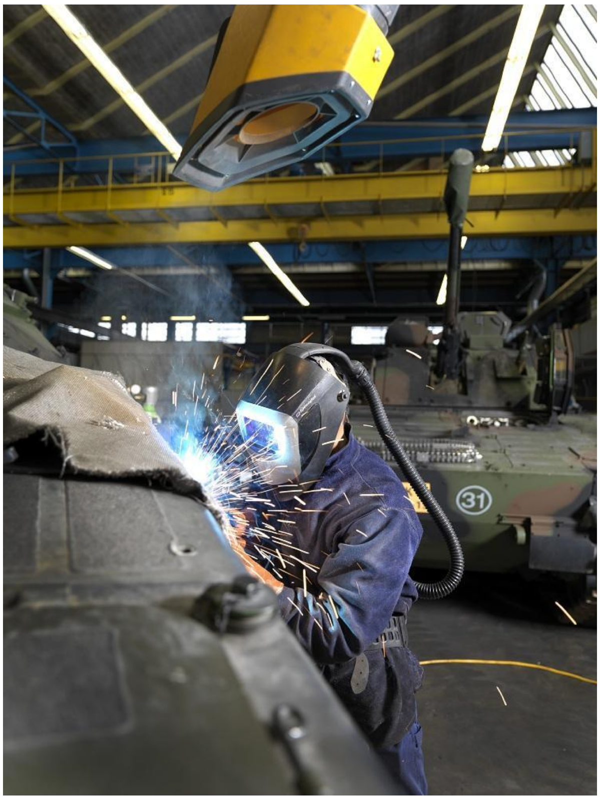

POTENTIAL OF ADDITIVE MANUFACTURING IN THE AFTER-SALES SERVICE SUPPLY CHAINS OF GROUND BASED MILITARY SYSTEMS

BSc Graduation Assignment – Final report

ABSTRACT

In this report, the potential of the application of Additive Manufacturing, also popularly known as 3D printing, within the Armed Forces of the Netherlands to print spare parts of ground based systems has been investigated and quantified by successfully identifying promising spare parts.

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BSc graduation assignment Industrial Engineering & Management
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On behalf of the Ministry of Defence (MinDef) /
the Royal Netherlands Army (RNLA) /
Army Maintenance and Logistics Command (MatLogCo) /
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As part of the research project "Sustainability Impact of New Technology on After-sales service Supply chains" (SINTAS)

"Potential of Additive Manufacturing in the after-sales service supply chains of ground based military systems"

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PREFACE

This graduation assignment is part of my Bachelor "Technische Bedrijfskunde (in English: Industrial Engineering and Management)" at the University of Twente in Enschede, the Netherlands. I started the assignment in March.

The graduation assignment is part of the SINTAS-project and one out of several performed Quick Scans.

I would like to thank many people for their help during this graduation assignment.
First of all, I would like to thank Dr. M.C. van der Heijden as the project leader of SINTAS for giving me the opportunity to perform one of the Quick Scans. Furthermore, I would like to thank MSc. N. Knofius as the PhD-student of one of the Work Packages within the SINTAS-project for giving me the opportunity to use the framework he created in order to perform the spare part analysis, as well as for all the help and feedback during the assignment. Both Dr. M.C. van der Heijden as well as MSc. N. Knofius always responded quickly when I had questions or in case I needed advice.

Consequently, I would like to thank Ir. D. Maatman for giving me the opportunity to perform the Quick Scan at the Royal Netherlands Army (RNLA) and also for all the help and feedback during the project. I would like to thank my other supervisor within MatLogCo as well, namely Ing. Van der Horst. The conversations concerning the actual printability of parts as well as the application of AM within the after-sales service supply chain of the RNLA have proven to be very helpful.

I have learned more about Additive Manufacturing (AM) than I expected beforehand. I learned not only about this technology from literature and interviews, but also by attending and participating in several meetings concerning AM within the SINTAS project as well as within the Armed Forces of the Netherlands.

Next to the technology, I also learned a lot about the maintenance and damage repair policy as well as the RNLA itself. It has been amazing to not only have interesting conversations about maintenance, security, threats, history, military systems and the unique organizational environment, but also to hear the many impressive experiences of (former) soldiers and civilians within the RNLA.

Furthermore, I would like to thank the people at the Systems & Analysis (S&A) Department for helping me in order to gather the necessary spare part data.
Finally, I would like to thank all employees within the RNLA and mainly within the Army Depot Level Maintenance Workshop that helped me during the assignment. Without the received help, it would have been substantially more difficult (if not impossible) to understand the unique organizational structure, the after-sales service supply chain, the spare part assortments and the ERP-system of the RNLA.

Gino Balistreri

Enschede, July 2015

EXECUTIVE SUMMARY

Nowadays, one of the new, rapidly developing technologies is Additive Manufacturing (AM), also popularly known as 3D-printing. The Army Maintenance and Logistics Command (MatLogCo) would like to know what the possibilities are for the Royal Netherlands Army (RNLA) of applying AM to print spare parts of ground based military systems that are used during maintenance or damage repair., given its possible logistical and economic advantages compared to conventional manufacturing techniques. In order to quantify this, a general framework is applied as a basis in order to perform a scoring procedure of the spare part assortment and to obtain the promising spare parts.
First, a model of the after-sales service supply chain of the RNLA is created in order to identify the several warehouses, suppliers, end-users and the corresponding item flow.

Opportunities of AM in the after-sales service supply chain

The opportunities in the after-sales service supply chain of organizations in the Defense industry are identified by means of a literature study. In the Maintenance, Repair and Overhaul (MRO)-process, the following opportunities are identified:

- By enabling the on-demand manufacture of a required part, it significantly improves the ability to respond to demand variability in the MRO-process;
- It minimizes the need to carry (excess) inventories in the MRO-process;
- The accumulated effects of the above-mentioned benefits will have a positive impact on the throughput during the repair stage of the MRO-process.

The history of experiments with AM and the actual application of additively manufactured parts within the United States Armed Forces (U.S. Forces) goes back to the 1990s. Therefore, the AFN needs to analyze the applications of AM by the Department of Defense (DoD). The most important applications of AM within the U.S. Forces are identified.

Scoring procedure method

The final set of criteria that is used in the spare part analysis is illustrated in Table 1.

Technological category *(exclusive)*	Logistical category *(weighting)*	Economic category *(weighting)*
Material (s)	Average annual usage	Purchasing cost
Dimension	Resupply lead time	Average days in inventory on hand
Complexity	Item in initial lifecycle phase	Design ownership
	ELOT-item	

Table 1. All relevant characteristics based on the organizational environment of the RNLA as well as the spare part data quality

The logistical and economic criteria that will be used during the spare part analysis are assigned to three identified company goals. These goals represent the benefits that the RNLA hopes to achieve by implementing AM in the after-sales service supply chain. The most important goal is to secure the supply of spare parts, followed by respectively improving service and reducing costs. In fact, AM could significantly improve service at the RNLA by drastically reducing the resupply lead time.

The analyzed data is not fully representative, because a fraction of the slow movers was supposed to move through the spare part supply chain in the considered period, but for some reason did not move at all.

Results

In total, 11944 spare parts are analyzed. These parts are assigned to six applied categories, as illustrated In Table 2. As can be seen, there is no logistical or economic incentive to consider AM as an alternative production method for around 50 % of the spare part assortment.
The overall potential of AM within the after-sales service supply chain of the RNLA is quantified by means of the average part score of all not-excluded parts, which is 0.61.
Finally, 2384 promising parts are identified. This corresponds with approximately 20 % of the analyzed spare part pool. 175 of these parts are considered to be very promising. For only 15-30 % % of these very promising parts, it might be technically feasible to manufacture these parts with AM.

Category	Potential of AM	Range (scores)	Number of unique spare parts	Percentage of total amount of spare parts
Category 1	None	Excluded parts (NO-GO)	5924	49.6
Category 2	Relatively very low	0.00 – 0.25	34	0.0
Category 3	Relatively low	0.25 – 0.50	2590	21.7
Category 4	Around average	0.50 – 0.75	1012	8.5
Category 5	Relatively high	0.75 – 0.85	2209	18.5
Category 6	Relatively very high	≥ 0.85	175	1.5

Table 2. Number of unique spare parts assigned to each applied category.

Recommendations

Further research is advised to be done, in which business cases can be made in order to come up with the actual printability and the expected gains of printing the (very) promising spare parts.
In addition, MatLogCo needs to actively track the technological development of AM closely, as well as the application of AM within the U.S. Forces. Also, the availability of spare parts needs to monitored closely, especially for system types that will reach their initial ELOT on the short term. Currently, the steps necessary for approval of an additively manufactured part to be used for the maintenance and/or damage repair of ground based (weapon) systems are unknown within MatLogCo and need to be identified. Moreover, the purchasing strategy needs to be revised, since for around 35% of the analyzed spare parts, there is more than approximately 10 years of inventory on hand. Finally, the Quick Scan should be repeated in the near future in order to analyze more data and more representative data. MatLogCo needs to be aware that the data gathering step for the Quick Scan is likely to take a significant amount of time as well.

MANAGEMENTSAMENVATTING

Eén van de snelst ontwikkelende technologieën gedurende de laatste jaren is Additive Manufacturing (AM), ook wel bekend als 3D-printing. Het Materieellogistiek Commando Land (MatLogCo) zou graag willen weten wat de mogelijkheden zijn van het toepassen van deze technologie binnen het Commando Landstrijdkrachten (CLAS) om reservedelen van grondgebonden militaire systemen te printen. Het betreft reservedelen die worden verbruikt tijdens onderhoud en schadeherstel. De mogelijke logistieke en economische voordelen van AM, in vergelijking met conventionele productiemethoden. dienen hierbij in acht te worden genomen. Om de potentie van AM binnen CLAS te kwantificeren, is een algemeen kader toegepast als een basis voor het toewijzen van scores aan de onderdelen met als resultaat de (zeer) veelbelovende reservedelen.
Allereerst is een model van de after-sales service supply chain van CLAS opgesteld om de verschillende depots, leveranciers, eindgebruikers en de onderdelenstromen in kaart te brengen.

Mogelijkheden van AM in de after-sales service supply chain

De mogelijkheden in de after-sales service supply chain voor organisaties in de Defensie-industrie zijn onderzocht door middel van een literatuurstudie. In het Onderhoud, Reparatie en Revisie (in het Engels: “Maintenance, Repair and Overhaul (MRO)”)-proces zijn de volgende mogelijkheden geïdentificeerd:

- Door “on-demand” fabricage van een benodigd onderdeel, neemt de mogelijkheid om te reageren op variabiliteit van de vraag aanzienlijk toe;
- Het neemt de noodzaak weg om (teveel) voorraad te houden in het MRO-proces;
- De geaccumuleerde effecten van bovengenoemde voordelen zal een positieve impact hebben op de doorzet van reparaties.

De Krijgsmacht van de Verenigde Staten (in het Engels: “United States Armed Forces”) experimenteert al sinds 1990 met AM en past onderdelen die zijn gefabriceerd door middel van deze technologie al vele jaren toe. De Nederlandse Krijgsmacht dient deze toepassingen te analyseren. De belangrijkste toepassingen zijn vermeld in dit rapport.

Methode van toewijzing scores

De criteria die zullen worden toegepast gedurende de analyse van de reservedelen zijn weergegeven in Tabel 1.

Technologische categorie *(uitsluitend)*	Logistieke categorie *(gewogen)*	Economische categorie *(gewogen)*
Materialen	Gemiddeld jaarverbruik	Aanschafkosten
Dimensie	Levertijd van herbevoorrading	Gemiddeld aantal dagen aan voorraad
Complexiteit	Onderdeel in initiële fase van de levenscyclus ELOT-onderdeel	Bezit van ontwerp

Tabel 1. Een overzicht van alle relevante criteria voor CLAS, gegeven de organisatie en de kwaliteit van de reservedelen-data.

De logistieke en economische criteria die zullen worden toegepast in de analyse van de reservedelen zijn toegewezen aan drie doelen. Deze doelen corresponderen met de voordelen die CLAS hoopt te bereiken door middel van het implementeren van AM in de logistieke keten van reservedelen.

Het belangrijkste doel is het veiligstellen van de levering van reservedelen, gevolgd door respectievelijk het verbeteren van de service en het reduceren van de totale kosten. In werkelijkheid zou AM de service binnen CLAS aanzienlijk kunnen verbeteren door het drastisch reduceren van de huidige (herbevoorradings)levertijden.

De geanalyseerde data is niet geheel representatief, omdat er om uiteenlopende redenen geen gebruik kon worden gemaakt van een fractie van de slow movers in de periode van drie jaar.

Resultaten

In totaal zijn 11944 reservedelen geanalyseerd. Deze reservedelen zijn toegewezen aan zes categorieën en de resultaten hiervan zijn weergegeven in Tabel 2. Er is geen enkele logistieke en/of economische reden om AM te beschouwen als een alternatieve productiemethode voor circa 50 procent van het reservedelen-assortiment.
De algehele potentie van AM in de after-sales service supply chain van CLAS is gekwantificeerd door middel van een gemiddelde score van alle niet-uitgesloten onderdelen: 0.61.
In totaal worden 2384 onderdelen beschouwd als veelbelovend. Dit komt overeen met circa 20 procent van het totale geanalyseerde assortiment van reservedelen. 175 reservedelen hiervan wordt beschouwd als zeer veelbelovend. Na het uitsluiten van zeer veelbelovende onderdelen op basis van de technologische criteria, blijkt dat ongeveer 15-30 procent van deze onderdelen ook daadwerkelijk te produceren zou kunnen zijn door middel van AM.

Categorie	Potentie van AM	Bereik (scores)	Aantal unieke reserevedelen	Percentage van het totale aantal unieke reservedelen
Categorie 1	Geen	Uitgesloten (NO-GO)	5924	49.6
Categorie 2	Relatief zeer laag	0.00 – 0.25	34	0.0
Categorie 3	Relatief laag	0.25 – 0.50	2590	21.7
Categorie 4	Rond gemiddelde	0.50 – 0.75	1012	8.5
Categorie 5	Relatief hoog	0.75 – 0.85	2209	18.5
Categorie 6	Relatief zeer hoog	≥ 0.85	175	1.5

Tabel 2. Aantal unieke reservedelen toegewezen per categorie

Aanbevelingen

Aanvullend onderzoek is aanbevolen, waarbij businesscases dienen te worden opgesteld om de daadwerkelijke printbaarheid en de verwachte voordelen van het printen van de (zeer) veelbelovende reservedelen exact in kaart te brengen.
Verder dient MatLogCo de technologische ontwikkelingen van AM actief in de gaten te houden, net als de toepassingen van deze technologie binnen de United States Armed Forces. Daarnaast dient de beschikbaarheid van reservedelen actief te worden gecontroleerd, met name voor systeemtypen waarvan op korte termijn de initiële ELOT zal worden bereikt.
De noodzakelijke stappen om een onderdeel dat is gefabriceerd door middel van AM goed te laten keuren voor gebruik tijdens onderhoud en/of schadeherstel van grondgebonden militaire systemen zijn op dit moment onduidelijk binnen MatLogCo. Deze stappen dienen dan ook helder in kaart te worden gebracht.
Daarnaast is het aanbevolen om de inkoopstrategie te herzien, aangezien voor circa 35 procent van de geanalyseerde reservedelen er voor meer dan 10 jaar aan gemiddelde voorraad aanwezig is.

Tenslotte dient de Quick Scan herhaald te worden in de nabije toekomst om zo meer data en meer representatieve data te analyseren. MatLogCo dient zich bewust te zijn van het feit dat het verzamelen van de data ook voor onderzoeken in de nabije toekomst een aanzienlijke hoeveelheid tijd zal kosten.

TABLE OF CONTENTS

GLOSSARY OF TECHNICAL TERMS

After-sales service supply chain	Supply chain of spare parts needed for maintenance & servicing of advanced capital goods
(Ground based) system	In this report: ground based vehicle

GLOSSARY OF ABBREVIATIONS

AM	Additive Manufacturing
AFN	Armed Forces of the Netherlands
AHP	Analytic Hierarchy Process
BU	Business Unit (In Dutch: “Producteenheid”)
DLM	Depot Level Maintenance
DoD	Department of Defense
ELOT	End Life of Type
ILM	Intermediate Level Maintenance
MatLogCo	Army Maintenance and Logistics Command (in Dutch: “Materieellogistiek Commando Land”)
MinDef	Ministry of Defence
OEM	Original Equipment Manufacturer
OLM	Organic Level Maintenance
RNLA	Royal Netherlands Army (in Dutch: “Commando Landstrijdkrachten (CLAS)”)
SINTAS	Sustainability Impact of New Technology on After-sales service Supply chains

CHAPTER 1 – INTRODUCTION

1.1 The host organisation – Army Maintenance and Logistics Command

For many years, the Army Maintenance and Logistics Command (MatLogCo) is responsible for the maintenance of almost all ground based systems of the Armed Forces of the Netherlands (AFN). 1300 employees are divided into four different departments and one staff group. The importance is clear: the organisation has a crucial role in maintaining the high quality level of the ground based systems.

Figure 1-1. *Insignia of MatLogCo (Ministry of Defence)*

The insignia of the organisation shows a gear wheel and four connected components. Together they symbolize the capacities of MatLogCo in the fields of technique and supply chains. The sword is pointed to the ground, in order to show that MatLogCo is a logistical unit of the RNLA. The soldiers are armed, but the most important task is the support of the combat units. The illustrated blue shade, named Nassau blue, is the international colour in the field of Logistics.

MatLogCo does not organize the after-sales service supply chains of all the system types. For example, it normally does not perform the maintenance of the ground based systems of the Royal Netherlands Air Force (RNLAF). It does however perform the maintenance of all the ground based system types of the RNLA and of some of the ground based system types of the Royal Netherlands Navy (RNLN) and the Royal Netherlands Marechaussee (RNM).

Maintenance levels

The maintenance is divided into different levels. For every system, ILM needs to be performed once every a year. It includes all the maintenance and damage repair that can be done without dismantling the system or components. For example, the replacement of an oil filter or even a complete engine are part of ILM. However, the broken engine will be dismantled and repaired at the next level of maintenance, DLM.
Next to ILM and DLM, there is one more level of maintenance used by the AFN. Organic Level Maintenance (OLM) is the lowest applied level of maintenance and is performed by the units itself. Practically, this includes all maintenance and damage repair that can be done by themselves. For example, the change of a flat tire is part of OLM.

1.1.1 Army Depot Level Maintenance Workshop

The host organisation of this research is the Army Depot Level Maintenance Workshop, which is part of MatLogCo and is located in Leusden, the Netherlands. The highest applied level of maintenance, DLM, is being performed here and is performed on a system every few years. The main task consists of the corrective and preventive maintenance of ground based systems as well as system components. For most of the system types, the exact cycle of DLM is about 5 years. A fraction of this level of maintenance is outsourced to civil companies and supervised and supported by the department. The insourced DLM is always performed by the host organisation. When DLM is performed on a system, normally ILM is performed on the particular system at the same time as well.

The organisation chart of the Army Depot Level Maintenance Workshop is illustrated in Appendix A (Commercial in Confidence).

Next to the preventive maintenance, component recovery (e.g. engine repair), system recovery (e.g. corrective maintenance) and system modifications are also part of DLM. Furthermore the department is able to provide technical expertise and support during military operations, handles the inflow guidance of new products and is able to carry out product verifications.

BU Technology

This assignment was executed on behalf of the Business Unit (BU) Technology. This BU conducts the research, testing and inflow guidance of ground based systems. Furthermore, the BU designs and develops product adjustments and continuously needs to investigate technological and technical developments concerning ground based systems to be aware of the applications of modern technologies. The BU Technology exists of a staff group and the clusters Engineering, Systems and Sub-systems.

1.1.2 Other departments

The **staff group** coordinates and supports all processes that contribute to the availability and maintenance of all the ground based systems of the AFN. The staff group is located in Utrecht.
The **Systems & Analysis** (S&A) **Department** is located in Utrecht as well. At this department, analyses are performed to get an impression of the current and future performance and costs of the currently used ground based systems and those to be used in the future.
The **Logistics Department** is not only located in Utrecht, but in Lettele, Steenwijk, Soesterberg and Stroe as well. The department has several main tasks. The relevant ones for this research are the following:

- The supply of spare parts to the Army Maintenance and Logistics Command and to the operational forces, in time of peace as well as in time of war;
- Optimization of the supply during the complete lifecycle of systems through Assortment Management;
- Management of maintenance contracts of system types;
- Review and if possible approve Requests To Order (ATB's; in Dutch: "Aanvragen Tot Behoeftevervulling") concerning system parts;
- Physical distribution of spare parts.

