme2	0.17	0	0.31	0	0.7	0.8	0.9	0.99
Extreme3	0	0	0	0	0.7	0.8	0.9	0.99
Extreme4	1000	0	1000	0	0.7	0.8	0.9	0.99
Extreme5	0	1000	0	1000	0.7	0.8	0.9	0.99
Extreme6	1000	1000	1000	1000	0.7	0.8	0.9	0.99
Extreme7	0.17	0.21	0.31	0.31	0	0	0	0
Extreme8	0.17	0.21	0.31	0.31	1	1	1	1

The following extreme parameters sets are tested trough the parts datasheet:

1. Situation where L_2 including delays is 0
2. Situation where L_3 including delays is 0
3. Situation where L_2 and L_3 including delays are 0
4. Situation where L_2 including delays is 2000 days i.e. improbably large
5. Situation where L_3 including delays is 2000 days i.e. improbably large
6. Situation where L_2 and L_3 including delays are 2000 days i.e. improbably large
7. Situation where all prints fail
8. Situation where no prints fail

Table 15: Extreme part parameter values

Parts	L1	Vp	Lambda	e1	e2	e3	Fleet	VAR(^Px)
Extreme1	3.29	2	250	32.84	32.84	49.26	143	-

Extreme2	3.29	2	0	32.84	32.84	49.26	143	-
Extreme3	0	2	0.06435	32.84	32.84	49.26	143	-
Extreme4	1000	2	0.06435	32.84	32.84	49.26	143	-
Extreme5	3.29	0	0.06435	32.84	32.84	49.26	143	-
Extreme6	3.29	1000	0.06435	32.84	32.84	49.26	143	-
Extreme7	0	0	0.06435	32.84	32.84	49.26	143	-
Extreme8	1000	1000	0.06435	32.84	32.84	49.26	143	-
Extreme9	3.29	2	0.06435	0	32.84	49.26	143	-
Extreme10	3.29	2	0.06435	32.84	0	49.26	143	-
Extreme11	3.29	2	0.06435	32.84	32.84	0	143	-
Extreme12	3.29	2	0.06435	1000000	32.84	49.26	143	-
Extreme13	3.29	2	0.06435	32.84	1000000	49.26	143	-
Extreme14	3.29	2	0.06435	32.84	32.84	1000000	143	-
Extreme15	3.29	2	0.06435	32.84	32.84	32.84	143	-
Extreme16	3.29	2	0.06435	32.84	32.84	49.26	143	1000
Extreme17	3.29	2	0.06435	32.84	32.84	49.26	143	0
Extreme18	3.29	2	0.06435	32.84	32.84	49.26	10000	-
Extreme19	3.29	2	0.06435	32.84	32.84	49.26	0	-

Note that the other parts of the datasheet are calculated automatically based on the parameters above.

1. Situation where the demand rate is 250 parts/day i.e. improbably large
2. Situation where the demand rate is 0
3. Situation where L_1 including delays is 0
4. Situation where L_1 including delays is 1000 days i.e. improbably large
5. Part for which the print volume is 0 and therefore the print time and costs are also 0
6. Part for which the print volume is 10000 cm^3 and therefore the print time and costs also are improbably large
7. Both L_1 and the volume are 0 leading to instant delivery and printing
8. Both L_1 and the volume are improbably large leading to a total backup of the printing facilities delivery and printing
9. Echelon 1 holding costs are 0
10. Echelon 2 holding costs are 0
11. Echelon 3 holding costs are 0
12. Echelon 1 holding costs are improbably large
13. Echelon 2 holding costs are improbably large
14. Echelon 3 holding costs are improbably large
15. Echelon 1, 2 and 3 holding costs are equal
16. Printing time variance is very high
17. Printing time variance is very small
18. The vehicle fleet is improbably large
19. There are no vehicles in the fleet

For the INIT datasheet we only adjust the **readiness**. We test a **readiness** of 0% and 100%. For all other tests the **readiness** is kept at 99.99%.

