Printing in the Army

Where to locate additive manufacturing capabilities in a remote spare parts supply chain?

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Printing in the Army: Where to locate additive manufacturing capabilities in a remote spare parts supply chain?

Master Thesis

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Abstract

In this research, we introduce a discrete-event simulation model to identify the effect of integrating additive manufacturing (AM) capability in a remote spare parts supply chain on vehicle readiness and total operating costs. We focus on using AM as an emergency option to supply a temporary fix in out-of-stock situations, which can then be used in a vehicle until a regular, conventionally manufactured part arrives. We identify different locations suitable to host AM capability and consider different AM capability types. We illustrate, via scenario analysis on two case studies of the Royal Netherlands Army, that integrating AM capability in a remote spare parts supply chain increases vehicle readiness, while decreasing the total operating costs for various scenarios. Specifically, we find AM capability to be most suitable to deploy in the most downstream location, closest to where demand arises, as this allows quick response to out-of-stock situations. Including AM capability simultaneously allows a reduction of base-stock levels, while maintaining the same level of vehicle readiness, under similar or lower operating costs. We also find that investment in more costly, more reliable AM capability results in higher vehicle readiness, under lower operating costs, than slightly less expensive, less reliable AM capability. While we focus on a military context, our model may have a broader application for organizations operating critical systems in remote environments as it may be suitable in deciding on a specific AM location-AM capability type combination.

Keywords: Additive Manufacturing; Spare Parts; Serial Supply Chain; Discrete-Event Simulation; Scenario Analysis.

Executive Summary

Introduction

Many organisations, like the Royal Netherlands Army (RNLA), keep large spare parts inventories in order to withstand equipment downtime caused by component failures. Due to the nature of military operations, component failure does not only have financial consequences, but may cause discontinuation of planned operations, or even endanger the lives of military personnel. Military operations can be conducted anywhere in the world, under varied exogenous circumstances, affecting equipment in a way that cannot easily be forecasted. To avoid costly system downtime, large numbers of spare parts are shipped to mission areas and even then it happens that critical components fail and spare parts are not available. In turn, spare parts need to be shipped from depots in the home country, or procured from part suppliers. In these instances, lead times may ascend up to weeks or months. Additive manufacturing (AM) has been identified as an additional sourcing option to manufacture parts on-site, close to where demand arises. AM may be used to temporarily satisfy spare part demand until a conventional spare part becomes available, for the purpose of reducing system downtime. The question remains if and where to locate these AM capabilities.

Research Design

In this research we focus on a remote spare parts supply chain whereby conventionally produced spare parts may be sourced through regular shipments. The RNLA is interested in whether or not to integrate AM capabilities as an additional sourcing option to supply spare parts for temporary use in out-of-stock situations, and if so, where to locate these AM capabilities. By producing spare parts where demand arises, lead times and, in turn, downtimes may be reduced. However, due to uncertainties in operations, such as a high level of threat, or a production environment affecting the quality of the printed part, it may be desirable to position the AM configuration more upstream in the supply chain. As the unavailability of vehicles may have large consequences besides financial, i.e., cancellation of military operations, or even endangerment of the lives of military personnel, we focus on both vehicle readiness and operating costs. The main research question is:

How can AM capability be deployed in mission areas to improve the trade-off between vehicle readiness and relevant operating costs?

Vehicle readiness is in literature often referred to as vehicle availability. As not having equipment available can have major consequences for the RNLA, the objective in mission areas is high vehicle readiness. As we acknowledge that not evaluating operating costs may result in a situation where we maximize vehicle readiness through keeping large spare part inventories, we also evaluate operating costs. In order to answer the main research question, the factors of influence on remote AM deployment are identified using literature and expert knowledge. Subsequently, a discrete-event simulation model is constructed. This allows assessment of different ways of AM integration on vehicle readiness and operating costs through scenario analysis. The scenarios may differ in terms of suitable AM location and AM capability type. The model also allows testing a scenario without AM integration. In order to assess the performance of these scenarios, two RNLA case studies are introduced, based on two different kinds of deployment.

General model

The model is a multi-echelon, multi-item serial supply chain for spare parts. The goal of this research is to evaluate the effect of different ways of AM integration, in terms of AM hosting location and AM capability type, on the vehicle readiness of the deployed fleet and the operating costs. Operating costs consist of holding costs throughout all echelons, failure costs, downtime costs and print costs. We consider three echelons that are regularly supplied during scheduled supply moments. Only in the most downstream location, where vehicles are operated, spare part demand occurs. The time between component failures is assumed to follow an exponential distribution. We only consider downtime critical components, that is, absence of such a component causes system downtime. All three locations may keep spare part inventories and are characterized by a $(S-1, S)$ inventory policy. AM capabilities may be located at the most downstream location, or one location upstream of the most downstream location. These AM capabilities are used whenever there is no conventional spare part available and the expected AM delivery time is (non-strictly) smaller than the expected delivery time of a conventional part. AM parts are only used temporarily, meaning these are replaced by conventionally produced spare parts when these are available. We consider that AM parts may fail before replacement by a CM counterpart. We encounter various uncertainties in the spare parts supply chain, as shipments may be cancelled and AM print orders may prematurely fail due to the AM capability type's print error.