Finally, the **300 Material Logistics Company** (300 MatLogCie) is located at several locations in the Netherlands and has several main tasks. For this research, the relevant main task is the performance of Intermediate Level Maintenance (ILM) for all the system types of which ILM is being insourced.

1.2 Indication of the problem

Nowadays, one of the new, rapidly developing technologies is Additive Manufacturing (AM), also popularly known as 3D printing. Canalys (2014) predicts that the size of the market, including 3D printer sales, materials and associated services, will rise from 2,5 billion US dollars in 2013 to 16,2 billion US dollars by 2018.

Since one of the tasks of Business Unit Technology is to research the applications of new technologies concerning the maintenance of ground based systems, it needs to focus on the potential application of AM as well.

AM is not new within the RNLA. Recently, a 3D printer has been purchased and facilitated at another location. It is mainly used to experiment with printing parts made of plastics. Next to that, the organisation would like to know what the possibilities are of applying AM for printing spare parts of systems. It concerns a wide range of different spare parts with different specifications.

When investigating the possibilities of applying this new technology, the main advantages of AM need to be known. Next to that, since the current spare part pool consists of tens of thousands of spare parts, a significant amount of time is needed to investigate the relevant parts. When the wrong method or the wrong criteria are used in the analysis, the results could contain spare parts that are not suitable for AM at all. Also, the research could become impossible to conduct because far too much time is needed to investigate all the parts. Since they lack the knowledge to investigate the current spare part pool by using a suitable method and suitable criteria, they will need external knowledge to investigate the potential of AM in their after-sales service supply chains.

In the Defence industry, lead times of spare parts of several months or even a whole year are not uncommon. Because of these long lead times, the purchase of these parts needs to be arranged intensively in order to still receive the spare parts when needed. The uncertainty of delivery problems and spare part failure make it even more complicated to be able to use the required spare parts on time. This makes it very interesting to investigate the opportunities of AM, since it has the potential to completely redesign the after-sales service supply chains.
Especially parts with a long lead time and a low demand rate seem interesting to be investigated, since it might not be economically relevant to keep manufacturing those parts by using conventional methods instead of AM.
An eventual shortage of spare parts could have dramatic effects for the RNLA. A shortage could lead to the situation where not all the required maintenance and damage repair can be conducted anymore, which then again could result in declining availability percentages of system types.
To prevent an eventual shortage of parts of which the lead times are long and/or the transportation cost are high, companies often start to stock these parts excessively.
Consequently, the general applicability of AM, given its possible logistical and economic advantages compared to conventional manufacturing techniques, needs to be investigated to minimize those risks.

1.3 Purpose

Based on the problem indication and the problem statement, the following purpose of this research can be described:

"The purpose of this research is to investigate and quantify the potential of the application of AM within the AFN to print spare parts of ground based systems, by identifying spare parts out of the spare part assortment of each of these systems by means of an extensive evaluation that will result in a significant logistical and/or economic improvement when manufactured by AM, given the advantages and feasibility of this technology."

1.4 Research Questions

Based on the problem indication, the problem statement as well as the research purpose, the research questions can be formulated. First, the main research question will be given, followed by an overview of all the formulated sub questions.

1.4.1 Main research question

"What is the potential of the application of AM within the AFN to print spare parts of ground based systems, given the significant logistical and economic improvement that can be achieved and the technological feasibility?"

1.4.2 Sub questions

1. **How do the after-sales service supply chains of the relevant system types function?**
2. **Which logistical and economic opportunities of applying AM in the after-sales service supply chains of the relevant system types can be identified?**
3. **What is the most suitable framework to be applied in order to successfully obtain the most promising spare parts?**
4. **How can the potential successfully be obtained?**
    - 4.1 Which set of criteria need to be applied?
    - 4.2 From which period can spare part data be retrieved?
    - 4.3 Which modifications need to be made to the method based on the data quality?
5. **What is the potential of AM in the considered after-sales service supply chain?**
    - 5.1 What is the overall potential of AM?
    - 5.2 What are the categorized results of the scoring procedure of the relevant scope of spare parts?

1.5 Demarcation

In this research, the following demarcations are applied:

- Only the after-sales service supply chains of ground based systems that are (partly) organized by MatLogCo will be considered;
- Spare parts used during outsourced maintenance will not be investigated;
- The opportunities of reducing the bill of material complexity by merging components will not be considered;
- Life Cycle Costs Analyses (LCCA's) of system types will not be considered.
- The many platoons within the RNLA that use the military systems can always be seen as operational; if there is no mission, the platoon will participate in drills. The spare parts sent to operations abroad are not considered, since these are sent at the start of the mission (along with the system types) and in principle, it is not part of protocol to send more spare parts. The spare part assortment that is sent along with the system types include all the parts that the particular platoon(s) in principle is allowed to use.

1.6 Methodology

To quantify the potential of the relevant scope of spare parts, an appropriate framework will be used. At the moment of writing, only a few frameworks are developed to select spare parts that are suitable for AM. A literature study needs to be performed to select the most suitable framework.

In every chapter, one research question will be answered.
In Chapter 2, the after-sales service supply chain of the RNLA is described.
In Chapter 3, the logistical and economic opportunities of AM in the after-sales service supply chain of the RNLA are identified.
In Chapter 4, the most suitable framework to be applied in this research is identified.
In Chapter 5, the method of obtaining the potential of AM within the RNLA is described.
Furthermore, in Chapter 6, the results of this research are given.
Finally, Chapter 7 contains the conclusion, the recommendations and the limitations of this research.

CHAPTER 2 – THE AFTER-SALES SERVICE SUPPLY CHAIN OF THE RNLA

In order to successfully identify the opportunities of Additive Manufacturing (AM) in the after-sales supply chain of the Royal Netherlands Army (RNLA), the supply chain needs to be described. The several applied maintenance levels are explained in Appendix B.

First, the military ground based (weapon) system types of which the Army Maintenance and Logistics Command (MatLogCo) organizes (at least a part of) the after-sales service supply chain are given in Appendix C. All of the mentioned system types are currently in use by the operational forces of each of the service branches of the Armed Forces of the Netherlands (AFN). In Figure 2-1, one of the most prominent military ground based weapon systems currently in use is illustrated, the Fennek.

Figure 2-1. *The Fennek LVB. Source: Dutch Defense Vehicle Systems*

Second, in order to successfully describe the after-sales service supply chain, a model of the after-sales is created during this research. The model does not include the information flow and is illustrated in Figure 2-2. A model of the after-sales service supply chain including the information flow is given in Appendix E.

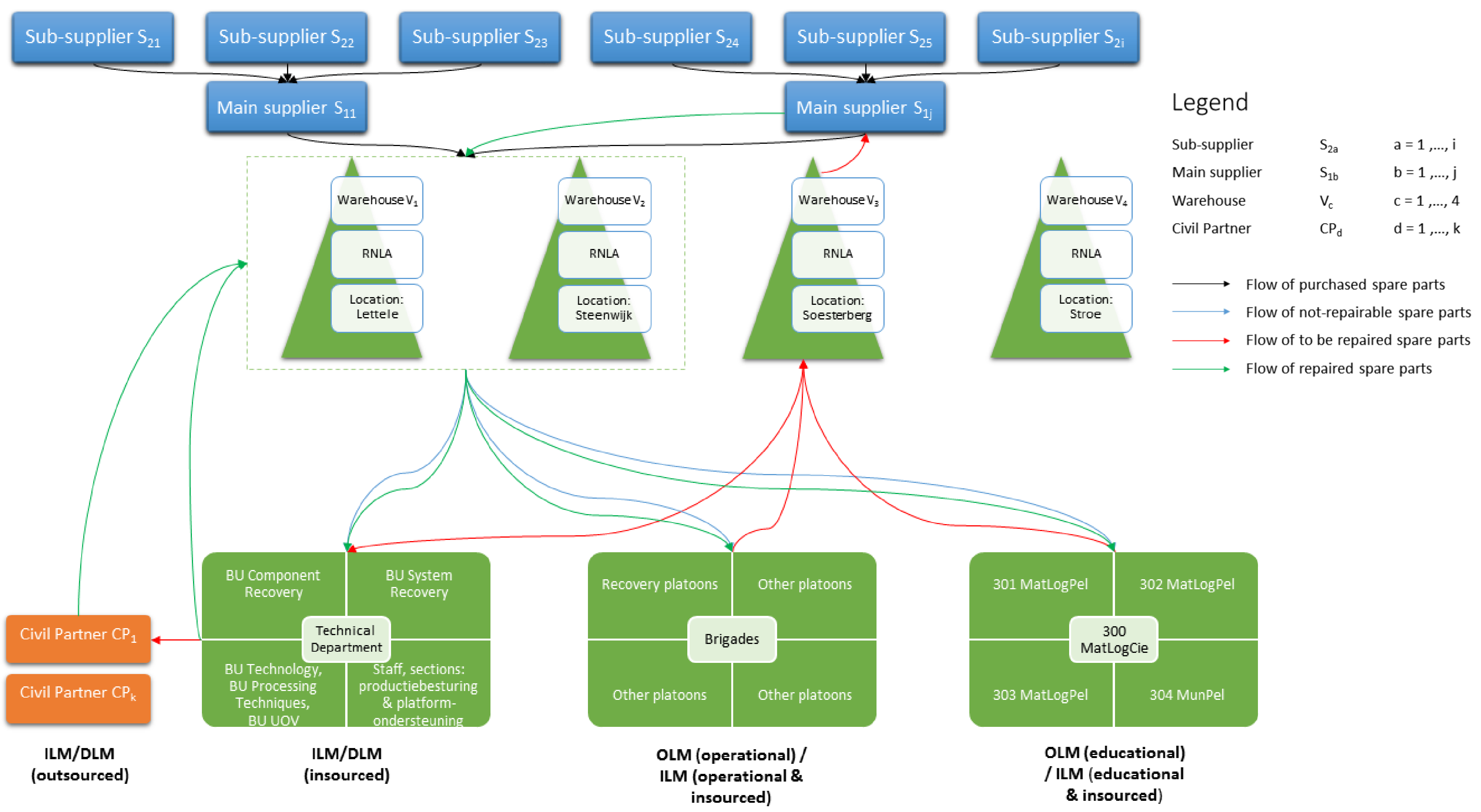

Figure 2-2. A model of the after-sales service supply chain of the RNLA, without the information flow

Warehouses

As illustrated in Figure 2-2, the RNLA has four main warehouses in use. The spare parts are delivered at the warehouses located in Lettele or Steenwijk, while the warehouse in Stroe is only used to receive and store recently purchased systems. The warehouse that is located in Soesterberg is used to store revision items and repairables that need to be repaired.

Suppliers

The RNLA does not manufacture the ground based systems itself. As an asset owner, most of the system types and the associated spare parts are purchased from the Original Equipment Manufacturers (OEM's). Next to the OEM's, another relevant main supplier is the NATO Support and Procurement Agency (NSPA), which is a non-profit agency and the executive body of the NATO Support and Procurement Organisation (NSPO), of which all 28 North Atlantic Treaty Organization (NATO) nations are members. Finally, systems and associated spare parts can also be purchased directly from Foreign Armed Forces with which the AFN has an agreement to exchange spare parts, for example the partners in the NATO.
The sub-suppliers of all the mentioned main suppliers mostly produce the spare parts that move through the after-sales service supply chain of the RNLA.

The main suppliers (with the exception of Foreign Armed Forces) normally are responsible for the supply of all unique spare parts of the system type until the End Life Of Type (ELOT) of the particular system type is reached. That means: if for example a certain sub-supplier goes bankrupt, the main supplier is responsible for finding an alternative sub-supplier for the same part or a comparable part. The initial ELOT of a system type mostly is set to around 30 years after the commission of the particular system type. After reaching the initial ELOT, the RNLA is responsible for the supply of all associated unique spare parts. That is why normally items are purchased and stocked excessively before reaching the initial ELOT.

Item flow

As can be seen in Figure 2-2, there are three groups of end-users of spare parts. These groups of end-users are also summarized in Table 2-1.

End-user	Entity
End-users of spare parts used at DLM	Army Depot Level Maintenance Workshop (BU System Recovery; BU Component Recovery)
End-users of spare parts used at ILM	Recovery platoons of brigades (operational ILM); 301, 302, 303 Material Logistic Platoons (MatLogPel's) (educational ILM); Army Depot Level Maintenance Workshop (BU System Recovery; BU Component Recovery)
End-users of spare parts used at OLM	All platoons of brigades (operational OLM); All platoons of 300 MatLogCie (educational OLM) Army Depot Level Maintenance Workshop (BU System Recovery; BU Component Recovery)

Table 2-1. Possible end-users of spare parts used during one of the maintenance levels.

Parts that are used during insourced Depot Level Maintenance (DLM), are used by the Business Unit (BU) System Recovery at the Army Depot Level Maintenance Workshop. However, the only end-user of items needed during the repair or overhaul of components is the BU Component Recovery.

First, a component that is considered to be defect need to be diagnosed by an expert technician of the BU. If it turns out that the component is not defect at all, it is sent to Lettele or Steenwijk. However, if the expert technician confirms that the component is not working properly, DLM is needed to be able to use the particular component again. The component is sent to Soesterberg where it will be stocked until it will be repaired, sold or disposed. Based on the maintenance contract between MatLogCo and the OEM, the overhaul or repair process is performed by the Army Depot Level Maintenance Workshop (or a civil partner of the RNLA) or by the OEM. In Figure 2-2, red arrows illustrate the item flow of components that need to be repaired or overhauled.
After the repair or overhaul process, the repaired item is transported to Lettele or Steenwijk, where they will be stocked. As discussed in Appendix B, these components can be used only at Intermediate Level Maintenance (ILM) or DLM. In Figure 2-2, the item flow of repairables is illustrated with green arrows.
Non-repairable spare parts can be used at any of the three applied maintenance levels. Therefore, any end-user of spare parts can receive non-repairable items. In Figure 2-2, the item flow of these items is illustrated with blue arrows.
At the Werkordermagazijn (WoMag), the spare parts necessary for jobs at the Army Depot Level Maintenance Workshop on the short term are stocked temporarily.

The appropriate lead time(s) needs to be investigated in order to successfully quantify the potential of AM. At the RNLA, it takes several days to deliver an order for one or more (unique) spare parts to the particular end-user. However, it takes multiple weeks or even months for an order at the main supplier to be delivered. Resupply lead times longer than 6 months are not exceptional.

CHAPTER 3 – OPPORTUNITIES OF AM IN THE AFTER-SALES SERVICE SUPPLY CHAIN

In this chapter, the opportunities of Additive Manufacturing (AM) in the after-sales service supply chain are investigated. An extensive literature study is performed to successfully identify the opportunities of AM in the after-sales service supply chains for organizations in the Defense industry. The results of the literature study are summarized in this Chapter. For more information about the results, please refer to Appendix F.

First, to give an idea what AM actually is, general information about the technology is given in appendix D.

The following opportunities in the after-sales service supply chain of organizations in the Defense industry are identified by Louis, Seymour & Joyce (2014):

- AM has the potential to lower the barriers to entry to manufacturing for a given location, and so the potential to impact how supply chains are designed;
- AM has the potential to impact product designs by reducing the costs associated with production changeovers and customization;
- Digital supply chains (supply chains where design data is used to create products and components on demand) can help eliminate the need for large, centralized production facilities to achieve economies of scale and reduce transportation cost, which will make the military significantly more agile through smaller and more secure supply chains;
- AM reduces the need to forecast supply chain capacity accurately;
- Digital supply chains open up the possibility of realizing higher operational readiness and more possible deployments of military units.

Bhasin & Bodla (2014) mention two additional opportunities:

- AM is especially suitable for low volume manufacturing and (very) slow movers;
- Potential increase in market share in the spare parts business;

In the Maintenance, Repair and Overhaul (MRO)-process, the following opportunities are identified (Louis, Seymour, & Joyce, 2014):

- By enabling the on-demand manufacture of a required part, it significantly improves the ability to respond to demand variability in the MRO-process;
- It minimizes the need to carry excess inventories in the MRO-process;
- The accumulated effects of the above-mentioned benefits will have a positive impact on the throughput in Gate 2 (Repair) of the MRO-process;

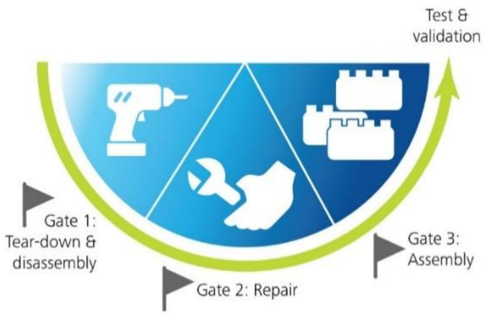

Figure 3-1. A generic MRO process (Louis, Seymour, & Joyce, 2014)

Furthermore, the main benefits of additively manufacturing spare parts in the Defense industry and in general are the following:

- Improvement in **part availability**, leading to higher satisfaction of end-users;
- **Overcoming obsolescence**: for parts of which the original manufacturer has stopped its production, AM could be a suitable alternative manufacturing method.
- **No economies of scale** during manufacturing with AM need to be achieved to cause minimal cost per part. The manufacturing can always start with just one part without exceeding minimum variable part costs.
- Significant improvements in geometric design (**complexity**) can be achieved, given the current geometric design constraints imposed by traditional manufacturing;
- Not only **component parts**, but also **sub-assemblies** and **inter-connected** parts are able to be manufactured with AM;
- Significant reductions could be made in:
  - **Total part cost**;
  - **Transportation cost**, which can result in a more **sustainable** after-sales service supply chain;
  - **Inventory** due to on-demand manufacturing**,** and therefore also in **holding cost**;
  - **Resupply lead time** due to on-demand manufacturing**;**
  - **Scrap rates;**
  - **Part weight;**
  - **Time-to-market** (that is: the length of time between the start of a product development process and the moment of introducing the final product on the market);
  - **Required manufacturing processes**.

Some consultancy offices still doubt the potential of AM and state that the potential might ultimately depend on how far the product quality and processing speed will be improved. However, companies in the Defense industry are recommended to actively track the technology developments and set threshold for the point at which it might be beneficial for the particular company to start investing in AM (Marx, Thompson, & Thut, 2013).

The history of experiments with AM and the actual application of additively manufactured parts within the United States Armed Forces (U.S. Forces) goes back to the 1990s. Therefore, the AFN needs to analyze the applications of AM by the Department of Defense (DoD). A summary of the most important applications of AM within the U.S. Forces in general are identified and given in appendix G. One of the main applications is the additive manufacturing of spare parts on-site in combat zones. The DoD can already produce a limited amount of spare parts close to the front line by means of the Mobile Parts Hospital and the Army Expeditionary Lab. For more information about additively manufacturing spare parts in combat zones, please refer to Appendix G.

It can be concluded that AM can definitely have a significant impact on the way the complex and immense spare part supply chains in Defense industries are being organized.

CHAPTER 4 – APPLIED FRAMEWORK

Few frameworks are developed to select spare parts that are suitable for Additive Manufacturing (AM). The most relevant frameworks are developed by Wullms (2014) and Knofius (2015). In this section, the most suitable framework to be used as a basis for this research is investigated and discussed.

The framework of Wullms (2014) was developed specifically for Philips Healthcare. The applied criteria are all go or no-go criteria, which means that if a spare part does not fit any of the criteria, the part is considered to be not suitable at all for AM. On the contrary, the framework of Knofius (2015) is a generic framework that can easily be adapted, according to the company considered. Another advantage of the framework of Knofius (2015) is that it includes a scoring procedure, instead of a procedure solely based on go or no-go criteria. Consequently, if a spare part is not considered to be very promising on a certain criteria, it will still be taken into account in the remaining of the scoring procedure. Therefore, to quantify the potential of the relevant scope of spare parts, the framework of Knofius (2015) will be used. The framework consists of four phases. The first two phases are 'Scoping' and 'Pre-selection' and are the scope of this assignment. An overview of these phases is illustrated in Figure 4-1.