Appendix D.2 Sensitivity analysis data

For the Sensitivity analysis the same parameters are tested as in the extreme scenario tests. The following parameter values are tested to find the $Output_{min}$ and $Output_{max}$:

1. $L_1 = 0$ and $L_1 = 2000$ days
2. $L_2 = 0$ and $L_2 = 2000$ days
3. $L_3 = 0$ and $L_3 = 2000$ days
4. $q_{j,m} = 0.001$ and $q_{j,m} = 1$
5. $\lambda = 0.001$ and $\lambda = 250$ parts/day
6. $v^p = 0$ and $v^p = 1000\ cm^3$
7. $e_1 = 0$ and $e_1 = €1{,}000{,}000.00$
8. $e_2 = 0$ and $e_2 = €1{,}000{,}000.00$
9. $e_3 = 0$ and $e_3 = €1{,}000{,}000.00$
10. $VAR(Z_{j,n,m}) = 0$ and $VAR(Z_{j,n,m}) = 1000$ days
11. Fleet size = 1 and fleet size = 10,000 vehicles
12. Readiness = 1 and 100 %

For some parameters we cannot use the minimum value of 0 as this will lead to an output of 0. Based on Equation (18) we can see that if $Output_{min} = 0$ and $Output_{max} > 0$, SI will always be 1.0. This would mean that these values are more sensitive than others, which is often not the case. We therefore try to avoid minimal parameter values for which $Output_{min} = 0$.

Appendix E. Extreme scenario output

Here we give an overview of the output for the validation gathered with the software tool. The output is summarized per tests. We focus on the output that is interesting for the test and anomalies in the output that have to be explained.

Appendix E.1 Extreme demand output

For λ = 250:

- The minimum stock required to reach a readiness of 99.99% is 140 parts. This is a fairly logical output since the shipment lead time to Installation 3 is less than one day.
- Running the optimization leads to a total stock of 163 parts, which is also logical since this extra stock is only to cover the total lead time in between the installations of around 4 days.
- $S_3^e = 140$, $S_2^e = 163$ and $S_1^e = 163$. This also raises no suspicion.
- The total costs for in transit and spare parts is €17832.12, which is also correct based on the total stock and demand.

For λ = 0:

- The minimum stock required to reach a readiness of 99.99% is 0 parts, logical for 0 demand.
- Running the optimization leads to a total stock of 0 parts, which is also logical.
- $S_3^i = S_2^i = S_1^i = 0$. This also logical.
- The total costs for in transit and spare parts is €0, which is also correct based on the total stock and demand.

Appendix E.2 Extreme holding cost output

For $\boldsymbol{e_j = 0}$:

- Zero holding costs at echelon 1 also means there are no holding costs for Installation 1. In this situation $S_1^i = 18$, whereas for the standard situation $S_1^i = 2$. So this is a logical outcome.
- Despite zero holding costs at echelon 2, $h_2 = €32.84$, due to the holding cost at echelon 1. This is not significantly different from the normal holding cost at Installation 2. Therefore $S_1^i = 0$, which is the same for the standard situation is a logical outcome.
- Zero holding costs at echelon 3 means the holding costs for Installation 3 is equal to those for Installation 2. This decreases $\hat{C}_3$ from €42.19 to € 18.19, which is to be expected. The holding cost does not affect S_3^i, which is logical as this is determined based on readiness.

For $\boldsymbol{e_j = 100,000}$:

- Extreme high holding costs at echelon 1 also means there are extreme holding costs for Installation 1, 2 and 3. In this situation $S_1^i = 0$, whereas for the standard situation $S_1^i = 2$. So this is a logical outcome. Also the costs are €1,413,755.54. This is logical since all installation holding costs are high due to the increased e_1.
- Extreme high holding costs at echelon 2 also means there are extreme holding costs for Installation 2 and 3. In this situation S_2^i remains 0, which is logical. Also S_3^i remains the same as it is determined based on readiness. The total costs are €694,681.62 which is also logical since the holding cost for echelon and Installation 1 are significantly lower than for the previous case.
- Extreme high holding costs at echelon 3 only means there are extreme holding costs for Installation 3. The holding cost does not affect S_3^i, which is logical as this is determined based on readiness. This increases backordering costs to €6,000,394.08. These have to be this high to balance the extreme holding costs and reach the desired readiness of 99.99%. Therefore the outcome is understandable.