Case studies

Two RNLA case studies are selected, based on different deployment types: *Case study 1: Lithuania* is based on combat deployment, while *Case study 2: Afghanistan* is based on peacekeeping deployment. *Case study 1* is a hypothetical case study, concerned with steel on steel fighting and dynamic operations. It is very important that supply occurrences take place to maintain a certain level of vehicle readiness. Therefore, this case study is characterized by frequent supply moments and a high probability of shipment continuation. While this may sound counter-intuitive, during combat deployment supply of resources is vital to ensure operational units are able to continue operations, despite high external threats on these supply occurrences. *Case study 2* is inspired by actual deployment. The case study setting is generally static: operational units operate from static bases. Continuation of operations is perceived as less vital than during combat deployment and shipment occurrences thus occur less frequently. As peacekeeping deployment is associated with little environmental threats, and spare part out-of-stock situations carry little risks compared to combat deployment, this case study is characterized by a higher probability of shipment cancellation than *Case study 1*. Furthermore, for both case studies we consider the same set of fourteen spare parts, solely from the Fennek reconnaissance vehicle. We identify five scenarios for each case study: we consider one scenario without AM integration and we evaluate two possible AM hosting locations, considering two AM capability types. This leaves us with a total of ten scenarios. We solely consider placement of AM capability in one of the two most downstream locations, location 2 or location 3. Furthermore, AM capability type A is generally less expensive, but is less reliable than AM capability type B, in terms of probability of print failure and failure rate of AM delivered parts.

Conclusions

We find that on-site AM capability, to produce temporary spare parts, may improve vehicle readiness and decrease operating costs opposed to a situation without AM capability, depending on the AM location-AM capability type combination. Our results show that AM capability is specifically useful in the most downstream location, close to where spare part demand arises, as this allows quick response to out-of-stock situations. On-site AM capability also enables base-stock level reduction in all locations from the AM host location and upstream. Moreover, when the probability of shipment cancellation increases, the vehicle readiness is barely affected in a situation with AM capability, as it allows local part production, opposed to a situation without AM capability. This suggests a higher degree of supply chain resilience can be reached when including AM capability. We find that a more expensive, slower, but more reliable AM capability is preferred over a cheaper, faster, but less reliable AM capability in terms of vehicle readiness and operating costs. This becomes more evident when the frequency of supply occurrences is reduced. Still, a cheaper, faster, but less reliable AM capability may already induce cost savings in a situation characterized by frequent supply occurrences. Finally, we find that AM is specifically useful for expensive components, characterized by infrequent demand, for which stocking spare parts is costly.

We made first attempts to determine scenario specific base-stock levels, depending on the location and type of the AM capability. Yet, we acknowledge that the base-stock level determination procedure can be optimized and so we recommend future research to explore ways in which to optimize base-stock levels throughout all echelons when including AM capability. Furthermore, we made various assumptions in the model that can be regarded as limitations. We solely consider AM to produce temporary fixes. We recommend the effect of using AM to supply part replacements in remote areas, changing the system to a pure dual-sourcing system. Similarly, for the RNLA specifically, we assume that after print interruption, the print process can immediately be started again. In practice, operational units spend time on relocating, which we disregard. We recommend future studies to investigate the effect relocation times may have on the desired location of AM capability.

Preface

This master thesis is the result of a project conducted in partial fulfillment of the requirements for the degree of Master of Science in Operations Management and Logistics at Eindhoven University of Technology. Essentially, this report marks the end of my time as a student. The past months spent on completing this research were challenging, though rewarding. I feel grateful for the course of this research, as it progressed with more ups than downs. Truthfully, I would not have completed this research without the support of several people.

First of all, I want to express my gratitude towards my academic supervisors. I would like to thank Rob Basten for his guidance and critical research perspective throughout this project. I really value the constructive feedback and insightful research ideas you provided me with during this project, and the time you spent on meeting me and reviewing my work. Similarly, I would like to thank Loe Schlicher for being open to review my work whenever I requested so, making me critically reflect on my own choices and keeping me on track when I needed it.

Secondly, I would like to thank my supervisors from the Royal Netherlands Army. I wish to thank to Tim Julsing for the many insightful meetings and much-needed (table tennis) distractions. You introduced me to various people within the organisation and fed me with your optimism and problem-solving attitude. I would also like to thank Ruben Cornelissen for his continuous support in meeting me and the frequent brainstorming sessions. You helped me to fully incorporate the Royal Netherlands Army's perspective by asking critical questions.

Besides my supervisors, I wish to specifically thank the AMEC members, and all other people working at the Royal Netherlands Army that have helped me in the realization of this master thesis report. I appreciate your open and helping attitudes in warmly welcoming me into the organisation and considering my research valuable. I truly value the unforgettable time I experienced at the Royal Netherlands Army.