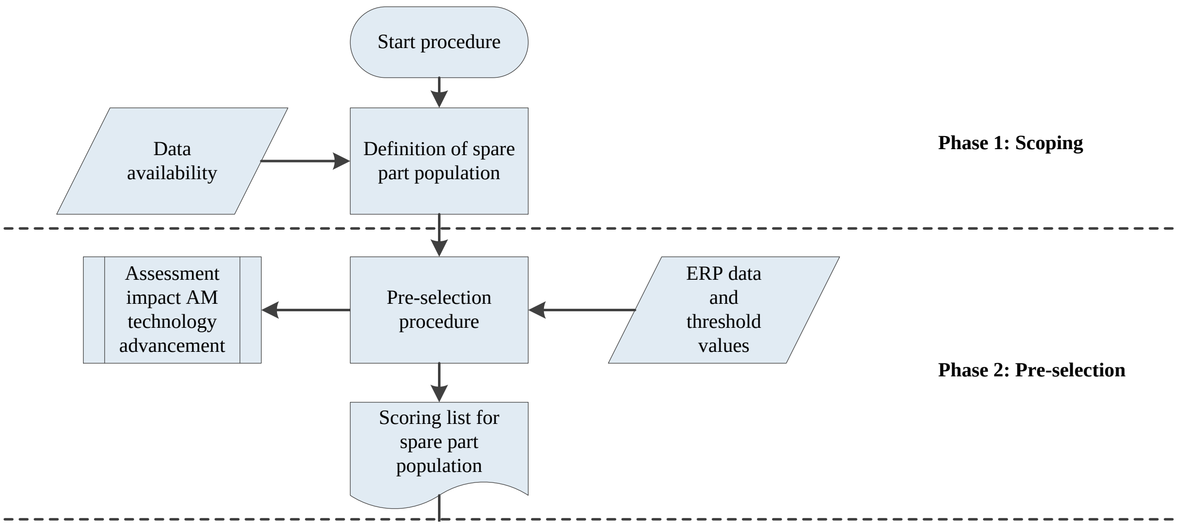

Figure 4-1. *An overview of the two considered phases: "Scoping" and "Pre-selection"* (Knofius, 2015)

4.1 Scoping phase

In the Scoping phase, the relevant spare part pool needs to be identified. In order to identify the relevant spare parts, two steps need to be taken. The very first step is to identify the system types that are currently in use by each of the service branches of the AFN and of which the after-sales service supply chain is (partly) being organized by MatLogCo. It also needs to be verified if spare part data is available for each of these system types.

The second step in this phase concerns the identification of logistical and economic opportunities in the after-sales service supply chains of the relevant system types. In order to identify those, it needs to be clear how the current after-sales service supply chains of relevant system types function and what the differences are between the spare part supply chains of different system types. After that, opportunities in these spare part supply chains can be identified by means of a literature study.

4.2 Pre-selection phase

The first step in the Pre-selection phase that needs to be taken, is to identify the list of characteristics per criterion that are relevant to be applied in the scoring procedure. This list will contain generic characteristics out of the framework, as well as organisation-specific characteristics. After the list is completed, the data need to be gathered. In case the required data of a characteristic cannot be retrieved, it will be removed from the list that will be used to perform the spare parts analysis.

After the data gathering, a data cleaning step is necessary to ensure a high quality of the spare part data. Without investigating the data quality, no reliable conclusions can be made. To make sure that the results will have a high reliability, unreliable data need to be identified and adjusted or excluded to the extent possible. Next to that, the presence of spare part assortments of irrelevant systems needs to be investigated as well. In case spare part assortments of systems are identified that are not included in the scope of this assignment, these will be excluded.

To be able to use the characteristics in the analysis, the threshold values need to be set. It is clear that this will be a crucial step for the outcome of this research, since for each spare part the score will be calculated based on these values. The values of the technological criteria are absolute, given the fact that this solely depends on the possibilities of AM nowadays and in the near future.
The values of the economical and logistical criteria are assigned relatively, since the threshold values of these characteristics could differ between organisations. For example for one organisation, an order lead time of 2 days can be seen as long; while for another organisation, order lead times less than 30 days can be seen as normal. As a result, the business environment of MatLogCo needs to be taken into account. Given the fact that MatLogCo operates in the Defence industry, this could have a significant effect on the assignment of the threshold values for the latter two criteria.

The final values that need to be assigned are the weights for each characteristic that will be used during the scoring procedure. The weights will be obtained by means of an Analytic Hierarchy Process (AHP). The importance of the applied characteristics can differ between organisations, so the customized weights obtained from the AHP are only suitable for the RNLA.
The weights can be obtained at the same time as the threshold values are assigned, since these values can be set independently of each other.

Having obtained the weights and threshold values successfully, the scoring procedure can now be performed. The characteristics in the technological category will be the bottleneck of this scoring procedure. This is due to the fact that technical data cannot be derived from the available spare part data. Therefore, the scoring procedure given in the applied framework needs to be slightly adapted in order to successfully analyze the spare part assortment. The following steps will be taken in this research to obtain a score for each spare part:

1. Multiply the value of each characteristic in the logistical and economic category with the weight obtained from the AHP and add up the results;
2. As a result, we obtain a score between 0 and 1, where 1 indicates the highest economic printability an item can achieve.
3. Based on the score, the spare part needs be placed in one of the categories that will be applied to categorize all the spare parts. The most promising spare parts will be assigned to highest applied category;

4. Based on the amount of parts that is assigned to the category that contains the most promising spare parts, a representative amount of parts will be randomly selected from the spare parts in this category. Based on the part description (if possible), the part needs to be assigned a 'GO' or 'NO-GO' criteria. If for a particular spare part at least one of the criteria is assigned a 'NO-GO', the part will not be further analyzed. A part can only be considered to be 'very promising' if the part is assigned a value of 'GO' for all technological characteristics. If the description is unclear, it needs to be verified if the RNLA currently possesses the part design, so the part can be further analyzed.
5. If the value for one of the characteristics is considered to be 'NO-GO', the part is considered not to be technologically feasible. However, if the value for all three characteristics is considered to be 'GO', additively manufacturing the part might be technologically feasible. If neither of these conditions are satisfied, the printability of the part cannot be further investigated.

The categories that will be applied in Step 3 are mentioned in Table 4-1. As can be seen in the table, the most promising spare parts will be assigned to Category 6.

Category	Range (scores)
Category 1	Excluded parts
Category 2	0.00 – 0.25
Category 3	0.25 – 0.50
Category 4	0.50 – 0.75
Category 5	0.75 – 0.85
Category 6	≥ 0.85

Table 4-1. Applied categories in Step 3 of the scoring procedure.

Finally, a sensitivity analysis of the results will be performed.

CHAPTER 5 – SCORING PROCEDURE METHOD

In this chapter, the method that will be used during the scoring procedure is explained in detail. First, a suitable set of criteria is defined. Second, the data quality will be investigated after the data has been gathered. Furthermore, the threshold values and the weights of the criteria are defined. Ultimately, the categories that will be applied to assign the results in are discussed as well.

5.1 Criteria

First, the characteristics mentioned in the applied framework of Knofius (2015) are given. The next step is to exclude the characteristics that are irrelevant for the spare part analysis. Finally, necessary modifications need to be made in order to end up with an organization-specific set of criteria.

5.1.1 Criteria in general framework

The characteristics that are given in the applied framework are shown in table 5-1.

Technological category *(exclusive)*	Logistical category *(weighting)*	Economic category *(weighting)*
Material (s)	Demand rate	Purchasing cost
Dimension	Customer order lead time	Manufacturing cost
Production tolerance	Installed base accessibility	Average days in inventory
	Item in initial lifecycle phase	Design ownership
		Holding cost

Table 5-1. All characteristics per criterion given in the framework (Knofius, 2015)

5.1.2 Excluded characteristics

The first step to define all the necessary characteristics, is to exclude the characteristics given in the framework that:

- are irrelevant for this particular analysis, because the particular characteristics do not match the current business environment of MatLogCo;
- cannot be measured, because the required data cannot be retrieved.

As an asset owner, the tolerance of the current manufacturing processes per spare part is unknown. Therefore, the characteristic **production tolerance** is excluded from the technological category. Furthermore, one characteristic from the logistical category will also be excluded. As discussed in Chapter 3, no remote locations are considered. Therefore, the **installed base accessibility** is irrelevant.

Also, the characteristic **manufacturing cost** is excluded; as an asset owner, these costs for each spare part are unknown. Instead of the manufacturing cost, the **purchasing cost** will be used to analyze the relevant spare part pool.

Finally, the **holding cost** per spare part is the final characteristic that needs to be excluded from the relevant set of criteria. This characteristic is not being measured or estimated at the RNLA. The holding cost could be estimated per spare part by means of a percentage of the purchasing cost. However, since the purchasing cost is already part of the set of criteria and given the fact that an increase in inventory means that holding cost will increase as well, the holding cost will be excluded.

5.1.3 Modifications to the set of criteria

The following changes need to be made in order to shape the general framework:

Technological category

Louis, Seymour & Joyce (2014) suggest to use the part complexity as well in order to successfully analyze the spare part data as well. This is due to the fact that some spare part types are not complex enough for AM to be an interesting alternative manufacturing technique (at the moment of writing) if it is not a remote location that is considered. In this case, it will be preferred to traditionally manufacture these spare part types (e.g. plates, tubes). For that reason, the characteristic **complexity** is added to the technological category. The data for this characteristic is not available in the ERP-system. However, since the criteria in the technological category will be applied only to the most promising parts, this characteristic can still be applied in the scoring procedure. After identifying the most promising spare parts based on the logistical and economic criteria, the parts that are considered not complex enough to be additively manufactured are excluded.

Logistical category

The **demand rate** is being measured by the average annual part usage in the last three years. Therefore, this characteristic will be renamed to **average annual usage**;

By additively manufacturing a certain part, lead times can be dramatically reduced by means of on-demand manufacturing. Therefore, the characteristic "customer order lead time" will be renamed to the **resupply lead time**.

The most important parts of which the supply needs to be secured, are the critical parts. A fast replacement of those items needs to be guaranteed. However, the characteristic **criticality** will not be included in the scoring procedure. The motivation for not including the characteristic is confidential and is discussed in the Appendix I (Commercial in Confidence).

In this report, the initial and final lifecycle phases will be taken into account as two separate characteristics. The characteristic "**item in initial lifecycle phase**" will be used, since the highest benefits of AM technology are achievable when the part is still in an early lifecycle stage (Knofius, 2015). In this report, items that belong to system types that are introduced by the AFN within the last five years, are considered to be items in the initial lifecycle phase.

Ultimately, the characteristic **ELOT-item** is added. As mentioned in Chapter 3, the main suppliers are responsible for the supply of all associated spare parts of a particular system type until the initial End Life of Type (ELOT) is reached. After reaching the ELOT, the RNLA is responsible for the supply of the items. Consequently, when the (sub-)supplier does not supply a specific part anymore or has announced to do so on the short term, the RNLA needs to find an alternative supplier for the same part of a comparable part relatively fast. Therefore, since the RNLA is responsible for the supply of these items, all items of system types that have reached their initial ELOT or will reach their initial ELOT within the next five years are considered to be ELOT-items. Additively manufacturing some of these parts could be a suitable alternative method to still be able to use the item during maintenance or damage repair. The ELOT is given per system type in Appendix O (Commercial in Confidence).

Economic category

The number of average days that spare parts of a certain spare part type are stocked in inventory is not being tracked. However, an approximation of the characteristic **average days in inventory** will be made by using the following formula for the number of days of average inventory on hand per Stock Keeping Unit (SKU):

$$Average\ days\ of\ inventory\ on\ hand\ per\ SKU = \frac{365\ days}{Average\ inventory\ turnover}$$

As can be seen, the average inventory turnover needs to be calculated to be able to use this formula. The average inventory turnover can be calculated by using the following formula:

$$Average\ inventory\ turnover = \frac{Average\ annual\ \ usage\ (unit\!: number\ of\ pieces)}{Average\ inventory\ (unit\!: number\ of\ pieces)}$$

One characteristic that has been taken into account in the relevant set of criteria has not been mentioned yet, since it does not have to be modified or excluded. This characteristic is called the **design ownership**. In order to print the component, the RNLA needs to hold the particular CAD-design. As a consequence, the RNLA safes time and/or money if it already possesses the design, since no solution with the supplier has to be found. As a result, the design ownership is a positive attribute for an item (Knofius, 2015). However, the designs are not owned by MatLogCo for all spare parts; the availability of designs is confidential and therefore discussed in Appendix I (Commercial in Confidence). As concluded in Appendix I, the characteristic will be taken into account in the analysis.

In table 5-2, the final set of criteria that will be used during the scoring procedure is given.

Technological category *(exclusive)*	Logistical category *(weighting)*	Economic category *(weighting)*
Material (s)	Average annual usage	Purchasing cost
Dimension	Resupply lead time	Average days in inventory on hand
Complexity	Item in initial lifecycle phase	Design ownership
	ELOT-item	

Table 5-2. All relevant characteristics based on the organizational environment of the RNLA as well as the spare part data quality

5.2 Data gathering

Before the scoring procedure can be performed, the reliability of the required data needs to be analyzed. The results are summarized in this Section. the necessary steps required to successfully gather the required data and investigate the data quality are described extensively in Appendix X.

Multiple sources have been used to retrieve the required data. Unfortunately, it is not possible to retrieve spare part data from the ERP-system from before 2014. The spare part data includes the average annual usage of the last three years. Unfortunately, only the spare parts that have been used at least once in the last three years could be gathered, since it would have been too time consuming to collect the data of all unique parts (the exact number of unique parts is given in Appendix K (Commercial in Confidence)). As mentioned in Appendix K (Commercial in Confidence), around 90% of the spare part assortment consists of very slow movers and non-movers. The data of all these parts could not be gathered. In addition, the inventory data per SKU (in order to calculate the average days in inventory on hand per SKU) could not be retrieved from the former system, since this would have been too time consuming as well. For that reason, only the spare part data since 2014 will be considered in order to calculate the average days in inventory on hand per SKU. Since the data need to be as reliable as possible, the values of this particular characteristic need to be gathered from multiple data points. Data between March 2014 and April 2015 is therefore used.

The data representativeness is discussed in Appendix K (Commercial in Confidence). Because the data of 2014 cannot be considered as fully representative, there will be a fraction of very slow movers that was supposed to move through the spare part supply chain in the considered period, but for some reason did not move at all. Furthermore, the data that is analyzed in a period of one to three years might not be completely representative. This is due to the fact that the cycle of necessary Depot Level Maintenance (DLM) per system type is at least five years.

The backlog of spare parts at MatLogCo is discussed in Appendix K (Commercial in Confidence) and has consequences for the average annual usage and the average days in inventory. Since the demand was not satisfied for all spare parts, the overall annual usage could be lower than required. Additionally, the total amount of purchase orders most likely was lower than required as well. As a consequence, the average inventory could have been lower in the considered period than normal.

After performing the data cleaning step, which is explained in Appendix K, the overview of the total spare part assortment consists of 11944 spare parts.

5.3 Threshold values

In this section, the threshold values per characteristic are set. Multiple analyses are obtained in order to obtain more differentiation. The results of all three performed analyses are illustrated in Table 5-6.

Analysis 1

In this analysis, only values of ‘0’ and ‘1’ are applied. If the value of a particular characteristic (for all spare parts) is at least as high as the threshold value, a ‘1’ is assigned. Else, a value of ‘0’ is assigned to the particular part. In this research, a **resupply lead time** of at least 14 days and an **average inventory on hand** of approximately 30 days are assumed to be positive indicators to consider AM as an alternative production method. **Items in the initial lifecycle phase** and **ELOT-items** are assumed to be positive indicators as well. Furthermore, some consultancy offices tend to delete all items of which the manufacturing cost is lower than € 25 and/or the demand rate in a considered period is more than 1000. Hence, the threshold value for the **purchasing cost** is set to € 25 and the threshold value for the **average annual usage** is set to ‘1000’.
Finally, the parts of system types of which at least a significant part of the designs are possessed by the RNLA are mentioned in Appendix I (Commercial in Confidence). The actual **design ownership** is considered to be a positive attribute for AM as well.

Characteristic	Threshold value	Unit	Percentage of unique spare parts with assigned value of ‘1’
Resupply lead time	≥ 14	Days	99,1
Average days in inventory on hand	≥ 30	Days	88,0
Purchasing cost	≥ 25	Euro	50,9
Average annual usage	≥ 1000	Units	99,8
Item in initial lifecycle phase	≥ 2010	Year of commissioning	3,4
ELOT-item	≤ 2020	Year in which ELOT is reached	52,2
Design ownership	Yes	-	32,9

Table 5-3. Applied threshold values during Analysis 1

As can be seen in Table 5-3, for the characteristics **resupply lead time, average days in inventory on hand** and **average annual usage**, almost all parts are assigned a value of '1'. As can be concluded, more differentiation in the threshold values is needed in order to obtain the most promising parts.

Analysis 2

Several modifications were made in order to investigate the effect of an alteration of the threshold values to gain more differentiation.
If the **resupply lead time** of a certain part is less than 14 days, a "NO-GO" is assigned instead of a '0'. Between 14 and 30 days, a relatively small benefit can be achieved by additively manufacturing the part. Therefore, a value of '0' will be assigned. A value of '1' will be assigned to all spare parts with a resupply lead time of at least approximately one month.
The threshold value for the **average days in inventory on hand** is still set to approximately one month as well. However, when for a particular part, an average of at least approximately 10 years of inventory is on hand, the assigned value is changed to '0'. This is due to the fact that if there are already enough spare parts to satisfy the demand for the upcoming 10 years, there is no potential to additively manufacture the considered part within 5-10 years. The parts are not excluded, because there might still be potential to start printing the part and sell most of the units of the particular SKU in order to save holding cost. However, since savings on holding cost do not have priority within the after-sales service supply chain of the RNLA, a value of '0' instead of '1' will be assigned.
If the **purchasing cost** of an item is low, AM is not a suitable alternative manufacturing method. Therefore, if the value for the purchasing cost lies between € 25 and € 100, a relatively small benefit can be achieved by additively manufacturing the part: a value of '0' will be assigned. If the purchasing cost exceeds the threshold value of € 100, a value of '1' will be assigned.
Finally, parts with an **average annual usage** of at least 1000 are assigned a "NO-GO" value. Parts with an average annual usage lower than 100 will be assigned a value of '1'. An average annual usage of between 100 and 1000 is assigned a value of '0'.
No modifications were made to the remaining characteristics. This is due to the fact that the ELOT of each system type given in Appendix N (Commercial in Confidence) is used as an indicator. For some system types, it is unclear if the mentioned ELOT is the initial value. Moreover, it can be decided that a particular system type will be in use longer than initially expected, which means that the initial ELOT will be exceeded. Therefore, the characteristic **ELOT-item** will not be modified. Consequently, the values of the other characteristic that concerns the lifecycle phase of the system type (**initial lifecycle phase**) will not be modified either. The results of Analysis 2 are illustrated in Table 5-4.

Analysis 3

In Analyses 1 and 2, a maximum of two threshold values per characteristic are set. However, in order to obtain more differentiation, multiple threshold values are set for some of the characteristics. For some characteristics, NO-GO criteria are applied as well, if parts for these values will never have potential to be additively manufactured. For all characteristics, the same NO-GO criteria will be applied as is done in Analysis 2.
If the **resupply lead time** of a certain part is less than 14 days, a "NO-GO" is assigned. The most promising parts have lead times of at least approximately 6 months (180 days).
In this report, it is assumed that parts with values for the characteristic **average days in inventory** between 360 and 900 days have the most potential to be additively manufactured.
A **purchasing cost** of at least € 100 is still considered to be the most promising. However, not all purchasing cost lower than € 100 will be assigned a '0', but values between '0' and '1', depending on

the value of the purchasing cost. Finally, if the value of the characteristic **average annual usage** is lower than 10, it had a value assigned of ‘1’. Between 100 and 1000, the values are between ‘0’ and ‘1’, depending on the value of the average annual usage.
Similar to Analysis 2, no modifications will be made to the remaining characteristics.
The results of Analysis 3 are illustrated in Table 5-4. More differentiation is achieved for four out of seven applied characteristics in compared to Analyses 1 and 2. The identified threshold values by performing Analysis 3 will therefore be applied in this research to obtain the scores.
It needs to be noted that after performing analysis 3, the **average annual usage** of still an approximate of 78 % of the analyzed spare parts is less than 10. This is due to the fact that approximately 67 % of the parts are used no more than five times in the last three years. Given the fact that these differences in average usage are minimal, no further differentiation will be made.