For $\boldsymbol{e_1 = e_2 = e_3}$:

- Although all echelon costs are equal there is still a difference in the installation holding costs. It is therefore fairly similar to the standard situation. The only difference is $h_3 = €98.52$ as opposed to the standard $h_3 = €114.94$. So this leads to the same outcome for the standard situation, which is understandable.

For $\boldsymbol{e_1 = e_2 = e_3}$ and $\boldsymbol{h_1 = h_2 = h_3}$:

- $S_3^i = S_2^i = S_1^i = 2$ meaning all stock is moved forward to the final echelon, which is to be expected.

Appendix E.3 Extreme lead time output

For $\boldsymbol{L_1 = 0}$ and $\boldsymbol{L_1 = 2000}$:

- $L_1 = 0$ means that lead time demand is 0 for Installation 1. Therefore $S_1^i = 0$ is a logical outcome. There is still stock kept further from the printing station, which is logical as demand is still larger than 0 and other lead times in the supply chain are also still larger than 0.
- $L_1 = 2000$ means that lead time demand is 321.75 parts for Installation 1. This leads to such high holding costs that keeping no stock is actually more beneficial than trying to keep stock. Backordering costs are also not that high since lead time demand at Installation 3 is kept the same. Therefore $S_1^i = 0$ is a logical outcome.

For $\boldsymbol{L_2 = 0}$ and $\boldsymbol{L_2 = 2000}$:

- $L_2 = 0$ means that lead time demand is 0 for Installation 2. Therefore $S_2^i = 0$ is a logical outcome. There is still stock kept further from the printing station, which is logical as demand is still larger than 0 and other lead times in the supply chain are also still larger than 0.
- $L_2 = 2000$ means that lead time demand is 321.75 parts for Installation 2. This leads to such high holding costs that keeping no stock is actually more beneficial than trying to keep stock. Backordering costs are also not that high since lead time demand at Installation 3 is kept the same. Therefore $S_2^i = 0$ is a logical outcome.

For $\boldsymbol{L_3 = 0}$ and $\boldsymbol{L_3 = 2000}$:

- $L_3 = 0$ means that lead time demand is 0 for Installation 1. Therefore $S_3^i = 0$ is a logical outcome.
- There is still stock kept further from the printing station, which is logical as demand is still larger than 0 and other lead times in the supply chain are also still larger than 0.
- $L_3 = 2000$ means that lead time demand is 321.75 parts for Installation 3. Because S_3^i is dictated by readiness high demand and costs cannot be circumvented. Therefore $S_3^i = 178$ is a logical outcome.

For $\boldsymbol{L_1 = L_2 = L_3 = 0}$:

- $L_1 = L_2 = L_3 = 0$ means that lead time demand is 0 for all installations. Therefore $S_1^e = 0$ is a logical outcome.

For $\boldsymbol{L_1 = L_2 = L_3 = 2000}$:

- $L_1 = L_2 = L_3 = 2000$ means that lead time demand is 321.75 parts for all installations. The high holding costs again lead to 0 stock.

Appendix E.4 Extreme production time output

For a print success rate of 0%

- If the print success is 0%, the calculation of λ_A contains a division through zero. This is not possible so λ_A becomes nan (not a number).
- The same holds for the calculation of the time a print order spends in the system W. This also becomes nan.
- Therefore the total costs are also not a number. Based on the calculations made the user should be made aware of the fact that a print success rate of 0 is not a value that the model can handle.

For a print success rate of 100%

- If the print success rate is set to 100% all prints will be successful. We see $\lambda_A = \lambda_B$ here, which is correct. Print times are still larger than 0, but do not include delays, which is also correct.
- We see this leads to lower installation stock required at the printing installations and all installations upstream, which is logical as demand is now smaller at these installations. For instance for printing part 2 in AM Scenario 0 the stock is now

For a $VAR(Z_{j,n,m})$ of 0

- Print times are still larger than 0, but W becomes smaller, which is correct.
- The print times is already very small in the standard value set. For printing part 2 in AM Scenario 0 it is $3.59{*}e^{-7}$ for instance. Therefore a printing variance of 0 does not affect the output significantly.