Lastly, I wish to thank my family and friends for their continuous encouragement and support, and believing in me. You provided me with the necessary distractions, and were always there to listen to me, or give me precious advice whenever I needed it. Not only during the completion of my master thesis, but during the entire period as a student.

As of now, I am curious what will come my way.

Véronique Zijlstra

Eindhoven, April 2022.

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Abbreviations

AM	Additive Manufacturing
AMEC	Additive Manufacturing Expertise Center
ASTM	American Society for Testing and Materials
BDR	Battle Damage Repair
BS	Base Stock
CM	Conventional Manufacturing
DCS	Deployed Central Stock
DES	Discrete-event Simulation
DMO	Defence Materiel Organisation
ERP	Enterprise Resource Planning
FES	Future Event Set
FOB	Forward Operating Base
FS	Floor Stock
MatLogCo	Material Logistics Command
MOB	Main Operating Base
MTO	Make-to-order
MTS	Make-to-stock
MTTF	Mean time to failure
NATO	North Atlantic Treaty Organisation
NSE	National Support Element
ODB	Onderhoud Diagnose Berging
OEM	Original Equipment Manufacturer
POD	Point of Debarkation
POE	Point of Embarkation
RNLA	Royal Netherlands Army
RQ	Research Question
SC	Supply Chain
SKU	Stock-keeping Unit
VEDN	Vital, Essential, Desirable, Non-supply

1 Introduction

In this chapter, the context of the thesis is discussed. The focus of the thesis lays on the supply of spare parts, based on additive manufacturing (AM) technologies, whereby remote locations are of particular interest. The American Society for Testing and Materials' (ASTM) standard F2792-12a provides a definition for AM: "Additive manufacturing is the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing technologies" (ASTM, 2013). The master thesis is carried out in collaboration with the Royal Netherlands Army (RNLA) because of their operations in remote, isolated areas. This master thesis came about by collecting information from people within the RNLA through personal interviews, to which we refer by stating the interviewee's background. For interviewees of the same department we use a number identifier. After completion of the research, the arguments and statements in this research were carefully reviewed and verified by two employees of the RNLA with an AM and logistics background.

This chapter starts by introducing the organisation, the RNLA's main tasks and types of deployment in Section 1.1 and proceeds in Section 1.2 by discussing the levels of maintenance and the spare part classification model the RNLA recognizes for materiel. The chapter continues by considering supply chain arrangements and spare part retrieval process during remote deployment in Section 1.3. In Chapter 2 the research design is discussed and the thesis outline is presented.

1.1 The Royal Netherlands Army

Defence is the second largest employer in the Netherlands. Over 68,000 people work for the organisation as military, reservist or civilian employee. A third of these people serve the RNLA (Ministerie van Defensie, 2022a). The expenses of the Military of Defence over 2022 are budgeted at 12.5 billion euros. While over a third of the budget goes to staff salaries, 2% is reserved for military deployment and another 2% for military readiness in the form of military exercises. Yet, 14% is budgeted for conservation of systems (air, water and land systems), stressing the importance of well-organized maintenance (Ministerie van Defensie, 2022c). The RNLA, together with the Royal Netherlands Navy, the Royal Netherlands Air Force and the Royal Netherlands Marechaussee (military police), make up the Netherlands Armed Forces, a body of the Netherlands Ministry of Defence. For a thorough overview of the organisational structure of the Ministry of Defence and the RNLA, Appendix A can be consulted.

1.1.1 Main tasks of the RNLA

The main tasks of the Netherlands Armed Forces are captured in Art. 97 of the Constitution of the Netherlands: to defend and protect the interest of the Kingdom, as well as maintain and promote the international legal order (Ministerie van Defensie, 2021b). This is translated to three main tasks:

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

The Netherlands is affiliated with the North Atlantic Treaty Organization (NATO), a major military alliance between Western countries for collective defence, peacekeeping and humanitarian aid. Together with these allies the Netherlands Armed Forces aim to contribute to peace, freedom and safety in different parts of the world through missions (Ministerie van Defensie, 2021a).

1.1.2 Types of deployment

The RNLA recognizes different types of deployment, in line with the three main tasks of the Netherlands Armed Forces (Ministerie van Defensie, 2021b). The first, *Protect own territory and that of allies*, is generally associated with deployment related to some form of combat. This type of deployment is often characterized by a high level of threat that increases when moving further towards the front line. Therefore, units are expected to operate dynamically, meaning they should be able to relocate within hours, or even minutes. Materiel and supplies that are carried along should be easily movable, to be able to respond quickly in dangerous situations. The second main task of the Netherlands Armed Forces, *Promote the (international) legal order and stability*, draws the second type of deployment. During a mission of this type, there is generally no word of steel on steel combat. Compared to the previously mentioned type of deployment, the level of threat is low. Deployed units are rather present to maintain stability in the country of deployment. During long-term deployment of this kind, static operating bases may be set-up, from which the deployed units operate. The third main task, *Provide assistance in the event of disasters and crises*, stresses the deployment of military personnel whenever external factors create a situation that requires prompt action. This could mean, for example, making the national infrastructure accessible or distributing food and water after a disaster, such as an earthquake or flood.