	Analysis 1			**Analysis 2**			**Analysis 3**		
Characteristic	Threshold value	Assigned value	Results	Threshold value	Assigned value	Results	Threshold value	Assigned value	Results
Resupply lead time *(number of days)*	< 14	0	111	< 14	NO-GO	111	< 14	NO-GO	111
	≥ 14	1	11833	14-30	0	347	14-30	0	347
	Unknown	NO-GO	0	> 30	1	11486	30-60	0.25	178
				Unknown	NO-GO	0	60-120	0.5	4160
							120-180	0.75	3166
							≥ 180	1	3982
							Unknown	NO-GO	0
Average days in inventory on hand *(number of days)*	< 30	0	1448	< 30	0	1448	< 30	0	1448
	≥ 30	1	10496	30-3600	1	6363	30-90	0.25	90
	Unknown	NO-GO	0	≥ 3600	0	4133	90-180	0.5	162
				Unknown	NO-GO	0	180-360	0.75	520
							360-900	1	1788
							900-1800	0.75	1830
							1800-2700	0.5	1192
							2700-3600	0.25	781
							≥ 3600	0	4133
							Unknown	NO-GO	0
Purchasing cost *(€)*	< 25	0	5695	< 25	NO-GO	5695	< 25	NO-GO	5695
	≥ 25	1	6076	25-100	0	2709	25-50	0.25	1357
	Unknown	NO-GO	173	≥ 100	1	3367	50-75	0.5	807
				Unknown	NO-GO	173	75-100	0.75	545
							≥ 100	1	3367
							Unknown	NO-GO	173
Average annual usage *(number of unique spare parts)*	< 1000	1	11921	< 100	1	11653	< 10	1	9324
	≥ 1000	0	23	100-1000	0	268	10-50	0.75	1969
	Unknown	NO-GO	0	≥ 1000	NO-GO	23	50-100	0.5	360
				Unknown	NO-GO	0	100-500	0.25	246
							500-1000	0	22
							≥ 1000	NO-GO	23
							Unknown	NO-GO	0
Item in initial lifecycle phase	YES	1	412	Same as in analysis 1			Same as in analysis 1		
	NO	0	11532						
ELOT-item	YES	1	6237	Same as in analysis 1			Same as in analysis 1		
	NO	0	5707						
Design ownership	YES	1	3929	Same as in analysis 1			Same as in analysis 1		
	NO	0	8015						
Total number of parts analyzed			11944			11944			11944
Total number of parts excluded			173			5924			5924

Table 5-4. Overview of the threshold values of the logistical and economic criteria per Analysis. Analysis 3 contains the threshold values that will be applied in the scoring procedure.

During the GO or NO-GO for the technological criteria, the values for each of the characteristics is assigned roughly.

Material: A particular part needs to satisfy the following constraints in order to be considered as a promising part (based on only this technological characteristic):

- It cannot contain an electric component (Wullms, 2014);
- It contains no more than two different types of material are used;
- Turning parts are excluded (Wullms, 2014).

Dimension: The following feasible dimension for AM is given by Wullms (2014):

- Metal: 550mm x 750mm x 550mm;
- Plastic: 2100mm x 800mm x 700mm.

These dimensions will be used as an indicator in order to decide if the part is not likely to exceed the technologically feasible dimension.

Complexity: Some spare part types are not complex enough for AM to be an interesting alternative manufacturing technique (at the moment of writing) if it is not a remote location that is considered. In this case, it will be preferred to traditionally manufacture these spare part types (e.g. plates and simple tubes).

5.4 Weights from AHP

As discussed in Chapter 4, the weights that are used in the analysis will be obtained by means of an Analytic Hierarchy Process (AHP). The importance of the applied characteristics can differ between organisations, so the customized weights obtained from the AHP are only suitable for the RNLA. First, the relevant characteristics defined in Section 5.1 need to be assigned to main company goals. These company goals represent the benefits that the RNLA hopes to achieve by implementing Additive Manufacturing (AM) in the after-sales service supply chain. In order to successfully identify these goals for the RNLA, the article “3D opportunity in the Department of Defense” of Louis, Seymour & Joyce (2014) is used. They identify the four tactical paths that organisations in the Defense industry can choose to pursue in order to successfully apply AM. Given the fact that the RNLA desires a low impact of AM on the product itself but wants to know the opportunities that AM can offer in their after-sales service supply chain, the path of “Supply chain evolution” is the appropriate path to be considered. In Figure 5-1, the strategic imperative, value drivers and key enabling AM capabilities per path are given. For more information about the opportunities of pursuing the path of “Supply chain evolution”, please refer to appendix F.

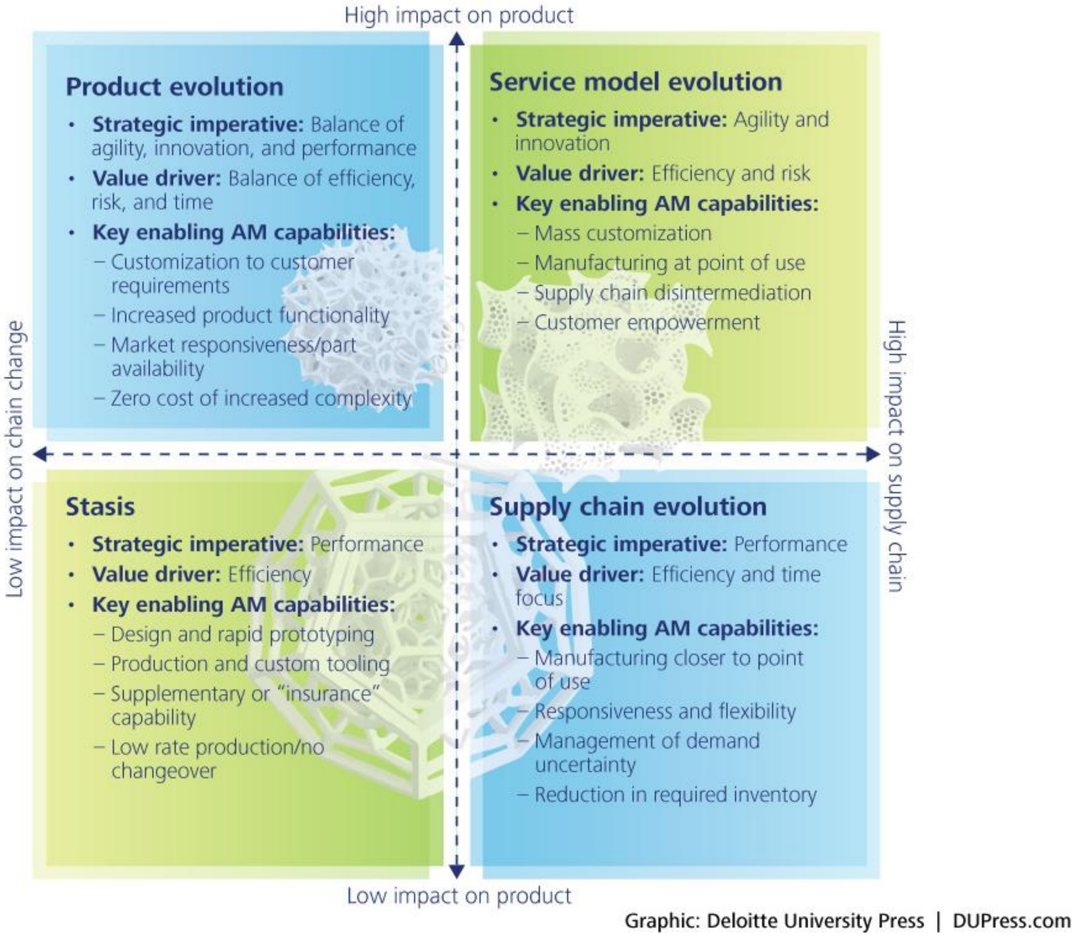

Figure 5-1. The four tactical paths organizations choose depending on their needs, goals and circumstances, with modified criteria for the mission-driven organization that the DoD is (Louis, Seymour, & Joyce, 2014)

Since the two value drivers of the path "Supply chain evolution" are "efficiency" and "time focus", the company goals should be in line with these drivers. First, the company goal "**reduce costs**" is identified, in order to operate more efficiently by starting to additively manufacture certain components. Second, since service at the RNLA can mainly be improved by reducing the resupply lead time, the company goal "**improve service**" is identified as well. This goal corresponds to the value driver "time focus". Furthermore, one particular company goal cannot be omitted. As mentioned in Chapter 2, the RNLA is responsible for the supply of spare parts of a particular system type after the initial ELOT is reached. When in this case a supplier unexpectedly will not deliver a particular part anymore, the RNLA can consider AM as an alternative manufacturing method to secure the supply of the particular part. This also corresponds to one of the key enabling AM capabilities given in Figure 5-1, namely: responsiveness and flexibility. Consequently, the final goal that is identified is called: "**secure the spare part supply**".

The relevant characteristics in the final set of criteria are assigned to these goals, as illustrated in Tables 5-5, 5-6 and 5-7.

Improve service	
Resupply lead time	Since resupply lead times are reduced significantly by applying AM, service can be improved by additively manufacturing items with relatively long lead times.
Item in initial lifecycle phase	In general, if the resupply lead times of two comparable items of different system types are equal (ceteris paribus), the advantages of a reduced lead time are more interesting for the item of the system type that is still in the initial lifecycle phase.

Table 5-5. Characteristics subdivided in goal: "improve service"

Reduce costs	
Average days in inventory on hand	When a relatively large quantity of a certain item is stocked, AM might be a suitable alternative to reduce the inventory level due to on-demand manufacturing.
Purchasing cost	High purchasing cost indicate a complex production process or a customized product. Both attributes might be solved more efficiently with AM technology which implies cost savings (Knofius, 2015).
Design ownership	The RNLA safes time and/or money if it already possesses the design, since no solution with the supplier has to be found (Knofius, 2015).
Item in initial lifecycle phase	In general, costs can be saved during a longer period if the system type is still in the initial lifecycle phase.

Table 5-6. Characteristics subdivided in goal: "reduce costs"

Secure the spare part supply	
Average annual usage	If the average annual usage is limited, AM might be a suitable alternative for traditional manufacturing.
ELOT-item	The RNLA is responsible for the supply of items of system types that already reached the initial ELOT.

Table 5-7. Characteristics subdivided in goal: "Secure the spare part supply"

The weights for these company goals can be obtained by calculating the vector or relative weights (Saaty, 1987). In order to calculate this vector, the pairwise comparison matrix needs to be obtained. The necessary pairwise comparisons are made during interviews with the head of section Productiebesturing, the manager of the Business Unit (BU) Technology and the head of the cluster Engineering within the BU Technology. Since the fields of these specialists differ greatly, the pairwise comparisons can successfully be obtained based on the opinion of specialists of different fields within the company.
The consistent pairwise comparison matrix C for the RNLA based on the identified company goals is illustrated in Table 5-8. For more information about the method, please refer to Appendix M.

Goal	Improve service	Reduce costs	Secure supply
Improve service	1	4	1/4
Reduce costs	1/4	1	1/8
Secure supply	4	8	1

Table 5-8. Consistent pairwise comparison matrix C

In order to obtain the weights for all characteristics per company goal, the weight of the company goal is equally distributed over these characteristics.
As can be seen in Tables 5-5 and 5-6, the characteristic "Item in initial lifecycle phase" occurs in the set of characteristics of two company goals. The obtained weight of this characteristic is the sum of these particular weights.

Based on the consistent pairwise comparison matrix, the weights are obtained per company goal. These weights are illustrated in Table 5-9. After the obtaining of these weights, the weights per characteristic are calculated. The results of these weights are given in Table 5-10.
An overview of the identified company goals and the corresponding characteristics is illustrated in Figure 5-2. Finally, an example of the results for one spare part is illustrated in Table 5-11.

Goal	Weight
Secure supply	0.7015
Improve service	0.2267
Reduce costs	0.0718

Table 5-9. Weights from AHP per goal

Characteristic	Weight
Overall annual usage	0.3508
EOL-item	0.3508
Item in initial life cycle phase	0.1313
Resupply lead time	0.1134
Average days in inventory on hand	0.0180
Purchasing cost	0.0180
Design ownership	0.0180

Table 5-10. Weights per characteristic

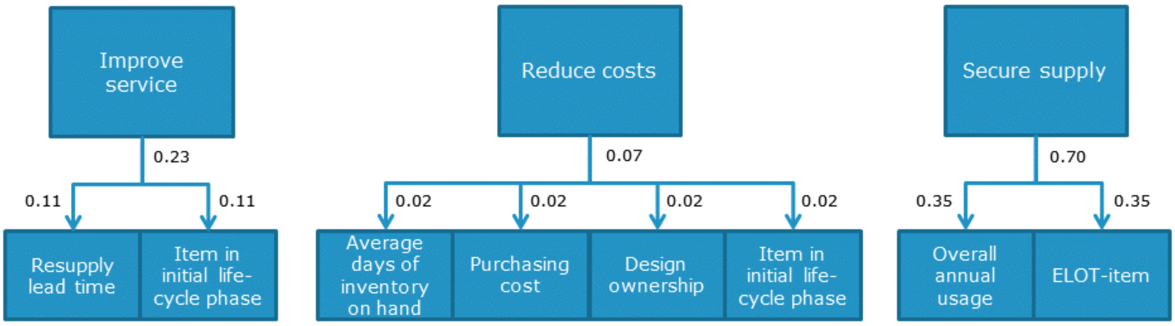

Figure 5-2. An overview of the characteristics per company goal, including the obtained weights.

Characteristic	Category	Weight from AHP	Value	Score
Overall annual usage	Logistical	0.3508	1	0.3508
EOL-item	Logistical	0.3508	1	0.3508
Item in initial lifecycle phase	Logistical	0.1313	0	0
Resupply lead time	Logistical	0.1134	1	0.1134
Purchasing cost	Economic	0.0180	1	0.0180
Average days in inventory on hand	Economic	0.0180	0.25	0.0045
Design ownership	Economic	0.0180	1	0.0180
Material(s)	Technological	-	GO	-
Dimension	Technological	-	NO-GO	-
Complexity	Technological	-	GO	-
Final score:				**0.8555**
To be assigned to category:				**1**

Table 5-11. Example of final data per spare part.

CHAPTER 6 – RESULTS

In this chapter, the results of the scoring procedure are given.

The average part score and the related standard deviation of the total number of analysed unique spare parts are given in Table 6-1. The overall potential of AM within the after-sales service supply chain is quantified by means of the average part score of all not-excluded parts, which is 0.61.

The number of unique spare parts that are assigned to each applied category as discussed in Chapter 5 is illustrated in Table 6-2. As can be seen, there is no logistical or economic incentive to consider AM as an alternative production method for around 50 % of the spare part assortment. Furthermore, the maximum possible score for a particular spare part cannot be higher than approximately 0.87, given the fact that any system type at the RNLA can never be in the initial lifecycle phase at the same time it is about to reach the initial ELOT.

The promising spare parts are assigned to Category 5, while the most promising spare parts are assigned to Category 6. 2209 unique spare parts are assigned to Category 5 and 175 spare parts are assigned to Category 6. Consequently, 2384 (very) promising spare parts are identified. This corresponds with approximately 20 % of the analyzed spare part pool. It needs to be noted that Categories 3 and 4 also contain promising parts. The potential is relatively lower than of the spare parts assigned to Categories 5 and 6. However, of parts of system types that are not reaching their initial End Life Of Type (ELOT) or are not considered to be in their initial lifecycle phase anymore, the resupply lead time can still be reduced significantly, just as transportation and holding costs as well as necessary inventory space to stock the particular items.

In order to see the number of parts assigned to each Category for each (sub) assortment, please refer to Appendix P (Commercial In Confidence).

	Considered spare parts	
Total number of analysed unique spare parts:	All	**11944**
Average part score:	Not excluded spare parts (Categories 2-6)	**0.61**
Standard deviation of average part score:	Not excluded spare parts (Categories 2-6)	**0.18**

Table 6-1. Average part score and standard deviation of average part score.

Category	Potential of AM	Range (scores)	Number of unique spare parts	Percentage of total amount of spare parts
Category 1	None	Excluded parts (NO-GO)	5924	49.6
Category 2	Relatively very low	0.00 – 0.25	34	0.0
Category 3	Relatively low	0.25 – 0.50	2590	21.7
Category 4	Around average	0.50 – 0.75	1012	8.5
Category 5	Relatively high	0.75 – 0.85	2209	18.5
Category 6	Relatively very high	≥ 0.85	175	1.5

Table 6-2. Number of unique spare parts assigned to each applied category.

The next step is to investigate the technological feasibility of each of the 175 very promising spare parts based on the part description (as given in the data set) and (if available at the Army Maintenance and Logistics Command) the part design. The results of this step are illustrated in Table 6-3.

To see the results per very promising part, please refer to Appendix Q (Commercial in Confidence). For only approximately 15-30 % of these very promising parts, it might be technically feasible to manufacture these parts with AM. About 70-85 % of these parts are not technically feasible. Next to that, out of the 10 parts of which the design was asked for, 6 designs were actually retrievable. Since it was already time consuming for only 10 parts, no further designs have been used to determine the technical feasibility.

	Amount of unique spare parts
Number of analysed unique spare parts:	**175**
- **Number of unique (sub) assortments**	11
Likely to be technologically feasible:	**26**
- **Number of unique (sub) assortments**	6
- **Number of parts with more than 3600 days of inventory**	7
- **Design might be available**	21
- **Design actually available**	6 out of 10*
Not technologically feasible:	**124**
Not possible to determine:	**25**

Table 6-3. Analysis of most promising spare parts

*For 10 parts, the availability of the particular design was actually checked.

The parts assigned to Category 6 that might be technologically feasible are given in Table 6-4. The parts assigned to Category 6 are considered not to be technologically feasible are given in Table 6-5. The Tables contain not only part types out of Category 6, but also part types out of other Categories. By adapting the threshold values and AHP-weights during the research, some parts were at first assigned to Category 6. The technical feasibility of these items was already investigated, before the assigned Category was changed.

Finally, a sensitivity analysis is performed. The values for the characteristics **average annual usage** and **ELOT-item** have the most impact on the results. The values for the **resupply lead time** also have a significant impact on the results in Categories 5 and 6. Furthermore, changing the values for the characteristic **purchasing cost** has a significant impact on all applied Categories.
The impact of changing the values for the characteristics **average days in inventory**, **item in initial lifecycle phase** and **design ownership** on the results in Categories 5 and 6 are limited. However, setting the values of the characteristic **average days in inventory** to ‘1’ for all high inventory levels does have a significant impact on the number of parts in Category 6.
For more information about the sensitivity analysis, please refer to Appendix R.

Might be technologically feasible	
English	**Nederlands**
Brake levers	Remhefbomen
Brake shoes	Remschoenen
(Front axle) casings	Behuizingen (vooras)
Cross pieces	Kruisstukken
Exhaust manifolds	Uitlaatspruitstukken
Fan clutches	Ventilatiekoppelingen
Flanges	Flenzen
(Metal/plastic) gaskets	(Metalen/kunststof) pakkingen
Guide carriages	Geleidingswagens
Hoods	Kappen
Levers	Hendels
(Mirror) mounts	(Spiegel-)frames
Specific rings	Specifieke ringen
Steering wheels	Sturen
Tow bars	Sleepstangen
Universal joints	Kruiskoppelingen
Vent valves	Ontluchtingskleppen
Thrust collars	Drukringen/drukkragen
Locking levers	Vergrendelingen
Filler necks	Vulpijpen (hals)

Table 6-4. Part types assigned to Category 6 that might be technologically feasible

Technologically not feasible	
English	**Nederlands**
Adaptors	Adapters
Amplifiers	Versterkers
Axles	Assen
(Parts that include) ball joints	Onderdelen die kogelgewrichten bevatten
Ball-head bolts	Kogelbouten
Bearings	Lagers
Cables	Kabels
Chairs	Stoelen
Clutch plates	Koppelingsplaten
Connecting-rods	Drijfstangen
(Camouflage) covers	Afdekkingen
Cylinders	Cilinders
Displays	Schermen
Drive flanges	Aandrijfflenzen
Excentric disks	Excentrische schijven
Exhaust pipes	Uitlaatpijpen
Filters	Filters
Flaps	Kleppen
Gaskets (not made of steel/plastic)	Pakkingen (niet gemaakt van staal/plastic)
Gears	Tandwielen
Hubs	Naven
Impellers	Loopwielen
Ladders	Ladders
Lighting	Verlichting
Locks	Sloten
Longitudinal links	Langsdraagarmen
Panels	Panelen
Pitman arms	Pitman-armen
Pulleys	Poelies
Pumps	Pompen
Regulators	Regelaars
Rocker arms	Tuimelaars
Seat belts	Gordels
Seats	Stoelen
Speedometers	Snelheidsmeters
Shield	Schild
Sideboards	Zijschotten
Springs	Veren
Stators	Statoren
Steering arms	Stuurarmen
Struts	Veerpoten
Switches	Schakelaars
Synchronizer rings	Synchroonringen
Synchronizer sleeves	Schakelmoffen
Thermostats	Thermostaten
Torsion bars	Torsiestaven
Wiring harnesses	Kabelbomen

Table 6-5. Part types assigned to Category 6 that are considered not to be technologically feasible

CHAPTER 7 – CONCLUSION

In this chapter, the conclusion, recommendations and limitations of this research are given.