For a $VAR(Z_{j,n,m})$ of 1000

- Print times are still relatively small, but W becomes larger, which is correct. W for part 2 in AM Scenario 0 is for instance over 100000 days. Looking at Equation (4) this is correct.
- The very large lead time from the printing installation leads to 0 stock.

For a print volume of 0

- Print times become 0 and variance also becomes 0, which is correct. This also leads the time a print order spends in the system becoming 0 for all print scenarios.
- The lead time from the printing station being zero leads to no stock at the printing station. This is understandable. There is still stock kept further from the printing station, which is logical as demand is still larger than 0 and other lead times in the supply chain are also still larger than 0.

For a print volume of 1000

- Print times are still relatively small, but W becomes larger, which is correct. W for part 2 in AM Scenario 0 is for instance over 100000 days. Looking at Equation (4) this is correct.
- The very large lead time from the printing installation leads to 0 stock. This can be explained by the utilization of the printer $\rho = \lambda \cdot \mathbb{E}[\hat{P}_{j,n,m}]$ being above 1.0. This causes the system to keep no stock as demand can never be fulfilled.

Appendix E.5 Extreme fleet size

For a fleet size of 10,000:

- The minimal stock at Installation 3 is 0 under a readiness rate of 99.99%. This is explicable as the demand rate remains unchanged. The maximum backorders becomes larger with a large fleet, even under 99,99% readiness. If demand remains relatively small, the maximum backorders are almost never reached anyway, so no stock is a logical outcome.

For a fleet size of 0:

- The minimal stock at Installation 3 is 1 under a readiness rate of 99.99%. Again this is explicable as the demand rate remains unchanged. The maximum backorders becomes 0 with 0 fleet. If the maximum backorders are 0 but demand remains larger than zero, the system ultimately assumes stock is needed. This is therefore something the user will have to be aware of.

Appendix E.6 Extreme readiness rate output

For a readiness of 100%:

- The minimum stock required to reach a readiness of 100% is 1 part.
- Running the optimization leads to a total stock of 1 parts, which is also logical. $S_3^e = S_2^e = S_1^e = 1$. This is the same for the standard scenario as the readiness rate was already 99.99%.
- Backordering cost are 53326.07 whereas holding costs are 32.84, this is expected for a readiness rate of 100%.
- The total costs are 2628.35, the in transit costs are 22.36 and spare part costs are 525.38. This seems acceptable given the input.

For a readiness of 0%:

- The minimum stock required to reach a readiness of 0% is 0 parts.
- Running the optimization leads to a total stock of 0 parts, which is also logical. For instance, $S_3^i = S_2^i = S_1^i = 0$.
- The total costs for in transit and spare parts is €0 which is also correct based on the total stock and demand.

Appendix F. Numerical experiment parameter values

Here we give an overview of the parameters we use for the numerical experiments. As we do not change all parameter values for each numerical experiment, we use a standard set of values that is adjusted for each experiment. We use the same starting set of parameter values as described in Appendix D.

Appendix F.1 Increased demand input

Here we describe the sets of parameters that are tested in the increased demand numerical experiment.

Increased demand test A:

All demand of the identified printable (polymer) parts is summed as if all demand is for one item.

Table 16: Test 1A input

Part	L1	Vp	Lambda	Cost	Print lvl	Fleet
NE1A	3.29	2	**0.14418**	32.84	1	143

Increased demand test B:

Another test is all demand of the identified printable (polymer) parts is summed as if all demand is for one item, but we assume printed parts are not 10 times as likely to fail but only 5 times as likely.

Table 17: Test 1B input

Readiness	Increase polymer demand	Increase metal demand	L1 polymer	L1 metal
0.9999	5	1	3	7

Part	L1	Vp	Lambda	Cost	Print lvl	Fleet
NE1A	3.29	2	**0.14418**	32.84	1	143

Appendix F.2 Increased lead time input

Here we describe the sets of parameters that are tested in the increased shipment lead time numerical experiment.

Increased lead time test A:

Table 18: Test 2A input

Scenario	L2	L3	E(Y2)	E(Y3)	qU	qM	qF	qD	Intensity
NE2A	0.17	0.21	**0.31*X**	0.31	0.7	0.8	0.9	0.99	5

The expected delay at Installation 2 is multiplied by the values 5, 10, 15, 20. We go up to 20 as the RNLA estimates that delays any longer than 7 days are not possible. Multiplying by 20 the delay remains just below this 7 day maximum.