1.2 RNLA materiel conservation

The RNLA manages a selection of materiel, ranging from (armored) vehicles to weapons and unmanned reconnaissance vehicles to support operations. Concerning vehicles, a distinction can be made between heavy ground-based weapon systems, reconnaissance and all-terrain vehicles, trucks and trailers, and other mobile facilities and installations (Ministerie van Defensie, 2022d). Depending on the goals and activities of different RNLA units, vehicles are allocated. Appendix B can be consulted for a comprehensive list of the quantities of RNLA materiel. As the RNLA operates advanced, specialist materiel that may be deployed under varying circumstances, anywhere in the world, a materiel maintenance strategy and a spare parts classification system are designed.

1.2.1 Levels of maintenance

In contrast to many commercial parties, the maintenance of vehicles within Defence is arranged somewhat differently due to the nature of business operations. Maintenance in the Netherlands, during peace, is aimed at delivering operationally ready units. Maintenance activities consist of preventive maintenance, corrective maintenance as a result of education or training, and modificative maintenance. During deployment, maintenance activities are aimed at supporting operational units to ensure equipment stays operational (OTCLOG Kenniscentrum Bureau Logistiek Doctirine en Voorschriften, 2017). The maintenance activities may be battle damage repair (BDR), corrective repairs, necessary preventive actions and may include modificative maintenance. Note that BDR includes improvised, effective fixes due to a lack of spares or time. Generally, deployment with a high level of threat requires a high level of mobility. As there is little time to maintain equipment, components are replaced or emergency repairs are executed. In instances that require a low level of mobility, there is generally more time to consider other options, such as part repair.

While literature recognizes three levels of maintenance - organizational, intermediate and depot level (Sheng and Prescott, 2019) - the RNLA distinguishes four maintenance levels: user maintenance, part maintenance, field and workshop maintenance and higher maintenance (OTCLOG Kenniscentrum Bureau Logistiek Doctirine en Voorschriften, 2017). The first three levels of maintenance are performed by the operational units: users, an ODB (onderhoud, diagnose & berging) group or a Maintenance Company. User maintenance is performed by the user and includes preventive maintenance subject to equipment use, some corrective maintenance tasks and if necessary, improvised repairs, such as BDR. Part maintenance is generally executed by an ODB group. This party is dedicated at maintaining vehicles during operations, diagnosing defects and salvaging vehicles if required. On a mission, ODB engineers travel along operational units to perform maintenance activities the users are not able to resolve, which includes BDR and in rare cases one on one part replacement if the part is available and there is sufficient time. Another task of the ODB group is to diagnose defects, such that the Maintenance Company is prepared to quickly perform vehicle maintenance with the required parts and tools once the vehicle returns to the base. Considering the maintenance levels recognized in literature, both user maintenance and part maintenance fall under organisational level maintenance.

Field and workshop maintenance is performed by the Maintenance Company and consists of preventive maintenance, corrective maintenance and modificative maintenance. During multi-day training and type one deployment (combat), preventive maintenance is only performed when not doing so leads to system failure. However, during type two deployment (peacekeeping), this is one of the primary tasks of the Maintenance Company. Corrective maintenance includes fixing defects that an ODB group cannot resolve, and modificative maintenance concerns non-drastic modifications. In literature this would be referred to as intermediate-level maintenance. In practice the situations' circumstances during deployment, such as level of danger, available time, skills of maintenance personnel, etc., largely influence which party performs which maintenance activities, i.e. an ODB group or a Maintenance Company. Higher maintenance includes conservation activities that serve to reach or extend the planned lifetime of equipment. The fourth level of maintenance focuses on fixing broken (repairable) components and heavy damage to the equipment that cannot be repaired by the Maintenance Company. Usually larger equipment modifications and higher maintenance are combined. Higher maintenance can be done by Defence, but it can also be outsourced to the civilian market. In literature, higher maintenance would be referred to as depot-level maintenance.

1.2.2 Spare part classification model

Spare parts are stocked to support maintenance activities of RNLA materiel. According to Liya et al. (2010), the military generally aims to stock spares in sufficiently large quantities to ensure a high fill rate, whereby minimizing costs is usually not the main objective. Part stock-outs may not only have financial consequences in terms of downtime, but system failure may also endanger the lives of people in combat areas (Den Boer et al., 2020). As it is impossible to stock all stock-keeping units (SKUs) with a fill rate approaching 100%, choices have to be made regarding SKU base-stock levels. Hence, the RNLA uses a classification model to determine the criticality of spare parts, based on the functional importance of the parts, whereby shortages can cause organisational risks. Hereby the focus is on deployability of materiel, meaning there is no clustering based on logistical or financial interests.