Conclusion

The overall potential of AM within the after-sales service supply chain of the RNLA is quantified by means of the average part score of all not-excluded parts, which is 0.61.
There is no logistical or economic incentive to consider AM as an alternative production method for around 50 % of the spare part assortment. Finally, 2384 promising parts are identified. This corresponds with approximately 20 % of the analyzed spare part pool. 175 of these parts are considered to be very promising. For only 15-30 % % of these very promising parts, it might be technically feasible to manufacture these parts with AM.

The most important application of AM for the RNLA is securing the supply of spare parts, followed by respectively improving service and reducing cost. Given the fact that most spare parts have relatively long resupply lead times, AM could significantly improve service at the RNLA by reducing the resupply lead times of the parts of which it is technically feasible to additively manufacture the particular part.

Recommendations

Further research is advised to be done, in which business cases can be made in order to come up with the actual printability and the expected gains of printing the (very) promising spare parts.
In addition, MatLogCo needs to actively track the technological development of AM closely, as well as the application of AM within the U.S. Forces. Also, the availability of spare parts needs to monitored closely, especially for system types that will reach their initial ELOT on the short term. Currently, the steps necessary for approval of an additively manufactured part to be used for the maintenance and/or damage repair of ground based (weapon) systems are unknown within MatLogCo and need to be identified. Moreover, the purchasing strategy needs to be revised, since for around 35% of the analyzed spare parts, there is more than approximately 10 years of inventory on hand. Finally, a Quick Scan should be repeated in the near future in order to analyze more data and more representative data. MatLogCo needs to be aware that the data gathering step for this Quick Scan is likely to take a significant amount of time as well. In order to gain better results, the material type, part dimension and part criticality need to be inserted in the spare part database and the part description needs to be updated.

Limitations

Approximately only 8 % of the total spare part assortment is analyzed. Unfortunately, the very slow movers could not be analyzed, while AM is more suitable for (very) slow movers. Next to that, the data is not considered to be fully representative. Moreover, the application of the technological criteria is partly based on assumptions. Finally, it is likely that a fraction of the values for the End Life Of Type (ELOT) that were successfully retrieved have been updated. In addition, of a significant fraction of the spare part (sub) assortments, the ELOT is unknown or could not be retrieved;

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APPENDICES

APPENDIX A – COMMERCIAL IN CONFIDENCE –

Army Depot Level Maintenance Workshop Organisation Chart

Use or disclosure of this information is subject to the restriction on the title page of this document. Please contact one of the following employees at the Army Depot Level Maintenance Workshop:

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APPENDIX B – Levels of maintenance used by the AFN

In this appendix, the three different levels of maintenance are explained.

OLM

OLM stands for Organic Level Maintenance. It is the lowest applied level of maintenance and is performed by the units itself. Practically, this includes all maintenance and damage repair that can be done by themselves. For example, the change of a flat tire is part of OLM.

ILM

The second level of maintenance is called ILM, which stands for Intermediate Level Maintenance. The ILM of all the ground based systems of which this level of maintenance is insourced, is performed once every year. It includes all the maintenance and damage repair that can be done without dismantling the system or components. For example, the replacement of an oil filter and even a complete engine are part of ILM. The engine will be dismantled and repaired at the next level of maintenance, DLM.

DLM

Finally, the highest applied level of maintenance is called Depot Level Maintenance (DLM). DLM is performed on a system every few years. For most of the system types, DLM is repeated every five years. The exact cycle of DLM is about 5 years, but this differs between the system types.
The insourced DLM is always performed by the Army Depot Level Maintenance Workshop. The outsourced DLM that is being done by civil companies, is supervised and supported by the department in the process.
Next to the preventive maintenance, component recovery (e.g. engine repair), system recovery (e.g. corrective maintenance) and system modifications are also part of DLM.

APPENDIX C – Overview of the system types currently in use by the AFN

In Table C-1, the most heavy ground-based weapon systems are mentioned.
In Table C-2, the reconnaissance and all-terrain (weapon) systems are given.
The trucks and trailers, the engineering systems and the weapon equipment are discussed in Tables C-3, C-4 and C-5. Finally, Tables C-6 and C-7 show the support systems, facilities and installations.

System type	Description
Leopard 2-bergingstank (Buffel)	Recovery tank
Leopard 2-geniedoorbraaksysteem (Kodiak)	Engineering tank
Leopard 1-bergingstank	Recovery Tank
Leopard 1-brugleggende tank	Tank equipped with a mobile bridge
Leopard 1-genietank	Engineering tank
Leopard 1-Beach Armored Recovery Vehicle (BARV)	Armoured recovery vehicle
CV90-infanteriegevechtsvoertuig (CV9035NL)	Infantry combat vehicle
Boxer	Wheeled armoured vehicle
Pantserhouwitser 2000NL (PzH2000NL)	Howitzer
YPR Pantserrupsvoertuig (all types: YPR-765 & 806 Pantserrupsberging)	Recovery tank
Mijnenruimvoertuig Scanjack 3500	Minesweeper
Mijnenruimvoertuig Bozena	Minesweeper
Mortar (in Dutch: “mortier”) (all types: 60-,81- and 120mm)	Mortar

Table C-1. An overview of the most heavy ground-based weapon system types

Figure C-1. *The CV90 infanteriegevechtsvoertuig (CV9035NL). Source: Ministry of Defence*

Figure C-2. *The Bushmaster. Source: Ministry of Defence*

System type	Description
Bushmaster	Wheeled armoured vehicle
LVB Fennek	Wheeled reconnaissance vehicle
Mercedes-Benz G280 CDI	Wheeled vehicle
Mercedes-Benz 290 GD (all types)	Wheeled vehicle
Land Rover Defender 110XD WW	Wheeled vehicle
Patria XA-188 GVV	Wheeled armoured reconnaissance vehicle
Fuchs EOV	Wheeled reconnaissance
BvS10 NLD (Viking)	All-terrain vehicle
Bv206 NLD	All-terrain carrier
Air Transportable Vehicle	Air transportable vehicle
Luchtmobiel Speciaal Voertuig (LSV)	Air transportable vehicle
KTM	Motorcycle

Table C-2. An overview of the reconnaissance- and all-terrain (weapon) systems

System type	Description
DAF YA-4442 (all types)	Truck
DAF Y-2300 (all types)	Truck
DAF YBZ-3300	Tow truck
DAF YWL-3300	Truck
DAF trekker-opleggercombinatie (TROPCO) (both types: 400 kN & 600 kN)	Flat-bed trailer
Scania Wissel Laad Systeem (WLS)	Truck

Table C-3. An overview of the trucks and trailers

System type	Description
Liebherr FKM	Crane
Liebherr LTM	Crane
Grader (Champion)	Engineering vehicle
Graafdozer	Engineering vehicle
Wiellaadschop	Engineering vehicle
Trilwals	Engineering vehicle
Unimog	Engineering vehicle
Mini-bouwmachine	Engineering vehicle
Rupsdozer	Engineering vehicle
Graaflaadcombinatie 4CX-M	Engineering vehicle
Uni-bouwmachine	Engineering vehicle
Werklust-wiellader	Engineering vehicle specialized to construct short temporary roads
MLC-70 wegenmatsysteem	Engineering vehicle specialized to construct short temporary roads
Opritset Mabey & Johnson brug	Mobile bridge system
Medium Girder Bridge	Mobile bridge system
Vouwbrug systeem	Mobile bridge system

Table C-4. An overview of the engineering systems

Weapon equipment	Description
Mijnenleguitrusting	Minelayer
Stinger	Anti-aircraft weapon
GILL	Medium Range Anti-Tank (MRAT) weapon
Panzerfaust	Short Range Anti-Tank (SRAT) weapon

Table C-5. An overview of the weapon equipment

Figure C-3. *A Pantserhouwitser PzH2000NL in action in Afghanistan. Source: Ministry of Defence*

System type	Description
Future Ground Bases Air Defense System (FGBADS)	Air defence system
Waarschuwingsradar Luchtmobiele Stinger (WALS)	Radar warning system
Wapen Locatie Radar (WLR)	Weapon locating radar system
Gevechtsveldcontroleradar	Battlefield radar system
Positie en Richtingbepalende Apparatuur (PERBA)	Equipment to determine position as well as direction
NSM20P	Equipment to determine position as well as direction
Geluidmeetinstallatie	Noise measurement system

Table C-6. An overview of the (radar) support systems

System type	Description
NBC-ontsmettingssysteem	Nuclear, Biological and Chemical (NBC) decontamination facility
Mobiel operationeel geneeskundig operatiekamersysteem (Mogos)	Mobile operating room facility
Brandstofopvoer en -distributiesysteem (BODS)	Fuel distribution system
Waterboorinstallatie	Drilling rig for water extraction
Mobiel waterbehandelingsysteem (drinkwaterinstallatie)	Mobile drinking water installation
Mobiel voedselbehandelingsysteem	Mobile food supply facility
Mobiel sanitair systeem	Mobile sanitation system
Afvalverwerkingsinstallatie	Waste processing installation
Proefdraai installatie voor motoren	Trial run installation for the purposes of testing engines

Table C-7. An overview of the support facilities and installations

Figure C-4. *The Leopard 2-geniedoorbraaksysteem, also called "Kodiak". Source: Ministry of Defence*

APPENDIX D – General information about AM

In this appendix, general information about the technology Additive Manufacturing (AM), also popularly known as 3D printing, is given.
In section D.1, the history of AM is illustrated.
In section D.2, the primary manufacturing processes are described.
Also, in section D.3, the AM technologies and the corresponding materials, advantages and disadvantages are illustrated.
In section D.4, the materials that can be printed with each of the AM technologies are illustrated.
Furthermore, in section D.5, the process flow of additively manufacturing an Aerospace & Defense (A&D) part is illustrated.
Finally, in section D.6, the most important current and potential future applications for several sectors are illustrated.

D.1 History of AM

Cotteleer, Holdowsky & Mahto (2014) identify the most important historical AM events, as illustrated in Figure D-1.

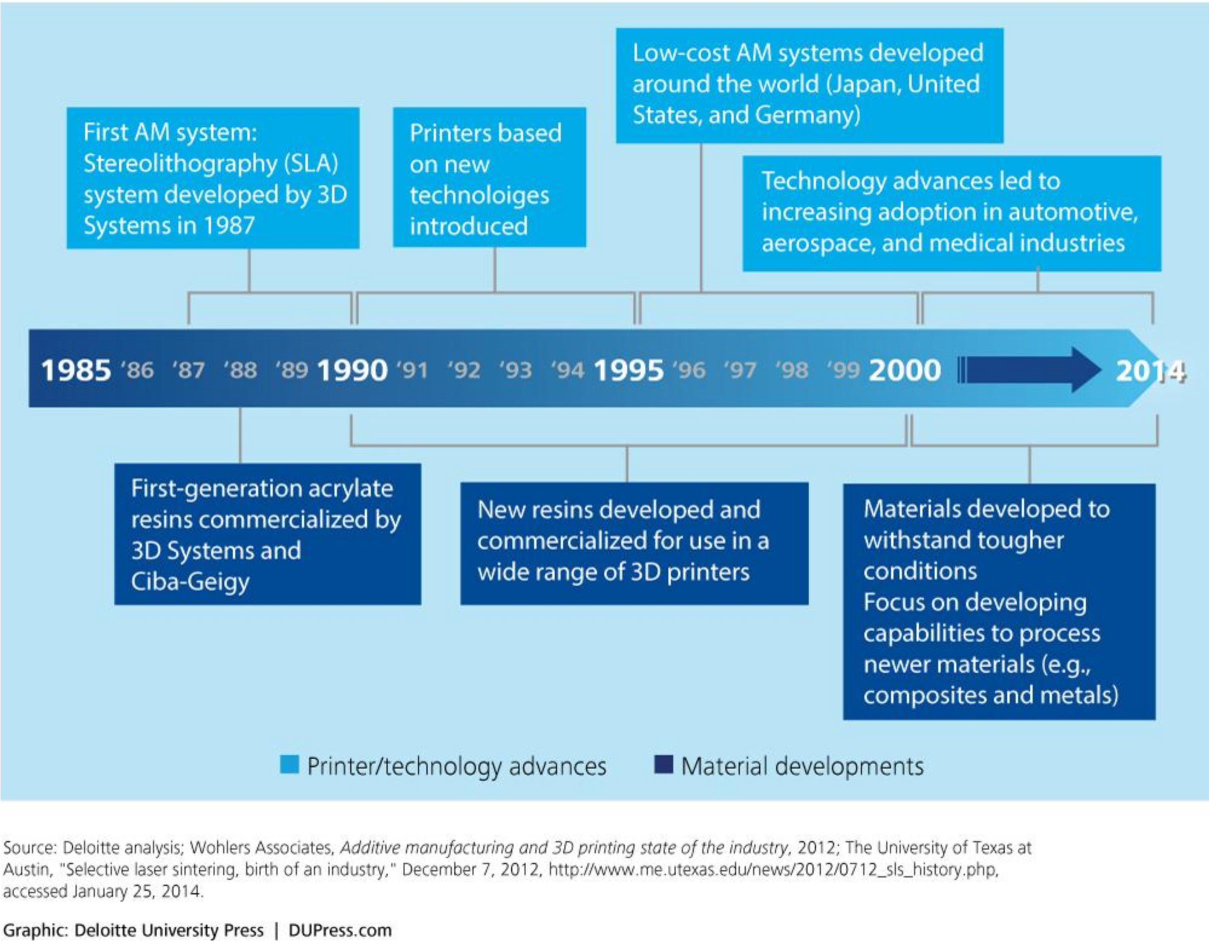


Figure D-1. History of AM (Cotteleer, Holdowsky, & Mahto, 2014)

D.2 Primary manufacturing processes

Cotteleer, Holdowsky & Mahto (2014) also describe the primary manufacturing processes of AM:

Vat photopolymerization

In vat photopolymerization, a liquid photopolymer (i.e., plastic) in a vat is selectively cured by light-activated polymerization. The process is also referred to as light polymerization.

Related AM Technologies: Stereolithography (SLA), digital light processing (DLP)

Material jetting

In material jetting, a print head selectively deposits material on the build area. These droplets are most often comprised of photopolymers with secondary materials (e.g., wax) used to create support structures during the build process. A UV light solidifies the photopolymer material to form cured parts. Support material is removed during post-build processing.

Related AM technologies: Multi-jet modeling (MJM)

Material extrusion

In material extrusion, thermoplastic material is fed through a heated nozzle and deposited on a build platform. The nozzle melts the material and extrudes it to form each object layer. This process continues until the part is completed.

Related AM technologies: Fused Deposition Modeling (FDM)

Powder bed fusion

In powder bed fusion, particles of material (e.g., plastic, metal) are selectively fused together using a thermal energy source such as a laser. Once a layer is fused, a new one is created by spreading powder over the top of the object and repeating the process. Unfused material is used to support the object being produced, thus reducing the need for support systems.

Related AM technologies: Electrom beam melting (EBM), selective laser sintering (SLS), selective heat sintering (SHS) and direct metal laser sintering (DMLS)

Binder jetting

In binder jetting, particles of material are selectively joined together using a liquid binding agent (e.g., glue). Inks may also be deposited in order to impart color. Once a layer is formed, a new one is created by spreading powder over the top of the object and repeating the process. This process is repeated until the object is formed. Unbound material is used to support the object being produced, thus reducing the need for support systems.

Related AM technologies: Powder bed and inkjet head (PBIH), plaster-based 3D printing (PP)

Sheet lamination

In sheet lamination, this sheets of material (e.g., plastic or metal) are bonded together using a variety of methods (e.g., glue, ultrasonic welding) in order to form an object. Each new sheet of material is placed over previous layers. A laser or knife is used to cut a border around the desired part and unneeded material is removed. This process is repeated until the part is completed.

Related AM technologies: Laminated object manufacturing (LOM), ultrasonic consolidation (UC)

Directed energy deposition

In directed energy deposition, focused thermal energy is used to fuse (typically metal) material as it is being deposited. Directed energy deposition systems may employ either wire-based or powder-based approaches.

Related AM technologies: Laser metal deposition (LMD)

D.3 AM technologies and corresponding base materials, advantages and disadvantages

Next to the history and the primary manufacturing processes, Cotteleer, Holdowsky & Mahto (2014) also describe the AM technologies, the corresponding base materials, advantages and disadvantages, as can be seen in Figure D.2.

Technology	AM process	Typical materials	Advantages	Disadvantages
Stereolithography	Vat polymerization	Liquid photopolymer, composites	Complex geometries; detailed parts; smooth finish	Post-curing required; requires support structures
Digital light processing	Vat polymerization	Liquid photopolymer	Allows concurrent production; complex shapes and sizes; high precision	Limited product thickness; limited range of materials
Multi-jet modeling (MJM)	Material jetting	Photopolymers, wax	Good accuracy and surface finish; may use multiple materials (also with color); hands-free removal of support material	Range of wax-like materials is limited; relatively slow build process
Fused deposition modeling	Material extrusion	Thermoplastics	Strong parts; complex geometries	Poorer surface finish and slower build times than SLA
Electron beam melting	Powder bed fusion	Titanium powder, cobalt chrome	Speed; less distortion of parts; less material wastage	Needs finishing; difficult to clean the machine; caution required when dealing with X-rays
Selective laser sintering	Powder bed fusion	Paper, plastic, metal, glass, ceramic, composites	Requires no support structures; high heat and chemical resistant; high speed	Accuracy limited to powder particle size; rough surface finish
Selective heat sintering	Powder bed fusion	Thermoplastic powder	Lower cost than SLS; complex geometries; no support structures required; quick turnaround	New technology with limited track record
Direct metal laser sintering	Powder bed fusion	Stainless steel, cobalt chrome, nickel alloy	Dense components; intricate geometries	Needs finishing; not suitable for large parts
Powder bed and inkjet head printing	Binder jetting	Ceramic powders, metal laminates, acrylic, sand, composites	Full-color models; inexpensive; fast to build	Limited accuracy; poor surface finish
Plaster-based 3D printing	Binder jetting	Bonded plaster, plaster composites	Lower price; enables color printing; high speed; excess powder can be reused	Limited choice of materials; fragile parts
Laminated object manufacturing	Sheet lamination	Paper, plastic, metal laminates, ceramics, composites	Relatively less expensive; no toxic materials; quick to make big parts	Less accurate; non-homogenous parts
Ultrasonic consolidation	Sheet lamination	Metal and metal alloys	Quick to make big parts; faster build speed of newer ultrasonic consolidation systems; generally non-toxic materials	Parts with relatively less accuracy and inconsistent quality compared to other AM processes; need for post-processing
Laser metal deposition	Directed energy deposition	Metals and metal alloys	Multi-material printing capability; ability to build large parts; production flexibility	Relatively higher cost of systems; support structures are required; need for post-processing activities to obtain smooth finish

Sources: Deloitte analysis; Wohlers Associates, *Additive manufacturing and 3D printing state of the industry*, 2012; Troy Jensen and Pipar Jaffray, *3D printing: A model of the future*, March 2013; Justin Scott, IDA Science and Technology Policy Institute, *Additive manufacturing: status and opportunities*, March 2012.

Figure D-2. AM technologies and correspoding base materials, advantages and disadvantages (Cotteleer, Holdowsky, & Mahto, 2014)

D.4 Materials per AM technology

Cotteleer, Holdowsky & Mahto (2014) identify the materials that are possible to be additively manufactured per AM technology, as can be seen in Figure D-3.