Increased lead time test B:

Table 19: Test 2B input

Scenario	L2	L3	E(Y2)	E(Y3)	qU	qM	qF	qD	Intensity
NE2B	0.17	0.21	0.31	**0.31*X**	0.7	0.8	0.9	0.99	5

The expected delay at Installation 3 is multiplied by the values 5, 10, 15, 20. We go up to 20 for the same reason as in test A.

Increased lead time test C:

Table 20: Test 3B input

Scenario	L2	L3	E(Y2)	E(Y3)	qU	qM	qF	qD	Intensity
NE2C	0.17	0.21	**0.31*X**	**0.31*X**	0.7	0.8	0.9	0.99	5

The expected delay at Installation 2 and 3 are multiplied by the values 5, 10, 15, 20. We go up to 20 for the same reason as in test A and B.

Appendix F.3 Material shortage input

Here we describe the sets of parameters that are tested in the increased raw material lead time numerical experiment.

Increased raw material lead time test A:

We test a lead time of 3 and 10 for raw material under *AM Scenario 1*. 10 days is chosen as a maximum as it is assumed that if the delay is longer than an alternative supply of raw materials will be realized.

Increased raw material lead time test B:

We test a lead time of 3 and 10 for raw material under *AM Scenario 1*. 10 days is chosen as a maximum as it is assumed that if the delay is longer than an alternative supply of raw materials will be realized.

Increased raw material lead time test C:

We test a lead time of 3 and 10 for raw material under *AM Scenario 1*. 10 days is chosen as a maximum as it is assumed that if the delay is longer than an alternative supply of raw materials will be realized.

Appendix G. Numerical experiment results

Here we give an overview of the output for the numerical experiments conducted with the software tool. The output is summarized per test. We focus on the output which is interesting for the test and anomalies in the output that have to be explained. The implications of the results are discussed in more detail in Section 7.2.

Appendix G.1 Increased demand results

For the tables given in this appendix the same notation is used as for Table 11 and Table 12 in Section 7.1. For **test 1A** we sum the demand for parts 1,2,11 and 12 as if all demand is for one item. This leads to a lambda of 0.14418 parts per day. All other parameter values are based on the standard scenario. We evaluate this for *Scenario 0* and the best performing AM scenario, which is *Scenario 1*.

Table 21: Test 1A results

	S_j^e *For combined demand*	$\hat{C}_1(y_1^*)$	C^{IT}	Total spare part costs	Total costs for policy
Scenario 0	$S_1^e = (4)$ $S_2^e = (1)$ $S_3^e = (1)$	*€193.64*	*€37.08*	*€135.36*	*€366.08*
Scenario 1	$S_{1A}^e = (19)$ $S_{1B}^e = (11)$ $S_2^e = (11)$ $S_3^e = (6)$	*€4633.16*	*€373.75*	*€6.46*	*€5013.37*

We can see from the results in Table 21 that, compared to Table 11, summing the demand for parts 1,2,11 and 12 causes slightly less stock. This is understandable as for instance part 1 and 2 require a stock of only just 1 part to reach an individual readiness of 99.99%. Aggregating the small demands for the two parts most probably leads 1 part to still be enough to reach an aggregated readiness of 99.99%. Therefore the summing of demand causes overall stocks to be slightly lower. The costs for this test are also in line with expectations.

For **Test 1B** we sum the demand for parts 1,2,11 and 12 as if all demand is for one item. We also assume printed parts are only 5 times as likely to fail. We test this for the 3 AM scenarios, but also compare performance for a regular part (part 11 in this case is selected as it represents a fairly standard part based on demand and costs) between all four scenarios. For the combined demand:

Table 22: Test 1B results

	S_j^e *For combined demand*	$\hat{C}_1(y_1^*)$	C^{IT}	Total spare part costs	Total costs for policy
Scenario 1	$S_{1A}^e = (16)$ $S_{1B}^e = (5)$ $S_2^e = (5)$ $S_3^e = (3)$	*€803.05*	*€186.87*	*€5.44*	*€995.36*
Scenario 2	$S_1^e = (9)$				