Parts are divided over four categories, diminishing in importance: vital (V), essential (E), desirable (D) and non-supply (N). This makes up the VEDN-model (Tromp, 2018). Vital parts are most critical, as these are vital for operations and the unavailability of these parts either carries high operational risks, or the parts are prone to failures. These parts are stocked in abundance to avoid stock-outs. Generally this category contains large and/or expensive components or sub-assemblies, such as entire engines. Essential parts are still necessary for operations, but these parts carry medium operational risks or are less prone to failures. Therefore, these items are stocked in medium amounts. Experience shows that this category mostly contains parts that can be found in sub-assemblies, for example, the single parts used in an engine. In turn, desirable parts carry low risk or low probability of failure. Shortage of this type of parts has hardly any influence on operations, meaning small stocked amounts suffice. Finally, non-supply parts are items that are not centrally stocked. These parts are generally not supplied, for example, in case parts are outdated. Figure 1.1 gives an overview of the spare part classification model of the RNLA.

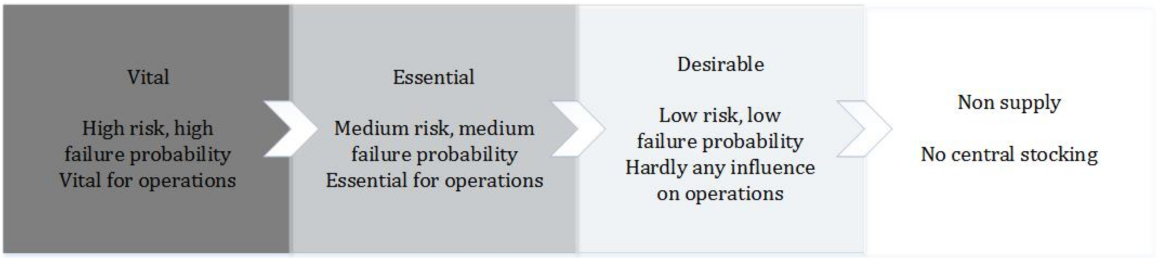

Figure 1.1: VEDN spare part classification model, from Tromp (2018)

1.3 Remote environment

The RNLA contributes to the defence of Dutch territory and that of its allies, and supports nations worldwide in times of calamities or when humanitarian aid is required. This means that the units can be deployed anywhere around the globe, in areas with a fixed infrastructure, yet also in areas that may be isolated. Units have to be trained to operate in various circumstances, but equally important is the proper arrangement of the logistics for each mission to supply food, medicines, fuel, spare parts, etc.

1.3.1 General mission supply chain

As the nature and location of each mission differs, the supply chain for each mission differs. The supply chain is organized prior to deployment, according to the guidelines in the RNLA Supply Chain Manual (OTCLOG Kenniscentrum Bureau Logistiek Doctirine en Voorschriften, 2015), based on the type of deployment (peacekeeping or combat), the different units and number of people deployed, the geographical area, and so on. Figure 1.2 visualises a representation of a general mission supply chain for type two deployment (peacekeeping). While the supply chain for type one deployment (combat) does not reckon the same designations for the different operating locations, the number of locations is quite similar. Though, during type one deployment (combat) there are no static bases as operations are dynamic.

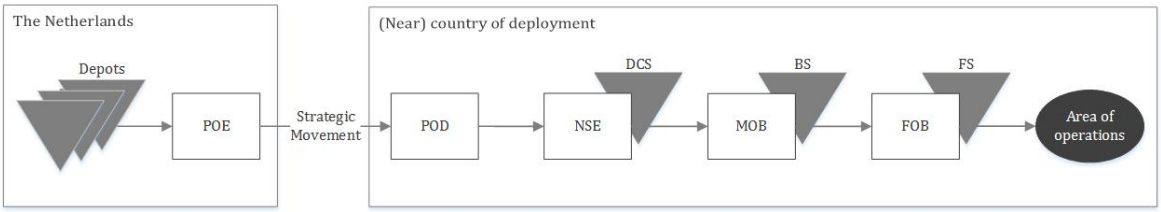

Figure 1.2: General mission supply chain

The rectangles denote physical service locations, a Point of Embarkation (POE), a Point of Debarkation (POD), National Support Element (NSE), a Main Operating Base (MOB) and a Forward Operating Base (FOB). The triangles display stocking locations, including depots in the Netherlands, Deployed Central stock (DCS), Base Stock (BS) and Floor Stock (FS). The arrows denote the physical flow of goods. Strategic movement, movement from the Netherlands to (a location near) the country of deployment, generally occurs on fixed intervals. Depending on the nature of deployment, the various locations are set up.

For some deployments, locations may be excluded or combined, depending on the mission scope. As an example, Westerweel et al. (2021) present a visualisation of a RNLA mission supply chain to Mali, a peacekeeping mission (type two deployment), which can be viewed in Figure 1.3. Note that during Mali deployment there was no FOB set up, and the NSE was located at the POD and thus left out of the figure. Cargo from depots in the Netherlands is shipped from the POE to the POD, and eventually shipped to the MOB. Deployed troops carry out assignments, such as patrols, from the MOB. In this context the MOB is the Netherlands' hub for operations, such as vehicle maintenance, and serves to support the deployed forces.