Technology	Polymers	Metals	Ceramics	Composites
Stereolithography	●			●
Digital light processing	●			
Multi-jet modeling (MJM)	●			●
Fused deposition modeling	●			
Electron beam melting		●		
Selective laser sintering	●	●	●	●
Selective heat sintering	●			
Direct metal laser sintering		●		
Powder bed and inkjet head printing[13]	●	●	●	●
Plaster-based 3D printing			●	●
Laminated object manufacturing[14]	●	●	●	●
Ultrasonic consolidation		●		
Laser metal deposition		●		●

Sources: Deloitte analysis; Wohlers Associates, *Additive manufacturing and 3D printing state of the industry*, 2012; Phil Reeves, *3D printing & additive manufacturing: Extending your printing capability in true 3D*, Econolyst, June 12, 2012; Justin Scott, IDA Science and Technology Policy Institute, *Additive manufacturing: Status and opportunities*, March 2012.

Graphic: Deloitte University Press | DUPress.com

Figure D-3. AM Technologies and materials matrix

D.5 AM process flow of an A&D part

Coykendall, Cotteleer, Holdowsky & Mahto (2014) show the process flow of manufacturing of an Aerospace & Defense (A&D) part with AM, as illustrated in Figure D-4. The process flow consists of five main steps.

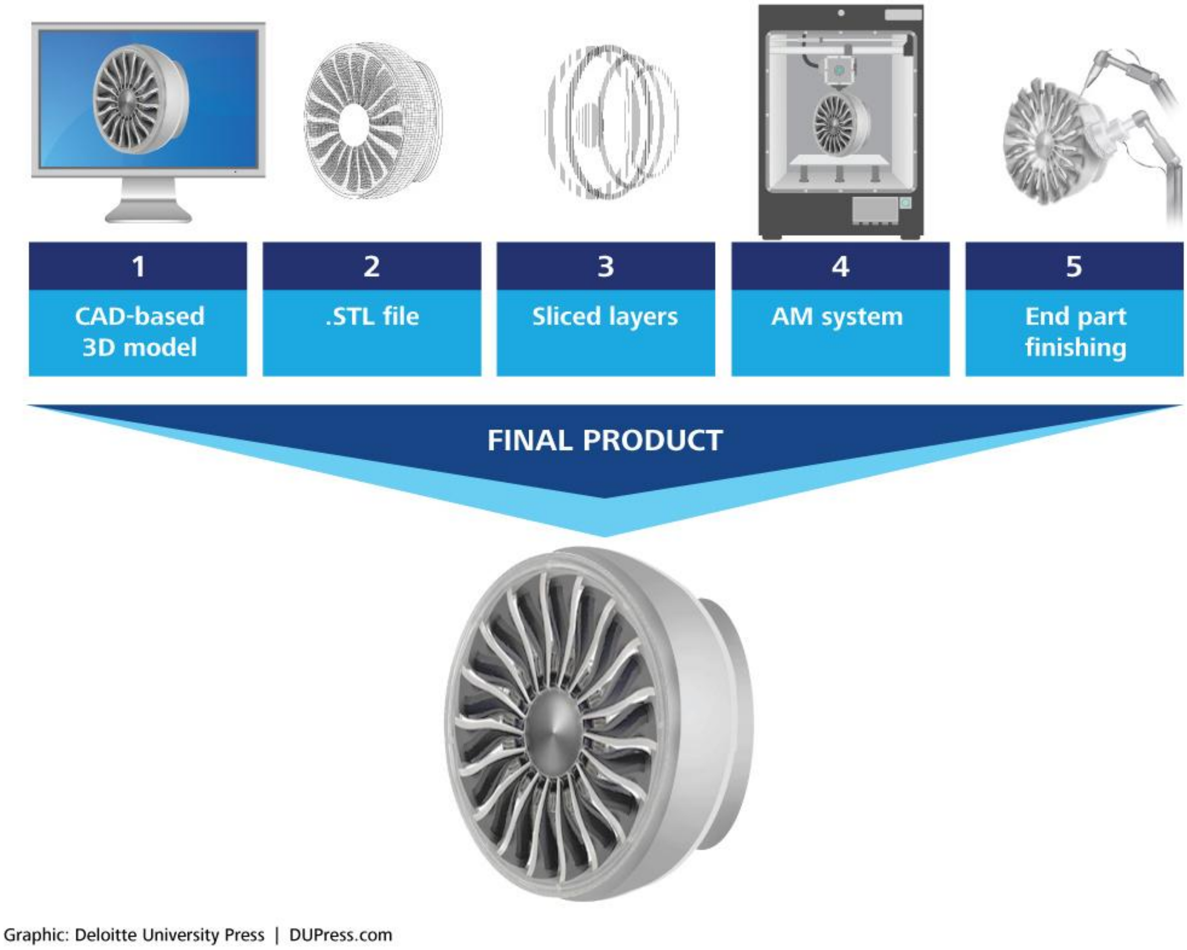


Figure D-4. AM Process flow of an A&D part (Coykendall, Cotteleer, Holdowsky, & Mahto, 2014)

D.6 Current and future applications of AM in several sectors

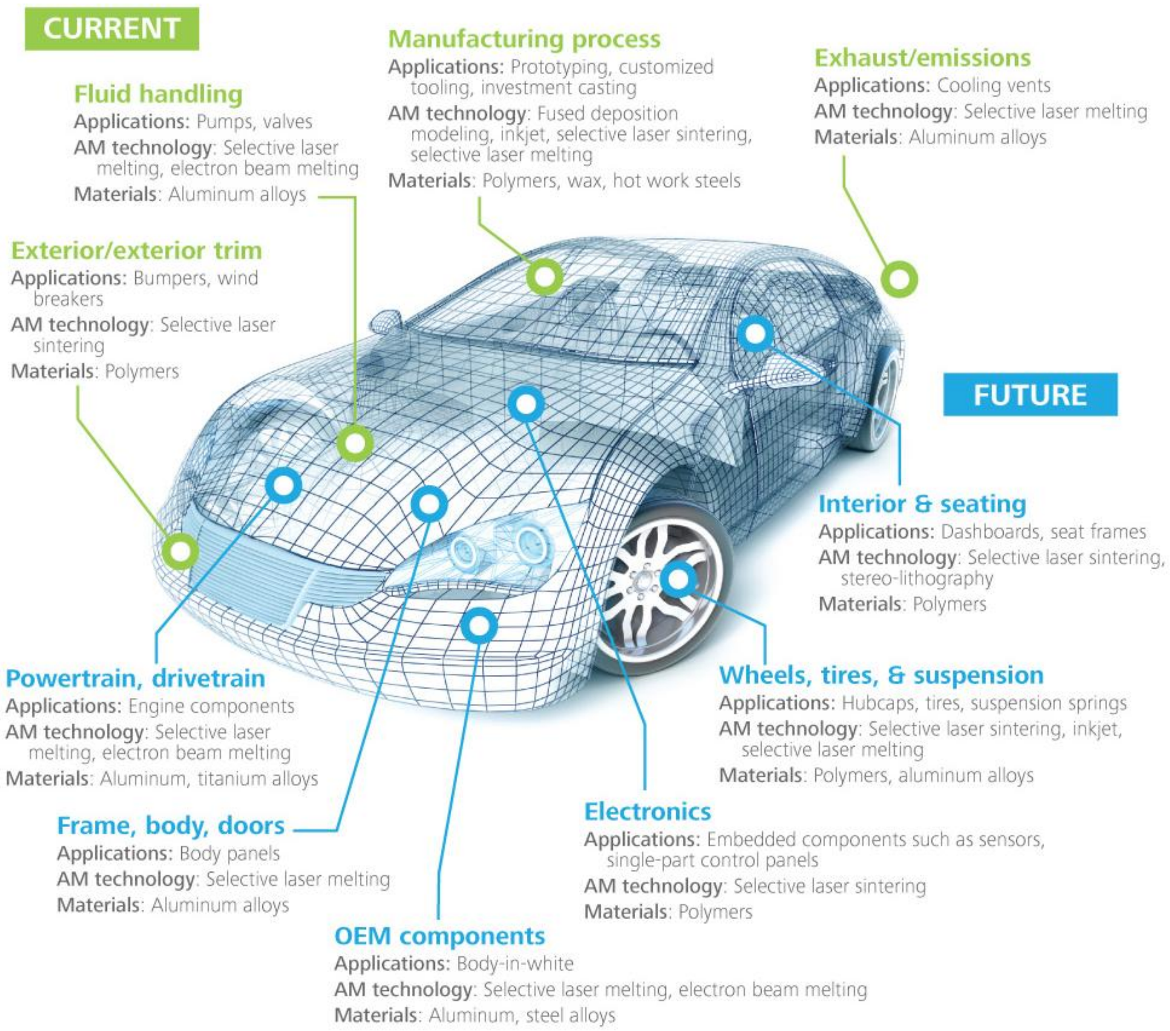
Finally, Cotteleer, Holdowsky & Mahto (2014) identify the most important current and potential future applications in several sectors, as illustrated in Figure D-5.
In Figure D-6, the current and expected future applications in the automotive industry are illustrated.

INDUSTRIES	CURRENT APPLICATIONS	POTENTIAL FUTURE APPLICATIONS
COMMERCIAL AEROSPACE AND DEFENSE[17]	• Concept modeling and prototyping • Structural and non-structural production parts • Low-volume replacement parts	• Embedding additively manufactured electronics directly on parts • Complex engine parts • Aircraft wing components • Other structural aircraft components
SPACE	• Specialized parts for space exploration • Structures using light-weight, high-strength materials	• On-demand parts/spares in space • Large structures directly created in space, thus circumventing launch vehicle size limitations
AUTOMOTIVE[18]	• Rapid prototyping and manufacturing of end-use auto parts • Parts and assemblies for antique cars and racecars • Quick production of parts or entire	• Sophisticated auto components • Auto components designed through crowdsourcing
HEALTH CARE[19]	• Prostheses and implants • Medical instruments and models • Hearing aids and dental implants	• Developing organs for transplants • Large-scale pharmaceutical production • Developing human tissues for regenerative therapies
CONSUMER PRODUCTS/RETAIL	• Rapid prototyping • Creating and testing design iterations • Customized jewelry and watches • Limited product customization	• Co-designing and creating with customers • Customized living spaces • Growing mass customization of consumer products

Sources: Deloitte analysis; CSC, *3D printing and the future of manufacturing*, 2012.

Graphic: Deloitte University Press | DUPress.com

Figure D-5. AM current and potential future applications in several sectors



Source: Deloitte analysis.

Graphic: Deloitte University Press | DUPress.com

Figure D-6. Overview of the current and expected future applications in the automotive industry

APPENDIX E – Model of the after-sales service supply chain including the information flow

For a given maintenance task, spare parts are needed. The RNLA uses the Enterprise Resource Planning (ERP) system SAP Material Logistics & Finance (M&F) to coordinate this process.
The spare parts need to be ordered in advance by means of a job order (WO, in Dutch: “Werk Order”): a summary of all necessary unique spare parts and their associated quantities to complete a certain maintenance job. A particular spare part can be ordered by multiple end-users during the same day. During a given working day, WO’s are inserted into the SAP-system. At the end of each working day, an MRP-run is being performed. If the inventory level is sufficient (that is: the On Hand Inventory (OHI) of a certain spare part minus the total amount ordered of that particular spare part on the same day is equal to or lower than the reorder point (ROP)), Internal Transport Needs (ITB’s, in Dutch: “Interne Transportbehoefte”) are generated and sent to the particular warehouse. However, if the inventory level is insufficient, an ATB (Request to order, in Dutch: “Aanvraag Tot Behoeftevervulling”) is generated and sent to the depot, that sends an ATB to the particular assortment manager at the Logistics Department. A recommendation of the amount of parts to be purchased of the considered spare part type is also calculated by the system. The assortment manager eventually determines the amount of parts to be purchased (if any). The Purchase section needs official approval of the assortment manager and the determined amount of spare parts to be purchased per spare part type to start the purchasing process: converting the ATB’s into purchase orders that will eventually be sent to the manufacturer.

At the beginning of the next working day, the MRP-run will be finished successfully. Before the several ITB’s and ATB’s are sent, they need to be authorized manually by the head of the unit that inserted the work orders in the first place.

A model of the after-sales service supply chain including the information flow is illustrated in Figure E-1.

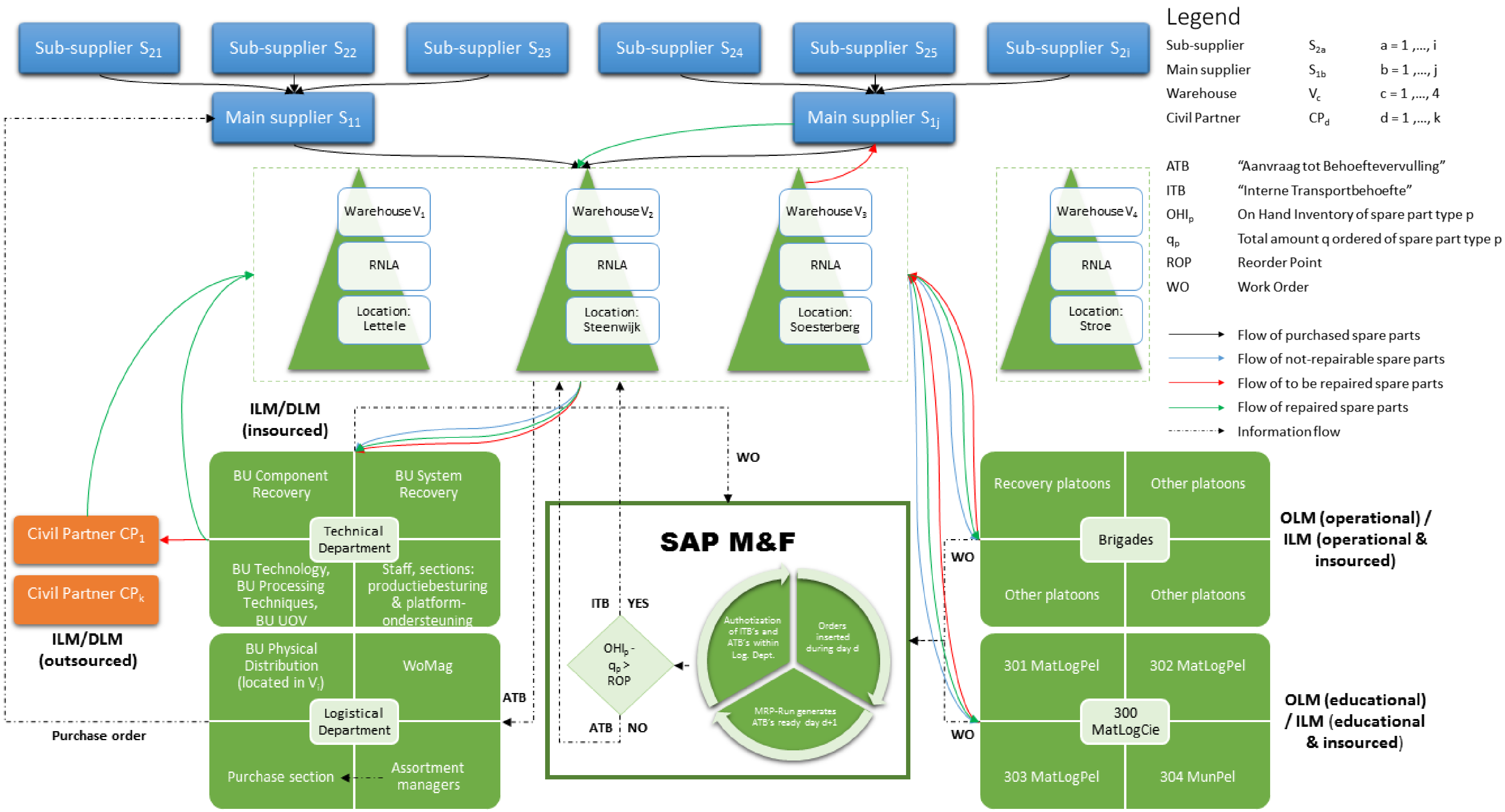


Figure E-1. A model of the after-sales service supply chain of the RNLA. Including the information flow

APPENDIX F – Opportunities of AM in the after-sales service supply chain

In this appendix, the opportunities of Additive Manufacturing (AM) in the after-sales service supply chain are discussed extensively. A literature study is performed to successfully identify the opportunities of AM in the after-sales service supply chains for organizations in the Defense industry.

First, to give an idea what AM actually is, general information about the technology is given in appendix D.
Second, the main benefits of additively manufacturing spare parts in the Defense industry in general are identified. According to by Coykendall, Cotteleer, Holdowsky & Mahto (2014), significant reductions can be made in **total part cost**, **scrap rates**, **part weight** and in **time-to-market** (that is: the length of time between the start of a product development process until the finished product).
Next to that, **no economies of scale** during manufacturing with AM need to be achieved to cause minimal cost per part. The manufacturing can always start with just one part without exceeding minimum variable part costs.
Due to on-demand manufacturing, **lead times** and **inventory** can be reduced significantly. As a result, the **transport- and inventory cost** will significantly be reduced as well. The significant savings on required transportation result in a more **sustainable** after-sales service supply chain. At the same time, also the **service level** and **flexibility** in the after-sales service supply chain are improved.
Another main advantage is the **complexity** of production units. Marx, Thompson & Thut (2013) state that "the complexity of the part is limited only by the imagination of the designer and the computing power of the 3D modeling software". These are significant improvements in geometric design, given the current geometric design constraints imposed by traditional manufacturing. Marx, Thompson & Thut (2013) also mention that not only **component parts**, but also **sub-assemblies** and **inter-connected** parts are able to be manufactured with AM.
Next to that, spare parts that require multiple manufacturing processes can be additively manufactured by means of just **one process**.

Marx, Thompson & Thut (2013) doubt the potential of AM: it will ultimately depend on how far AM can improve the product quality and processing speed. Aerospace & Defense (A&D) companies are recommended to actively track the technology developments and set threshold for the point at which it might be beneficial for the particular company to start investing in AM.

Louis, Seymour & Joyce (2014) describe the opportunity of AM for the American Defense industry. The type of industry might be the same, the total obligation authority differs greatly between the Dutch and the American defense industry. The total obligation authority of the Department of Defense (DoD) was around $650 billion in 2011 (Louis, Seymour, & Joyce, 2014), compared to around € 7,6 billion for the Dutch Ministry of Defense (MinDef) in 2013 (Rijksoverheid, 2013).
A major explanation for this difference is the fact that the United States Armed Forces (U.S. Forces) possesses many more (combat) systems than the AFN.
The history of experiments with AM and the actual application of additively manufactured parts within the Department of Defense (DoD) goes back to the 1990s. Therefore, the AFN needs to analyze the applications of AM within the U.S. Forces. A summary of the most important applications of AM within the U.S. Forces in general are identified and given in appendix G. As mentioned in Appendix G, it is even possible to produce spare parts on-site in combat zones with AM.

F.1 Potential impact of AM within the Department of Defense

According to Louis, Seymour & Joyce (2014), AM has the potential to transform the after-sales service supply chains within the DoD in two fundamental ways:

1. AM has the potential to lower the barriers to entry to manufacturing for a given location, and so the potential to impact how supply chains are designed;
2. AM has the potential to impact product designs by reducing the costs associated with production changeovers and customization.

As an asset owner, only the potential impact how supply chains are designed is relevant.

F.2 Opportunities for the Department of Defense

The following opportunities for the DoD are given by Louis, Seymour & Joyce (2014):

- Digital supply chains (supply chains where design data is used to create products and components on demand) can help eliminate the need for large, centralized production facilities to achieve economies of scale and reduce transportation cost, which will make the military significantly more agile through smaller and more secure supply chains;
- It reduces the need to forecast supply chain capacity accurately;
- Digital supply chains open up the possibility of realizing higher operational readiness and more possible deployments of military units.

To better understand the opportunities AM can offer, Louis, Seymour & Joyce (2014) mention how organizations are leveraging AM to create digital supply chains. The conclusion was that organizations choose one of the following four tactical paths, depending on their needs, goals, and circumstances. The tactical paths are based on two variables: the desire to change supply chain and the desire to change the product within the supply chain. For the AFN, the desired impact on product change is low. Therefore, only the first two tactical paths will be discussed. All the four tactical paths are illustrated in Figure F-1. In Figure F-2, examples of AM applications of DoD entities that pursuit one of the paths are given.