	$S_{2A}^{e} = (4)$ $S_{2B}^{e} = (3)$ $S_{3}^{e} = (3)$	*€803.52*	*€194.85*	*€3.06*	*€1001.43*
Scenario 3B **(Markforged)**	$S_{1}^{e} = (14)$ $S_{2}^{e} = (6)$ $S_{3A}^{e} = (5)$ $S_{3B}^{e} = (1)$	*€7224.07*	*€191.57*	*€4.76*	*€7420.40*

We see this significantly decreases the amount of spare parts required and the total costs. This is understandable as we have halved the demand rate for spare parts. We however still see that the stocks required and costs for the AM scenarios is significantly higher than for *Scenario 0*. This is also understandable as the demand rate for printed polymer parts is still 5 times higher than the demand rate for conventional parts. The other results for this test are also in line with expectations.

We also make the analysis for part 11 to see if the findings also hold for a fairly standard individual part:

Table 23: Test 1B results for part 11

	S_{j}^{e} *Part: (11)*	$\hat{C}_1(y_1^*)$	C^{IT}	Total spare part costs	Total costs for policy
Scenario 0	$S_{1}^{e} = (2)$ $S_{2}^{e} = (1)$ $S_{3}^{e} = (1)$	*€171.59*	*€16.06*	*€65.68*	*€253.33*
Scenario 1	$S_{1A}^{e} = (7)$ $S_{1B}^{e} = (2)$ $S_{2}^{e} = (2)$ $S_{3}^{e} = (1)$	*€422.29*	*€80.85*	*€2.38*	*€505.52*
Scenario 2	$S_{1}^{e} = (5)$ $S_{2A}^{e} = (1)$ $S_{2B}^{e} = (1)$ $S_{3}^{e} = (1)$	*€351.65*	*€84.39*	*€1.70*	*€437.74*
Scenario 3B **(Markforged)**	$S_{1}^{e} = (13)$ $S_{2}^{e} = (4)$ $S_{3A}^{e} = (4)$ $S_{3B}^{e} = (1)$	*€2756.72*	*€82.53*	*€15.28*	*€2854.53*

As expected we see similar results for an individual part as for the combined demand. The difference is less noticeable. This is to be expected as the demand for an individual spare part is lower than the combined demand, leading the required stock to also be less. The decrease in required stock by decreasing the demand is therefore also less. The costs for this test are also in line with expectations.

Appendix G.2 Increased lead time results

The expected delay at Installation 2 is multiplied by the values 5, 10, 15, 20. We test this for *Scenario 0 and Scenario 1* as these are the best performing scenarios from the scenario analysis. The results for **test 2A** on Scenario 0 are:

Table 24: Test 2A results for Scenario 0

	S_j^e *Part: (11)*	$\hat{C}_1(y_1^*)$	C^{IT}	Total spare part costs	Total costs for policy
Scenario 0 L2*5	$S_1^e = (3)$ $S_2^e = (1)$ $S_3^e = (1)$	*€211.51*	*€29.16*	*€98.52*	*€339.19*
Scenario 0 L2*10	$S_1^e = (3)$ $S_2^e = (2)$ $S_3^e = (1)$	*€247.79*	*€45.54*	*€98.52*	*€391.85*
Scenario 0 L2*15	$S_1^e = (4)$ $S_2^e = (3)$ $S_3^e = (1)$	*€285.77*	*€61.92*	*€131.36*	*€479.05*
Scenario 0 L2*20	$S_1^e = (4)$ $S_2^e = (3)$ $S_3^e = (1)$	*€319.43*	*€78.30*	*€131.36*	*€529.09*

We see that the more the demand is increased, the more stock and costs are required. The differences in stock and costs also scale in a fairly linear way with the increase in demand rate. These results are as expected. For Scenario 1, we only review the effect of the multiplier 5. This since we only want to compare the increase for Scenario 1 with Scenario 0. One multiplier is sufficient for this as the increase in stock and costs is linear with the increase in demand rate. We chose 5, as increasing the demand further is noted as unrealistic by RNLA experts. The results are:

Table 25: Test 2A results for Scenario 1

	S_j^e *Part: (11)*	$\hat{C}_1(y_1^*)$	C^{IT}	Total spare part costs	Total costs for policy
Scenario 1 L2*5	$S_{1A}^e = (10)$ $S_{1B}^e = (8)$ $S_2^e = (8)$ $S_3^e = (2)$	*€1259.68*	*€102.85*	*€3.40*	*€1365.93*

As expected we see similar increases in stock for *Scenario 1* as for *Scenario 0*. The costs for this test are also in line with the increase in costs and therefore understandable.