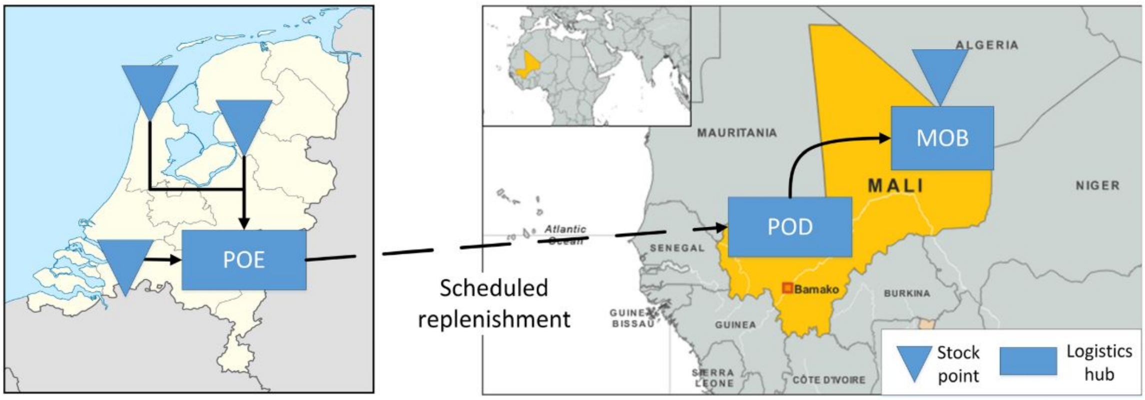

Figure 1.3: RNLA mission supply chain of Mali deployment, from Westerweel et al. (2021)

1.3.2 Spare part demand during deployment

During patrols or combat, vehicle defects may arise. As the RNLA aims to deliver operationally ready vehicles, failed parts are generally one on one replaced by a spare (OTCLOG Kenniscentrum Bureau Logistiek Doctirine en Voorschriften, 2017). This is often the quickest option resulting in the least downtime. ODB engineers travelling along military units during operations carry a primitive tool case and are skilled to creatively fix defects, such that the vehicle can return to the Maintenance Company in the operating base for proper maintenance actions. The process of requesting a spare part is explained here, according to a description by logistics experts within the RNLA (Material Logistics Command; Supply & Transport Command). When spare part demand arises, a SAP order is created, triggering an inventory check to ensure the part can or cannot be immediately replaced from stock. When the part is available, it is simply replaced. In the latter case, when a part is not available, the SAP order is forwarded to the next stocking location for a shipment request. An instance may occur that the part is not in stock in any depot of the RNLA. The SAP order is then forwarded to an external supplier, to start the part procurement process. The part either travels through the POE, or is directly send to the POD, and in turn the FOB, where it is built in. After replacement by a spare, the broken part is disposed or repaired. In case the part is repairable, the part is either repaired by the Maintenance Company, or returned to the Netherlands when specialized tooling is required. After repair, the part can be added to spare part inventories again. When the damage to the vehicle is irreparably large, the vehicle is sometimes disposed and only used for the parts.

As already discussed in Section 1.2.2, spares are classified according to the VEDN-model, based past data of spare part requests. However, in preparation of a mission, the spare part inventory levels are determined of the parts that are brought along to any of the stocking locations. To do so, data of spare part requests over the past few years is consulted (Systems & Analysis Department 1). It is worth noting that, during missions, equipment is often subject to more excessive use as compared to peacekeeping. This is considered in the calculation of spare part inventory levels, along with the mission duration and the size of the fleet. However, in practice, during mission deployment equipment is generally exposed to other environmental factors as compared to operations in the Netherlands (13 Maintenance Company). Consequently, failure behavior of components can differ considerably from the known failure behavior: components that generally show little or no failure behavior during peacekeeping can fail en masse during a mission. Since the stock levels of parts are not resistant to this, part shortages may arise (Systems & Analysis Department 1).

2 Research Design

Availability of high-end equipment is vital for the RNLA operations. Not only does system downtime drive up operational costs, it may induce great operational risks for military personnel in mission areas. AM has been recognized by the RNLA to improve vehicle availability, while questions regarding the actual implementation of the technology remain. This chapter covers the problem statement of the RNLA in Section 2.1, followed by a description of the research questions and methodology, in Section 2.2. Section 2.3 discusses the project scope and Section 2.4 presents the research' deliverables. In turn, the practical and theoretical contribution of the project are described in Section 2.5. The chapter concludes with the thesis outline in Section 2.6.