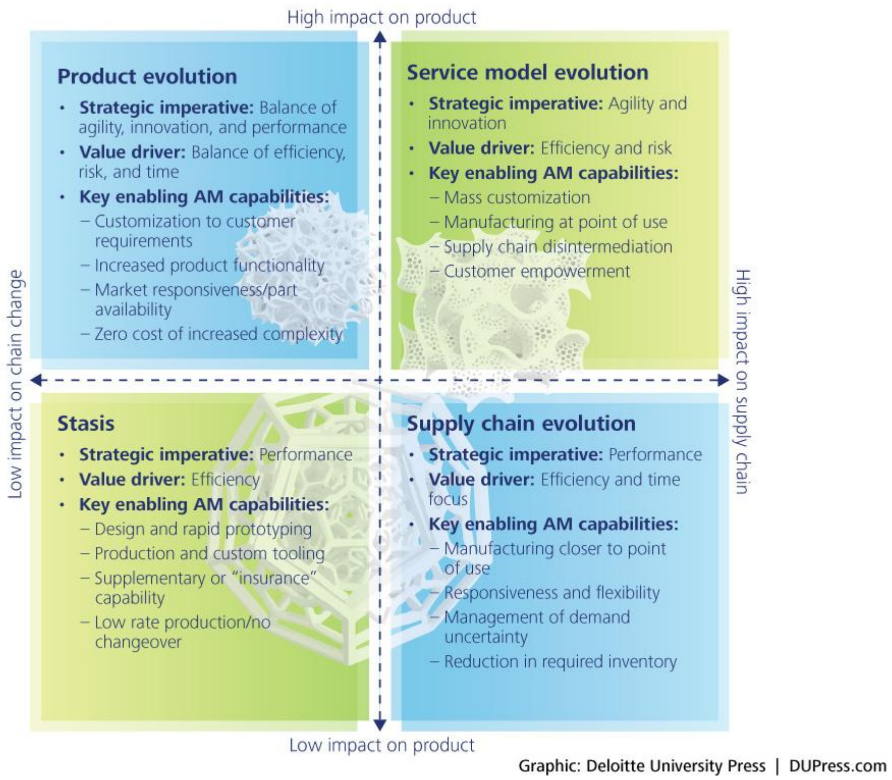


Figure F-1. The four tactical paths organizations choose depending on their needs, goals and circumstances, with modified criteria for the mission-driven organization that the DoD is (Louis, Seymour, & Joyce, 2014)

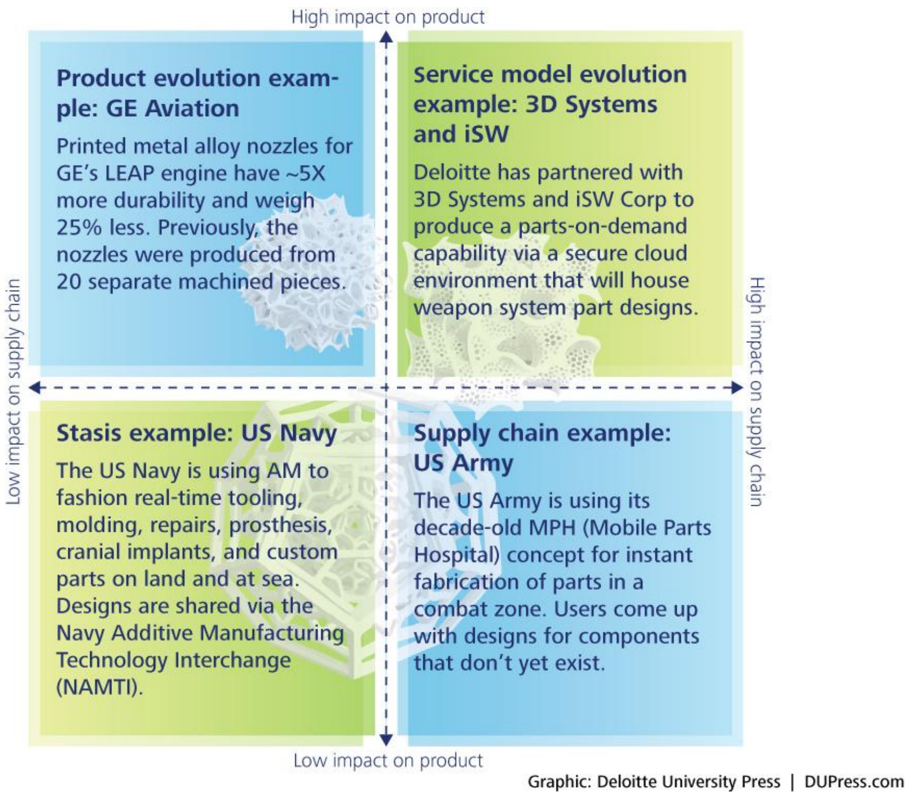


Figure F-2. Examples of AM applications of DoD entities that pursuit one of the four tactical paths (Louis, Seymour, & Joyce, 2014)

Path I: Stasis

If the Royal Netherlands Army decides to consider AM to have only a low impact on both the systems as well as the after-sales service supply chain, several opportunities are identified by Louis, Seymour & Joyce (2014). By pursuing this path, organizations mainly tend to explore AM to eventually improve the value of current products without changing the configuration of their current physical supply chains. This is the path that most DoD entities pursuit, mainly because they are tend to be conservative in implementing new technologies. Therefore, most of these entities will continue to pursue this path until the AM applications are proven to be combat-ready.
There are many examples of AM applications where the pursuit of the Stasis Path leads to:

- **Lead time reduction**;
- **Improved functionality of parts**;
- **Increased ability to customize parts**;
- **Overcoming obsolescence**: AM can produce parts of which the original manufacturer has stopped its production. This is especially interesting for the Defense industry, since most of the systems and equipment in this industry is in use for decades.

Path II: Supply chain evolution

By choosing the path of 'Supply chain evolution', AM is applied to result in a high impact on only the supply chain, and at the same time a low impact on the products within these supply chains.
Since the AFN does not manufacture the system themselves, which the U.S. Forces does not either, its primary task in the product lifecycle is to use and maintain the systems it has been provided with. This task has become extremely important, since the purchased military systems are used for decades. The corresponding Maintenance, Repair and Overhaul (MRO) enterprise is complex, requires skilled labor at relatively few locations and the particular after-sales service supply chain carries buffer inventory of millions of parts from suppliers geographically dispersed all over the world. A generic MRO process is viewed in Figure F-3 and it exists of three primary steps.
At Gate 1 (Tear-down & disassembly), the equipment, end-item, or its sub-assemblies are disassembled and inspected to determine the type and degree of repair required or whether the parts need to be replaced. At Gate 2, disassembled parts are repaired and gathered for the final assembly. Finally, at Gate 3, the parts are assembled into sub-assemblies, which on their turn are assembled back into end-items. After the complete MRO-process has been finished, the assembled end-items are tested and validated before they are returned to their end user.
In Gate 1 as well as in Gate 2 (Repair), several opportunities for the application of AM are identified:

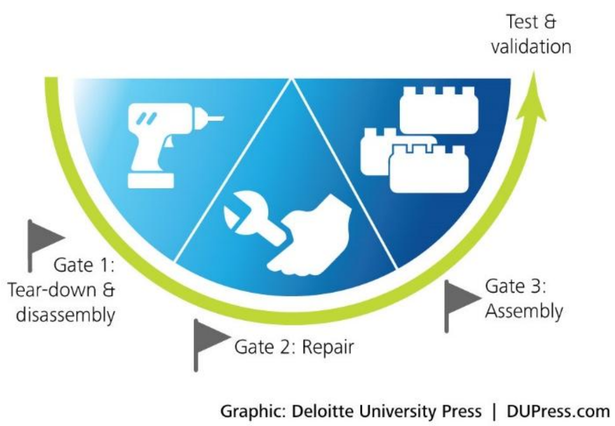


Figure F-3. A generic MRO process (Louis, Seymour, & Joyce, 2014)

Since the necessary repairs vary by time and the usage can differ significantly from end-item to end-item and sub-component to sub-component, demands on the physical supply chain and the resulting throughput are incredibly variable. However, when these parts are manufactured with AM, the ability to respond to that variability is significantly increased by enabling the on-demand manufacture of a new part, while the traditionally manufactured part is sent to Gate 2 for repair and/or overhaul.

The variability between repairs at Gate 2 is caused by differences in volume, necessary steps and specifications between parts. Next to that, it can take a significant amount of time to repair many traditionally manufactured part, especially those with tight quality tolerance or made from unique materials. For these reasons, traditional supply chains tend to excessively stock the parts that take a long time to repair (Louis, Seymour, & Joyce, 2014).

In conclusion, the following opportunities in the MRO-process are identified:

- **By enabling the on-demand manufacture of a required part, it significantly improves the ability to respond to demand variability;**
- **It minimizes the need to carry excess inventories;**
- **The accumulated effects of the above-mentioned benefits will have a positive impact on the throughput in Gate 2.**

F.3 Potential supply chain cost savings

Since at the RNLA all the end-users of spare parts are served from the warehouses, the consequences of transitioning a fraction of the spare part assortment from traditional manufacturing by the OEM or its sub-supplier to additively manufacture the required spare part at the warehouses needs to be considered. Bhasin & Bodla (2014) prove that significant cost savings can be made in the supply chain by comparing current total supply chain cost and total supply chain cost with AM. The most important benefits are identified:

- Reduction in total product cost, mainly by means of significant savings in transportation cost and inventory cost;
- Significant savings can already be achieved by relatively low adoption of AM in the after-sales service supply chain.
- Improvement in product availability, leading to higher customer satisfaction;
- Potential increase in market share in the spare parts business.

The limitations of the business case need to be mentioned:

- The model is biased towards the automotive industry and the considered geography;
- The data for the presented cases has been gathered from a limited number of sources;
- Only injection molding was considered as the traditional manufacturing method;
- A uniform cost of materials and local availability of the required 3D print material was assumed;
- Quality aspects were not taken into account;
- The manufacturing time with AM was not considered.

APPENDIX G – Applications of AM within the United States Armed Forces

The history of experiments with AM and the actual application of additively manufactured parts within the United States Department of Defense (DoD) goes back to the 1990s. The main applications are the following:

Figure G-1. Symbol of the DoD

G.1 Army Expeditionary Lab

The Rapid Equipping Force (REF) uses Expeditionary Labs (fully equipped and easily deployable rapid prototyping laboratories) which contains 3D printers and other computer-directed manufacturing devices. The materials can be used to construct parts consist of plastic, steel and aluminum (Kuneinen, 2013). The main task of these labs is to allow soldiers and engineers to solve problems on the battlefield. In 2012, two of these labs were deployed in Afghanistan. The reengineering by the Expeditionary Labs of a Mine Resistant Ambush Protected (MRAP) valve that frequently broke in the battlefield, is a good example of how these labs contribute to improved product flexibility in the Army supply chain. After testing multiple new valve covers, the new designs were sent to the United States and the new manufactured parts were sent back to Afghanistan. According to REF Director Peter Newell, it was a "30-day discussion rather than a multi-year process" (Chayka, 2013).

G.2 Mobile Parts Hospital

One step further in the application of AM in the supply chain of the United States Army is the Mobile Parts Hospital (MPH), which are developed to be deployed in battle zones. It is designed to produce low volume spare parts on-site and can produce almost all the low volume spare parts used in the battlefield. It produced around 100,000 spare parts and special tools in the period starting from 2003, when it was first deployed in Kuwait, until 2011 (Zhang, Zhang, Zhang, Jin, & Liu, 2011).

Figure G-2. Drawing of an example of a future lab of the US Army's Mobile Parts Hospital. Required spare parts are manufactured at the point of use in the US Army (Louis, Seymour, & Joyce, 2014)

G.3 Rapid Manufacturing and Repair Program

The Rapid Manufacturing and Repair (RARE) Program is one of these applications and need to be mentioned in this chapter. The RARE program started in 1991 and is applying AM within the maintenance base of the US Army in several ways. It analyzes the cost savings, cost avoidances and the improvement to be achieved on the depot efficiencies (Mackley, 2014):

- Improvement in flexibility;
- Rapid response capability in event of supply chain deficiency/disruption;
- Capability to replicate, redesign and print obsolete but critical parts;
- Capability to create improved part designs.

The main applications within the RARE Program are the following (Mackley, 2014):

- The additively manufacturing of tools in the Fleet Readiness Center (FRC) East;
- The combination of using 3D Laser Scanning and AM within the FRC Southwest Advanced Technology Center resulted in a proof of concept project for the F-18 E/F engine bay door hat stiffener layup tooling. The estimated savings could exceed $1.5 million per year.
- At the Anniston Army Depot, AM is applied to add corrosion- and wear- resistant materials to specific areas of carbon steel parts. Next to that, it is also applied to print balance material on components that are reassembled, rebalanced, and reused. An example the external air seal edge of a gas turbine wheel.

G.4 Edgewood Chemical and Biological Center

This center is part of the Research Development and Engineering Command within the United States Army. It manufactures prototypes for testing with AM since the 1990s. Two successful developments of the Edgewood Chemical and Biological Center is the night-vision battery storage and unmanned vehicle tools (Chayka, 2013).

G.5 Chief of Naval Operation's Rapid Innovation Cell

Not only in the United States Army, also in the United States Navy AM is applied. Within the Navy Warfare Development Command, the Chief of Naval Operations´ Rapid Innovation Cell (CRIC) a trial with this technology is conducted. A trial 3D printer was installed on a carrier in 2014. It is deployed for trials with four applications: to print medical instruments, to print prosthetics, to print items that are generally used by the carrier's crew and to experiment. Eventually the CRIC wants to create a database of digital models, which can be used to print on-demand for afloat units (Chayka, 2013).

G.6 Walter Reed National Military Medical Center

This center was established in 2002 and manufactures multiple surgical instruments with AM. The first project was to create medical models of body parts. This lead to reduced surgery times by an average of six hours. Next to that, they now use custom surgical guides that are produced by AM as well, which can assist the surgeons of the center during the surgery. Custom metal implants manufactured with this technology are currently used as well, such as cranial implants for just $75, while the original implants cost $15,700. The price of $75 is without the costs for the 3D printer itself. If this is included, the price for the printed implant will be similar to the original one, but the printed implant still fit the patient better (Mackley, 2014). Another main advantage is the fact that no specialists are needed anymore to manufacture the implants with AM, so the risk of not being able to print the part is therefore reduced.

G.7 Combat Support Hospitals

The surgical supplies used by Combat Support Hospitals of the United States Armed Forces in war zones is an example in which the application of AM could lead to improved treatment of patients and eventually save lives in the process. Significant improvements in the supply chains of surgical supplies can be made. The increasingly complicated injuries of soldiers and civilians in war zones, mainly because of the increased use of Improvised Explosive Devices (IED's), makes it extremely difficult to predict the usage of surgical supplies. Therefore, extremely high transportation costs involved in shipping large volumes of surgical instruments and implants are needed. On-demand printing of surgical supplies could therefore be a solution, which is currently being investigated (Yu & Khan, 2015).

G.8 Mississippi National Guard

Another example of the application of AM within the US Army is the following:
EOIR Technology was contracted to create 40 camera mounts for gun sights on M1 Abrams tanks and Bradley fighting vehicles for the Mississippi National Guard. After its subcontractor's designs for the mount failed performance tests, they contacted Stratasys, a company that manufactures 3D printers. EOIR concluded that the mounts manufactured by AM did pass performance tests and at the same time dramatically reduced cost from over $100,000 by using traditional manufacturing, to less than $40,000 by using AM (Stratasys).

APPENDIX H – COMMERCIAL IN CONFIDENCE –

Overview of the spare part (sub) assortments

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APPENDIX I – COMMERCIAL IN CONFIDENCE –

Limitations of characteristics criticality & design ownership

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APPENDIX J – COMMERCIAL IN CONFIDENCE – Sources of applied data fields

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APPENDIX K – Data gathering

Before the scoring procedure can be performed, the reliability of the required data needs to be analyzed. The first step to achieve this, is to investigate the ERP-system that is used to coordinate the spare parts through the after-sales service supply chain to their end-users. The next step is to successfully gather the required data based on the relevant set of criteria. Subsequently, the representativeness of the collected data needs to be investigated. In order to successfully use the necessary values for each characteristic, inconsistencies in the data need to be identified and removed. This last step is called data cleaning.

In this Appendix, these necessary steps required to successfully gather the required data and investigate the data quality are described.

K.1 Source of retrieved data

In order to successfully retrieve the data per characteristic, first the appropriate source of data per characteristic needs to be identified. For some of these characteristics, the data is not available in the ERP-system and therefore, the following alternative sources will be used to estimate the values for each spare parts for these characteristics:

- The End Life Of Type (ELOT) is considered the same for all components of a particular system type. The alternative sources are confidential and therefore mentioned in Appendix N (Commercial in Confidence). In this Appendix, an overview of the ELOT per system type is given, including the particular source (if accessible);
- All components of the system types that are considered to be in the initial lifecycle phase are considered to be "items in the initial lifecycle phase". Based on interviews with employees and the confidential sources that are also used to retrieve the ELOT per system type, the system types that are in the initial lifecycle phase can be identified;
- Of a confidential amount of system types (mentioned in Appendix I (Commercial in Confidence)), the RNLA possesses a significant amount of the part designs. Unfortunately, it is obvious that it will be very time consuming to find out of which components the designs are available. Therefore, for these system types, it is first assumed that designs are possessed of all associated components. After identifying the most promising spare parts based on the logistical and economic criteria, the actual availability of the designs of these components will be verified.

For most remaining criteria, only real-time data is needed in order to analyze the relevant spare part pool. However, in order to calculate the average annual usage and the average days in inventory, additional historical data is needed as well in order to come up with a representative analysis.

A summary of the necessary data per characteristic is given in Table K-1.

Real-time data only:	Real time data as well as additional historical data:
Resupply lead time	Average annual usage
Purchasing cost	Average days in inventory
Criticality	

Table K-1. Characteristics for which only real-time data is needed versus characteristics for which additional historical data needs to be retrieved.

As mentioned in Appendix E, the Enterprise Resource Planning (ERP) system that is used by the several maintenance locations is called SAP M&F, of which M&F stands for Material logistics & Finance (in Dutch: "Materieellogistiek & Financiën"). The several maintenance locations were transferred to SAP in stages. This process started in 2012 and ended at the end of 2013. This means that it is not possible to retrieve spare part data from this particular ERP-system from before 2014. Furthermore, as mentioned in Appendix E, the required spare parts for a certain job are inserted in the SAP-system by means of work orders (WO's). Because of that, it will take a significant amount of work to create an overview of all the used spare parts. Fortunately, the staff at the Systems & Analysis (S&A) Department can execute these analyses relatively easy. For that reason, an overview can be created by the staff of the S&A-Department to analyze the data. This overview will include the average annual usage of the last three years, since the data of the overall annual usage per spare part was already retrieved from the former system. Unfortunately, only the spare parts that have been used at least once could be gathered, since it would have been too time consuming to collect the data of all unique parts (the exact number of unique parts is given in Appendix L (Commercial in Confidence)).
Also, the inventory per SKU (in order to calculate the average days in inventory on hand per SKU) could not be retrieved from the former system, since this would have been too time consuming. For that reason, only the spare part data since 2014 will be considered in order to calculate the average days in inventory on hand per SKU. Since the data need to be as reliable as possible, the values of this particular characteristic need to be gathered from multiple data points.

K.2 Data points

A limited amount of data points is available in order to calculate the values of the characteristic average days in inventory. The data of five months is considered, as illustrated in Table K-2. If the part is inserted in the ERP-system before March 2014, five data points will be considered. If the part was inserted between December 2014 and April 2015, only one data point will be considered. The number of (unique) spare parts considered per data point is confidential and therefore given in Appendix L (Commercial in Confidence).

Characteristic	Month(s) considered
Average days in inventory	March 2014 May 2014 September 2014 December 2014 April 2015

Table K-2. An overview of the used data points for the characteristic "average days in inventory"

K.3 Data representativeness

The data representativeness is discussed in Appendix L (Commercial in Confidence).
Because the data of 2014 cannot be considered as fully representative, there will be a fraction of very slow movers that was supposed to move through the spare part supply chain in the considered period, but for some reason did not move at all. Unfortunately, it is not (yet) possible to make a distinction between the actual non-movers and the very slow movers that would have been used in a representative period.