The expected delay at Installation 3 is multiplied by the values 5, 10, 15, 20. We test this for *Scenario 0 and Scenario 1* as these are the best performing scenarios from the scenario analysis. The results for **test 2B** on Scenario 0 are:

Table 26: Test 2B results for Scenario 0

	S_j^e *Part: (11)*	$\hat{C}_1(y_1^*)$	C^{IT}	Total spare part costs	Total costs for policy
Scenario 0 L3*5	$S_1^e = (2)$ $S_2^e = (1)$ $S_3^e = (1)$	*€140.30*	*€42.27*	*€65.68*	*€248.25*
Scenario 0 L3*10	$S_1^e = (2)$ $S_2^e = (2)$ $S_3^e = (2)$	*€178.41*	*€75.02*	*€65.68*	*€319.11*
Scenario 0 L3*15	$S_1^e = (3)$ $S_2^e = (2)$ $S_3^e = (2)$	*€207.02*	*€107.78*	*€98.52*	*€413.32*
Scenario 0 L3*20	$S_1^e = (3)$ $S_2^e = (3)$ $S_3^e = (3)$	*€237.36*	*€140.53*	*€98.52*	*€476.41*

We see that the more the demand is increased the more stock and costs are required. The differences in stock and costs also scale in a fairly linear way with the increase in demand rate. These results are as expected. We also see that the effect of the increase for the lead time to installation 3 is less significant than the effect in test 2A. This can be explained by the fact that the required stock at the most downstream location is low due to the small demand rate. It is also mainly dictated by the required readiness. This might also be explained by the fact that the lead time for Installation 2 is longer and is therefore affected more by the increase in delay.

For Scenario 1, we only review the effect of the multiplier 5 under the same logic as for test 2A. The results are:

Table 27: Test 2B results for Scenario 1

	S_j^e *Part: (11)*	$\hat{C}_1(y_1^*)$	C^{IT}	Total spare part costs	Total costs for policy
Scenario 1 L3*5	$S_{1A}^e = (16)$ $S_{1B}^e = (14)$ $S_2^e = (14)$ $S_3^e = (11)$	*€2015.49*	*€164.56*	*€5.44*	*€2185.49*

We see a higher increases in stock for *Scenario 1* as for *Scenario 0*. The increase is also more significant than the increase in Test 2A. This can be explained the increased demand for AM parts having an inflated effect on the stock kept at installation 3 due to the increase lead time.

The expected delay at Installation 2 and 3 is multiplied by the values 5, 10, 15, 20. We test this for *Scenario 0 and Scenario 1* as these are the best performing scenarios from the scenario analysis. The results for **test 2C** on Scenario 0 are:

Table 28: Test 2C results for Scenario 0

	S_j^e *Part: (11)*	$\hat{C}_1(y_1^*)$	C^{IT}	Total spare part costs	Total costs for policy
Scenario 0 **L2*5** **L3*5**	$S_1^e = (2)$ $S_2^e = (1)$ $S_3^e = (1)$	*€167.11*	*€55.37*	*€65.68*	*€288.16*
Scenario 0 **L2*10** **L3*10**	$S_1^e = (3)$ $S_2^e = (2)$ $S_3^e = (2)$	*€228.30*	*€104.50*	*€98.52*	*€431.32*
Scenario 0 **L2*15** **L3*15**	$S_1^e = (4)$ $S_2^e = (3)$ $S_3^e = (2)$	*€287.76*	*€153.63*	*€131.36*	*€572.75*
Scenario 0 **L2*20** **L3*20**	$S_1^e = (5)$ $S_2^e = (4)$ $S_3^e = (3)$	*€339.43*	*€202.77*	*€164.20*	*€706.40*

We see that the more the demand is increased the more stock and costs are required. The differences in stock and costs also scale in a fairly linear way with the increase in demand rate. These results are as expected. We also see that the effect of a small increase of both the lead time to installation 2 and installation 3 is less significant than the effect in tests 2A. The even distribution of lead times along the supply chain might have a dampening effect on the increased lead times. The effects in tests 2A and 2B can then be attributed to installations becoming bottlenecks and causing a more significant increase in the required stock.