2.1 Problem definition

Spare part inventories are generally very large in order to withstand equipment downtime caused by component failures, and to deal with long supply lead times or spare part obsolescence (Den Boer et al., 2020). Determining the right inventory levels of spare parts for military equipment is challenging: equipment usage in mission areas is typically more intensive than during day to day operations, and equipment is exposed to different environmental conditions, resulting in different failure behavior (Systems & Analysis Department 1). Furthermore, there is a level of threat that usually increases when moving downstream the supply chain towards the mission area. The level of threat and other factors such as limited infrastructure, may influence the number of supply moments and the lead times between locations (Board of Operations). As a consequence, containers full of spares are shipped to mission areas and even then it happens that critical components fail and spare parts are not available (Supply & Transport Command). In these instances, spare parts need to be shipped from depots in the home country, or be procured from original equipment manufacturers (OEMs) or external part suppliers. In some instances procurement lead times of conventionally manufactured (CM) spare parts may even ascend up to a few months (Den Boer et al., 2020). System failure causes downtime and affects the overall vehicle readiness of the military vehicles required to perform operations in the deployment area, resulting in cancellation of planned operations. Vehicle readiness is described in literature as availability, which is a measure for a capital goods' ability to function according to its purpose, expressed as uptime over total time, i.e., the total of uptime and downtime (Busachi et al., 2018).

The RNLA has considered AM as a valuable manufacturing technology to satisfy outstanding spare part demand, besides CM parts, to increase vehicle readiness. Ideally, AM would complement the options of spare part acquiring, especially in mission areas where high vehicle readiness is of great importance. Several advantages regarding the use of AM are mentioned in literature by Ghadge et al. (2018) and Westerweel (2019) that favor AM integration. One example is that AM enables part manufacturing without specialized tooling, which makes small production quantities economically feasible. Furthermore, AM has the potential to simplify supply chains through local production, thereby reducing lead times and inventory base-stock levels. The technology can be deployed as a local production facility in remote areas that are difficult to supply and might be able to resolve the problem of spare part obsolescence. However, AM also faces various challenges, mentioned by Den Boer et al. (2020) and Ghadge et al. (2018), such as high machine and material costs and often requires preor postprocessing, as well as high calibration efforts. Some other challenges are intellectual property rights, warranty limitations, part certification and the costs associated with these aspects. Furthermore, training and qualifying personnel remains a challenge. Thus, the problem is that there is insufficient knowledge within the RNLA on how AM can be deployed in mission areas, and what effect this may have on vehicle readiness and relevant costs.

2.2 Research questions and methodology

This section addresses the research questions, intended to tackle the problem definition. First, the main question is introduced. Subsequently, the research questions (RQs) are presented that serve as a guideline in answering the main question. The research questions are accompanied by a brief description of the methodology to answer the concerning research question.

As indicated in Section 2.1, the RNLA is interested in the way AM should be integrated in a mission specific spare part supply chain. Hereby, AM should serve to complement the existing spare part supply sources. By producing spare parts locally where spare part demand arises, lead times and, in turn, downtimes may be reduced significantly. Producing more upstream in the supply chain may however be favorable to deal with uncertainties in operations, such as a high level of threat, extreme environmental conditions affecting the quality of a printed part, or print orders that are prematurely interrupted. As AM technologies are generally more expensive than conventional alternatives, the relevant costs should be regarded. Expenses related to equipment's operations make up the relevant costs, such as inventory holding costs of spares, downtime costs, etc. Consequently, the main question is as follows:

How can AM capability be deployed in mission areas to improve the trade-off between vehicle readiness and relevant operating costs?

Various research questions are proposed, serving as a guideline in answering the main research question. In order to determine in what way AM can be integrated in the RNLA mission's spare parts supply chain, it is relevant to uncover which factors influence decisions on AM deployment. A large advantage of AM is deployment close to the service location, to reduce lead times of spare parts, and thereby downtime. However, not all AM production configurations may be suitable to deploy, e.g. based on the number of parts that can be manufactured, or AM part quality may be insufficient due to extreme environmental factors. Therefore, the first research question is:

RQ1. What factors influence AM deployment options in a remote spare parts supply chain?

Expert knowledge, in the form of open-ended interviews, should serve to uncover relevant factors that influence decisions on how to integrate AM in the spare parts supply chain. As the nature of this question is exploratory investigation, experts will be consulted in the form of in-depth interviewing (Blumberg et al., 2014). To uncover the relevant influencing factors, various people within the RNLA with different backgrounds (i.e. maintenance, logistics) will be approached. Besides expert knowledge, literature can be consulted to assist in determining factors that may influence the way of AM integration.

Secondly, it is important to develop a model that is appropriate to assess different ways of integrating the AM sourcing option in the spare parts supply chain. To evaluate different scenarios, the model should allow for comparison to a base situation that does not include

AM deployment. The model should be based on quantitative assessment of possible ways of AM integration, as this is limited in existing literature. Consequently, the second research question is as follows:

RQ2. Which quantitative model can be used to assess different ways of integrating AM as sourcing option in a remote spare parts supply chain?