The data that is analyzed in a period of one to three years might not be completely representative. This is due to the fact that the cycle of necessary Depot Level Maintenance (DLM) per system type takes multiple years. The duration of the DLM-cycle could differ between several system types. The intention of the BU System Recovery is to equally distribute the quantity of systems per system type over the years of one DLM-cycle. Next to that, the intention is also to equally distribute the systems, that are assigned to a particular year in the cycle, over the year itself as well.
However, it can be concluded that even though all the maintenance locations implemented the system before the beginning of 2014, the available data that can be extracted from the SAP M&F-system is not fully representative at the time of writing.

The backlog at the Logistical Department of MatLogCo is discussed in Appendix L (Commercial in Confidence) and does not have consequences for all criteria during the considered period. It does however have consequences for the average annual usage and the average days in inventory. Since the demand was not satisfied for all spare parts, the overall annual usage could be lower than required. Additionally, the total amount of purchase orders most likely was lower than required as well. As a consequence, the average inventory could have been lower in the considered period.

K.4 Results of data gathering

The overview of the total spare part assortment of 11944 spare parts with the data of each applied characteristic was created by the staff of the S&A-Department.

Of some assortments, no spare parts have been used in the considered period. To see an overview of all the considered spare part assortments, please refer to appendix H.

As mentioned in Appendix L (Commercial in Confidence), around 90% of the spare part assortment consists of very slow movers and non-movers. The annual usage of these parts in general is less than one and therefore barely ‘move’ through the spare part supply chain. There are several reasons why around half of the complete assortment can be considered as a very slow mover:

- Spare parts purchased for the Life Of Type (LOT); the duration of operational functionality of a particular system type until it needs to be upgraded or replaced (Acuitas Reliability Pty Ltd). After taking the system type into operation, it could take years until these parts are used;
- Spare parts that will only be necessary in wartime;
- Spare parts that barely move for several other reasons, for example because the particular parts that are installed in the operational systems that will not break down during the LOT;

Unfortunately, the data of the very slow movers could not be gathered.

Next to the very slow movers, the data also consists of non-movers. These are spare parts that have become obsolete, for example because the maintenance policy has been adjusted or because the particular system type is not in use anymore. Because of that, these parts do not ‘move’ through the spare part supply chain anymore, so significant cost savings can only be achieved on holding cost. However, savings on holding cost do not have priority for the RNLA within their after-sales service supply chain. Hence, the non-movers should not be part of the spare part analysis.

In Appendix L (Commercial in Confidence), the data fields that are used to gather the required data are illustrated. In total, the data of 15455 unique parts is gathered.

K.5 Data cleaning

In this section, the amount of excluded unique spare parts is mentioned and discussed.

Excluded from spare part analysis

Nine spare part assortments (one spare part assortment contains all parts of mostly one system type) are considered to be irrelevant for the data analysis in this research and need to be excluded from the initial data set. Because of this, a total of 2237 spare parts was excluded.
Second, non-overhaul parts need to be excluded from the analysis as well to make sure no assemblies and complete systems are analyzed, since no differentiation is made between different components, assemblies or end products.

In order to still be able to exclude the most complex assemblies, only non-overhaul parts are taken into account. In this step, 1272 overhaul parts were excluded. Furthermore, as mentioned in Chapter 2, the spare parts stocked at the depot in Soesterberg are overhaul parts and must be must not be analyzed. By excluding this depot, no further parts are excluded, since all overhaul parts are already removed from the data set. This step also dramatically reduced the number of items that remains at the depot in Stroe, where normally only new systems are stocked temporarily. Only 33 non-overhaul parts remain at the depot in Stroe, after excluding 248 overhaul parts from the total spare part pool of 281 spare parts. Of these 33 items that are considered non-overhaul parts, two items are actually military systems. Clearly, these must not be analyzed.

After excluding all the necessary parts, 11944 parts remain that will be further analyzed in this research. An overview of the exact steps is confidential and therefore illustrated in Appendix L (Commercial in Confidence).

Included in spare part analysis

Of these 11944 parts that will be analyzed, the spare parts of which the data for one or more characteristics is inconsistent or unknown, need to be identified.

In order to add a spare part into the current SAP-system by MatLogCo, the purchasing cost needs to be inserted. Since these were not always known, there is a fraction of spare parts with inconsistent values for the purchasing cost (mostly below € 1). Fortunately, it is already clear that prices below € 1 will be excluded by setting threshold values in Section 5.3. This is due to the fact that there is no incentive to print items with prices as low as (or even lower than) € 1. Because of that, it is clear that these parts will already be excluded during further analysis.

Furthermore the spare parts with unknown purchasing price, inventory, lead time or average annual usage need to be excluded, just as the spare parts that are supposed to have zero days of lead time of a purchasing price of € 0.
As a result, 173 parts are identified, all based on an unknown purchasing price. Fortunately, there are no parts for which one of the criteria other than the purchasing cost is unknown.

APPENDIX L – COMMERCIAL IN CONFIDENCE – Data gathering

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APPENDIX M – AHP METHOD

In this Section, the use of the AHP method in this research is described.

As stated in Chapter 5, the necessary pairwise comparisons are made during interviews with the head of section Productiebesturing, the manager of the Business Unit Technology and the head of the cluster Engineering within the Business unit Technology. Since the fields of these specialists differ greatly, the pairwise comparisons can successfully be obtained based on the opinion of specialists of different fields within the company. The interviews were taken separately. The results of the pairwise comparison matrix that needs to be obtained, must be based on the fundamental scale of Saaty (1987), which is illustrated in Table M-1.

Intensity of importance on an absolute scale	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance of one over another	Experience and judgement strongly favor one activity over another
5	Essential or strong importance	Experience and judgment strongly favor one activity over another
7	Very strong importance	An activity is strongly favored and its dominance demonstrated in practice
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2, 4, 6, 8	Intermediate values between the two adjacent judgements	When compromise is needed
Reciprocals	If activity *i* has one of the above numbers assigned to it when compared with activity *j*, then *j* has the reciprocal value when compared with *i*	

Table M-1. The fundamental scale (Saaty, 1987)

Matrix A

Fortunately, without knowing the results of each other in advance, each interview resulted in the same pairwise comparison matrix A. This matrix is illustrated in Table M-2.

Goal	Improve service	Reduce costs	Secure supply
Improve service	1	7	1/5
Reduce costs	1/7	1	1/7
Secure supply	5	7	1

Table M-2. Pairwise comparison matrix A initially derived from interviews

The next step is to calculate the weights w_1, w_2 and w_3. The following two-step procedure is described by (Winston, 13.7 The Analytic Hierarchy Process, 2004) and is applied in this research to calculate these weights.

1. For each of A's columns, divide each entry in column *i* of A by the sum of the entries in column *i*. This yields a new normalized matrix A_{norm} in which the sum of the entries in each column is 1:

Goal	Improve service	Reduce costs	Secure supply
Improve service	0,1627	0,4667	0,1489
Reduce costs	0,0233	0,0667	0,1064
Secure supply	0,8140	0,4667	0,7447

Table M-3. Matrix A_{norm}

2. Estimate w_i as the average of the entries in row *i* of A_{norm}:

$$w_1 = \frac{0{,}1627+0{,}4667+0{,}1489}{3} = 0{,}2594$$

$$w_2 = \frac{0{,}0233+0{,}0667+0{,}1064}{3} = 0{,}0655$$

$$w_3 = \frac{0{,}8140+0{,}4667+0{,}7447}{3} = 0{,}6751$$

The next step is to check matrix A for consistency.

Consistency of matrix A

The following four steps are given by (Winston, 13.7 The Analytic Hierarchy Process, 2004) to check a pairwise comparison matrix A for consistency:

1. Compute Aw^T:

$$\begin{matrix} 1 & 7 & 1/5 \\ 1/7 & 1 & 1/7 \\ 5 & 7 & 1 \end{matrix} * \begin{matrix} 0{,}2594 \\ 0{,}0655 \\ 0{,}6751 \end{matrix} = \begin{matrix} 0{,}8529 \\ 0{,}1990 \\ 2{,}4306 \end{matrix}$$

2. Compute $\frac{1}{n}\sum_{i=1}^{i=n}\frac{ith\ entry\ in\ row\ AwT}{ith\ entry\ in\ wT} = \left(\frac{1}{3}\right) * \left(\frac{0{,}8529}{0{,}2594} + \frac{0{,}1990}{0{,}0655} + \frac{2{,}4306}{0{,}6751}\right) = 3{,}3088$

3. Compute the Consistency Index (CI) as follows: $CI = \frac{(Step\ 2\ result)-n}{n-1} = \frac{3{,}3088-3}{2} = 0{,}1544$

4. Compare CI to the Random Index (RI) for the appropriate value of n. For matrix A, n = 3: $RI = 0{,}58$ (Winston, 13.7 The Analytic Hierarchy Process, 2004).
   If $\frac{CI}{RI} < 0.1$, the matrix is consistent enough to give useful estimates of the weights. In the case of matrix A, $\frac{CI}{RI} = \frac{0{,}1544}{0{,}58} = 0{,}27$. $\frac{CI}{RI} > 0{,}1$, which means that matrix A is not consistent enough to give useful estimates of the weights.

Because matrix A is inconsistent, the results need to be revised and adapted by making minimal changes in order to obtain a consistent matrix. As a result, matrix B and matrix C were obtained. The matrices are illustrated in Table M-4 and Table M-5 and slightly differ from matrix A. Next, it needs to be proven that these matrices are consistent.

Goal	Improve service	Reduce costs	Secure supply
Improve service	1	5	1/4
Reduce costs	1/5	1	1/9
Secure supply	4	9	1

Table M-4. Adapted pairwise comparison matrix B

Goal	Improve service	Reduce costs	Secure supply
Improve service	1	4	1/4
Reduce costs	1/4	1	1/8
Secure supply	4	8	1

Table M-5. Adapted pairwise comparison matrix C

The weights and consistency of matrices B and C can be obtained by following the same steps as we did for matrix A.

Weights and consistency of matrix B

1. B_{norm}:

Goal	Improve service	Reduce costs	Secure supply
Improve service	0,1923	0,3333	0,1837
Reduce costs	0,0385	0,0667	0,0816
Secure supply	0,7692	0,6000	0,7347

Table M-6. Matrix B_{norm}

2.

$$w_1 = \frac{0{,}1923+0{,}3333+0{,}1837}{3} = 0{,}2364$$

$$w_2 = \frac{0{,}0385+0{,}0667+0{,}0816}{3} = 0{,}0623$$

$$w_3 = \frac{0{,}7692+0{,}6000+0{,}7347}{3} = 0{,}7013$$

Consistency of matrix B

1. Bw^T:

$$\begin{matrix} 1 & 5 & 1/4 \\ 1/5 & 1 & 1/9 \\ 4 & 9 & 1 \end{matrix} * \begin{matrix} 0{,}2364 \\ 0{,}0623 \\ 0{,}7013 \end{matrix} = \begin{matrix} 0{,}7232 \\ 0{,}1875 \\ 2{,}2076 \end{matrix}$$

2. $\left(\frac{1}{3}\right) * \left(\frac{0{,}7232}{0{,}2364} + \frac{0{,}1875}{0{,}0623} + \frac{2{,}2076}{0{,}7013}\right) = 3{,}0722$

3. $CI = \frac{(Step\ 2\ result)-n}{n-1} = \frac{3{,}0722-3}{2} = 0{,}0361$

4. $RI = 0{,}58.$ $\frac{CI}{RI} = \frac{0{,}0361}{0{,}58} = 0{,}0623.$ $\frac{CI}{RI} < 0{,}1$, which means that matrix A is consistent enough to give useful estimates of the weights.

Weights and consistency of matrix C

1. C_{norm}:

Goal	Improve service	Reduce costs	Secure supply
Improve service	0,1905	0,3077	0,1818
Reduce costs	0,0476	0,0769	0,0909
Secure supply	0,7619	0,6154	0,7273

Table M-7. Matrix C_{norm}

2.

$$w_1 = \frac{0{,}1905+0{,}3077+0{,}1818}{3} = 0{,}2267$$

$$w_2 = \frac{0{,}0476+0{,}0769+0{,}0909}{3} = 0{,}0718$$

$$w_3 = \frac{0{,}7619+0{,}6154+0{,}7273}{3} = 0{,}7015$$

Consistency of matrix C

1. Cw^T:

$$\begin{matrix} 1 & 4 & 1/4 \\ 1/4 & 1 & 1/8 \\ 4 & 8 & 1 \end{matrix} * \begin{matrix} 0{,}2267 \\ 0{,}0718 \\ 0{,}7015 \end{matrix} = \begin{matrix} 0{,}6893 \\ 0{,}2162 \\ 2{,}1827 \end{matrix}$$

2. $\left(\frac{1}{3}\right) * \left(\frac{0{,}6893}{0{,}2267} + \frac{0{,}2162}{0{,}0718} + \frac{2{,}1827}{0{,}7015}\right) = 3{,}0544$

3. $CI = \frac{(Step\ 2\ result)-n}{n-1} = \frac{3{,}0544-3}{2} = 0{,}0272$

   a. $RI = 0{,}58.\ \frac{CI}{RI} = \frac{0{,}0272}{0{,}58} = 0{,}0469. \frac{CI}{RI} < 0{,}1$, which means that matrix A is consistent enough to give useful estimates of the weights.

Matrix C is more consistent (0,0469 < 0,0623). Therefore, matrix C will be applied as the consistent pairwise comparison matrix.

For more information about the AHP, please refer to Saaty (1987) or Winston (2004).

APPENDIX N – Output of Descriptive Statistics of part scores

In this section, the mean, the standard deviation, variance, the minimum and maximum value as well as a 95% Confidence Interval of all the analyzed spare parts together and of all of the spare parts assigned to each Category 1-6 are illustrated. These values are calculated by using IBM SPSS Statistics 23 software and can be found by using "Descriptive Statistics".

The Descriptive Statistics of the part scores (of all the parts that are not excluded) without considering the applied Categories are given in Table N-2, while the descriptive statistics of the part score per applied Category are given in Table N-3.

Category	Potential of AM	Range (scores)	Number of unique spare parts	Percentage of total amount of spare parts
Category 1	None	Excluded parts (NO-GO)	5924	49,6
Category 2	Relatively very low	0.00 – 0.25	34	0,0
Category 3	Relatively low	0.25 – 0,50	2590	21,7
Category 4	Around average	0.50 – 0.75	1012	8,5
Category 5	Relatively high	0.75 – 0.85	2209	18,5
Category 6	Relatively very high	≥ 0.85	175	1,5

Table N-1. Number of unique spare parts assigned to each applied category.

			Statistic	Std. Error
Part_score	Mean		,6098	,00227
	95% Confidence Interval for Mean	Lower Bound	,6053	
		Upper Bound	,6142	
	Median		,5200	
	Variance		,031	
	Std. Deviation		,17581	
	Minimum		,15	
	Maximum		,87	
	Range		,72	

Table N-2. Descriptive Statistics of the part scores with IBM SPSS Statistics 23, without considering the applied Categories.

Category				Statistic	Std. Error
Part score	2	Mean		,2041	,00565
		95% Confidence Interval for Mean	Lower Bound	,1926	
			Upper Bound	,2156	
		Variance		,001	
		Std. Deviation		,03295	
		Minimum		,15	
		Maximum		,25	
	3	Mean		,4415	,00084
		95% Confidence Interval for Mean	Lower Bound	,4399	
			Upper Bound	,4432	
		Variance		,002	
		Std. Deviation		,04264	
		Minimum		,25	
		Maximum		,50	
	4	Mean		,5922	,00290
		95% Confidence Interval for Mean	Lower Bound	,5865	
			Upper Bound	,5979	
		Variance		,009	
		Std. Deviation		,09221	
		Minimum		,50	
		Maximum		,75	
	5	Mean		,8019	,00054
		95% Confidence Interval for Mean	Lower Bound	,8009	
			Upper Bound	,8030	
		Variance		,001	
		Std. Deviation		,02516	
		Minimum		,75	
		Maximum		,85	
	6	Mean		,8546	,00048
		95% Confidence Interval for Mean	Lower Bound	,8537	
			Upper Bound	,8556	
		Variance		,000	
		Std. Deviation		,00632	
		Minimum		,85	
		Maximum		,87	

Table N-3. Descriptive Statistics of the part scores with IBM SPSS Statistics 23 per applied Category 2-6.

APPENDIX O – COMMERCIAL IN CONFIDENCE – ELOT of analyzed (sub) assortments

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APPENDIX P – COMMERCIAL IN CONFIDENCE – Results for each (sub) assortment

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APPENDIX Q – COMMERCIAL IN CONFIDENCE –

Scores for all technological criteria of the most promising spare parts

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APPENDIX R – Sensitivity analysis

A sensitivity analysis of the results is performed and discussed. In order to define the sensitivity of the results for all the applied criteria, the values are set to zero for one characteristic at a time. Then, the number of parts that are assigned to each of the six applied Categories are obtained. The results are illustrated in Table R-1. It needs to be stated that for the characteristic **average days in inventory**, a second sensitivity analysis is performed. The impact of setting the value of the inventory for a particular part that on average satisfies the demand for at least one year to '1' is obtained.

Category	Analysis 3	Resupply lead time	Average annual usage	Average days in inventory	Average days in inventory*	Purchasing cost**	ELOT-item	Item in initial lifecycle phase	Design ownership
Category 1	5924	5871	5921	5924	5924	134	5924	5924	5924
Category 2	34	91	3196	39	32	111	79	37	40
Category 3	2590	2933	2580	2725	2277	5152	5175	2850	3077
Category 4	1012	2976	247	962	1300	1834	766	749	524
Category 5	2209	73	0	2188	2003	4684	0	2209	2323
Category 6	175	0	0	106	408	29	0	175	56
Average score	0.61	0.53	0.28	0.60	0.62	0.61	0.45	0.60	0.60
Standard deviation	0.18	0.17	0.17	0.17	0.18	0.18	0.06	0.18	0.18

Table R-1. Sensitivity analysis. In every step, all values for only characteristic are set to zero.
*In this step, the value of the inventory for a particular part that on average satisfies the demand for at least one year is set to '1'.
**Parts with an unknown purchasing cost are not excluded either.

The values for the characteristics **average annual usage** and **ELOT-item** have the most impact on the results. In this analysis, a particular part with a value of zero for one of these characteristics will not be considered (very) promising.
The values for the **resupply lead time** also have a significant impact, since no parts are considered to be very promising anymore after setting these values to '0'. In addition, only approximately 3% of the identified promising parts in analysis 3 remain in Category 5.

The consequences of setting the values to zero for the characteristics **average days in inventory**, **item in initial lifecycle phase** and **design ownership** are limited. However, setting the values of the characteristic **average days of inventory** to '1' for all high inventory levels does have a significant impact on the number of parts in Category 6. In this case, a total number of 408 very promising parts would have been identified.
Setting the values for the characteristic **item in initial lifecycle phase** to zero does not have any influence on the total number of parts assigned to Category 5 or 6. At the RNLA, the Life Of Type (LOT) for almost all system types is at least 25 years. Consequently, system types that will reach the initial ELOT within five years cannot be introduced during the last five years.

Furthermore, changing the values for the characteristic **purchasing cost** has a significant impact on all applied Categories. Compared to the results of Analysis 3, an approximate of 17% of all parts assigned to Category 6 remain in this Category. Furthermore, the number of identified promising parts has more than doubled to a total number of 4684 parts. Most of these parts were first assigned to Category 1. Given the fact that in this sensitivity analysis no parts are excluded based on relatively low purchasing cost, only a fraction is assigned to Category 1 again. Since in Analysis 3 approximately half of the spare part assortment is excluded solely based on a low purchasing cost, the consequences of having applied a slightly different value for the purchasing cost need to be defined. As illustrated in Table R-2, the total number of spare parts that would have been assigned to Category 1 differs between 4733 and 7052 parts, depending on the height of the purchasing cost. The maximum analyzed threshold value for this characteristic is a purchasing cost of € 50, which is consistent to be twice the threshold value obtained in Section 5.3.

Purchasing cost (€)	Total number of spare parts assigned to Category 1
15	4733
20	5249
25	5695
30	6048
35	6368
40	6650
45	6849
50	7052

Table R-2. The total number of spare parts assigned to Category 1 based on a purchasing cost between € 15 and € 50