For Scenario 1, we only review the effect of the multiplier 5 under the same logic as for test 2A and 2B. The results are:

Table 29: Test 2C results for Scenario 1

	S_j^e *Part: (11)*	$\hat{C}_1(y_1^*)$	C^{IT}	Total spare part costs	Total costs for policy
Scenario 1 **L2*5** **L3*5**	$S_{1A}^e = (16)$ $S_{1B}^e = (14)$ $S_2^e = (14)$ $S_3^e = (11)$	*€3423.75*	*€208.85*	*€2.38*	*€505.52*

We see a higher increases in stock for *Scenario 1* as for *Scenario 0*. The increase is also more significant than the increase in Test 2A. Similar to test 2B for *Scenario 1,* this can be explained the increased demand for AM parts having an inflated effect on the stock kept at installation 3 due to the increase lead time.

Appendix G.3 Material shortage results

For test 3A, we test a lead time of 3 and 10 for raw material under AM Scenario 1. A lead time of 3 days is the standard situation. The results for part 11 to compare to the standard situation are:

Table 30: Test 3A results

	S_j^e *Part: (11)*	$\hat{C}_1(y_1^*)$	C^{IT}	Total spare part costs	Total costs for policy
Scenario 1 **L1 = 10**	$S_{1A}^e = (10)$ $S_{1B}^e = (4)$ $S_2^e = (4)$ $S_3^e = (2)$	*€3330.69*	*€161.71*	*€3.40*	*€3495.80*

As expected an increase in the lead time for raw materials also leads to an increase in stocks to reach the required readiness. The increase in costs is also in proportion to the increased stocks. We therefore deem these results to be as expected.

For test 3B, we test a lead time of 3 and 10 for raw material under AM Scenario 2. A lead time of 3 days is the standard situation. The results for part 11 to compare to the standard situation are:

Table 31: Test 3B results

	S_j^e *Part: (11)*	$\hat{C}_1(y_1^*)$	C^{IT}	Total spare part costs	Total costs for policy
Scenario 2 **L1 = 10**	$S_1^e = (14)$ $S_{2A}^e = (3)$ $S_{2B}^e = (2)$ $S_3^e = (2)$	*€1007.80*	*€168.79*	*€4.76*	*€1173.55*

As expected an increase in the lead time for raw materials also leads to an increase in stocks to reach the required readiness for *Scenario 2*. The increase in costs is also in proportion to the increased stocks. The effect of the increased lead time is more significant than for *Scenario 1*. This is understandable as the print success probability is lower, and demand for raw materials therefore higher. This increases the effect of material shortages on the required stocks.

For test 3C, we test a lead time of 3 and 10 for raw material under AM Scenario 3. A lead time of 3 days is the standard situation. The results for part 11 to compare to the standard situation are:

Table 32: Test 3C results

	S_j^e *Part: (11)*	$\hat{C}_1(y_1^*)$	C^{IT}	Total spare part costs	Total costs for policy
Scenario 3B **L1 = 10**	$S_1^e = (24)$ $S_2^e = (5)$ $S_{3A}^e = (5)$ $S_{3B}^e = (1)$	*€28490.19*	*€165.95*	*€8.16*	*€28664.30*

As expected an increase in the lead time for raw materials also leads to an increase in stocks to reach the required readiness for *Scenario 3*. The increase in costs is also in proportion to the increased stocks. The effect of the increased lead time is more significant than for *Scenario 1* and *Scenario 2*. This is understandable as the print success probability is even lower for *Scenario 3*, and demand for raw materials therefore even higher. This increases the effect of material shortages on the required stocks even more.