Based on the information gathered for RQ1, literature is consulted to gain insights in the design of a model that can be applied to quantitatively assess different ways AM supply chain integration. Khajavi et al. (2014) propose scenario modeling to assess centralized versus decentralized AM deployment, which can also be used to assess various decentralized production locations. In essence, we desire to model a situation approaching reality, that recognizes different deployment types, and may incorporate a number of influencing factors. It is important that the model considers both vehicle readiness and relevant operating costs, and allows for different sourcing options.

To be able to eventually assess the proposed model, a case study should be selected to retrieve model output. This concerns a selection of parts that can either be sourced conventionally, or can be printed. Furthermore, this includes the selection of the mission area and deployment type, which influences the supply chain set-up. Therefore, the third research question is:

RQ3. What is an interesting case study to evaluate using the proposed model?

Again, expert knowledge will serve as a basis in defining a suitable case study, accompanied by data retrieved from SAP. Open interviews will be used in selecting a case study, as discussion with informants may unravel more of the case's issues, but may also direct towards other sources of information (other informants or documents) (Blumberg et al., 2014). Maintenance experts will be consulted, who have mission experience and may be able to determine some spare parts that are interesting to include in the case study. Examples of potential case studies are Afghanistan and Lithuania. In turn, the Logistics Knowledge Center, within the RNLA Training Command, will be approached to validate the selected case study.

After the development of a suitable model and the selection of a case study, the model input parameters should be determined. As these values eventually influence the model outcomes, it is important to determine realistic parameter values. Therefore, the fourth research question is formulated as follows:

RQ4. What are the model input values for the AM and CM sourcing options?

Once the case study is validated, expert knowledge and literature will be used to assign realistic input values to the proposed model. For example, expert knowledge can be consulted to determine lead times between locations. Experts may be RNLA employees, but also AM industry parties collaborating with the RNLA. Additionally, literature may be consulted to complement this. For example, literature may assist in determining realistic printing times of specific printer types.

Combining the answers of RQ1 through RQ4, allows for model testing using empirical data. This will provide information on the various options of AM as a sourcing option in the spare parts supply chain, as compared to the base situation, without AM as a sourcing option. Adding to that, analysis is required on the sensitivity of the model parameters to the models' performance, which will reveal more on the robustness of the overall model. As such, the last research question is:

RQ5. How is vehicle readiness affected by the integration of AM compared to the base situation and how sensitive is the performance of the proposed model to the model parameters?

Integrating the results of RQ1 through RQ4 allows for execution of a RNLA specific case study. The model output then serves to quantitatively express the possible options of AM integration in terms of expected downtime or system availability and expected relevant costs, e.g. inventory holding costs of spares, downtime costs. The model output can, in turn, be analysed to decide the mission specific deployment of AM. As a situation without AM integration is considered, the model shows how AM integration affects vehicle readiness opposed to a situation without AM deployment. Finally, in order to assess the robustness of the model, sensitivity analysis is be performed. This serves to explore how the predetermined influencing factors affects the model outcome.

2.3 Project scope

The scope of the research is limited to the integration of AM in the remote spare parts supply chain. The research does thus not cover AM integration in the day to day peacekeeping environment in the Netherlands. Furthermore, the research assesses AM as additional, emergency sourcing option. Additionally, the scope of the research is limited to studying the various options of consumable spare part supply. Repair of broken parts using CM or AM techniques is therefore not taken into account. This research only considers spare parts that can be sourced both conventionally and through AM.

2.4 Deliverables

The research project yields deliverables for the RNLA and Eindhoven University of Technology, which are listed below.

Royal Netherlands Army:

- Model to assist in deciding how AM can be deployed in the mission specific spare part supply chain
- Manual complementing the model with explanation
- Results on a case study
- Presentation on the proposed model

Eindhoven University of Technology:

- Report on the topic of integrating AM as a sourcing option in a spare part supply chain
- Presentation on the master thesis research and results

2.5 Practical and theoretical contribution

This master thesis has a contribution that is twofold: practical and theoretical. For the RNLA, the contribution of this thesis is practical, as it yields a model that can be used to assess different ways of AM integration in a mission context along with the use of conventionally produced spares, to improve vehicle readiness. In turn, the model can be used prior to missions, to help determine the deployment of AM in the set-up of the mission specific spare part supply chain. As AM and CM are considered along one another, the model may influence spare part inventory levels, as a selection of spares can be produced on demand.

The master thesis has a theoretical contribution to literature, by proposing a model to evaluate different ways of integrating AM in a remote spare part supply chain. Various studies consider in which instances deployment of AM can be cost-effective (e.g. Knofius et al. (2021), Song and Zhang (2020), Westerweel et al. (2021)). Furthermore, various researchers stress that AM is especially promising for deployment in remote locations (e.g. Holmström et al. (2010), Knofius et al. (2021), Pérès and Noyes (2006), Westerweel et al. (2021)). However, to our knowledge literature on models that can assist in determining how AM may be integrated in a context specific spare part supply chain and which factors influence this decision is lacking. Furthermore, a great number of studies use qualitative models to identify benefits of AM, but lack empirical field research, which is included in this master thesis.

2.6 Thesis outline

This remainder of this thesis is structured as follows: Chapter 3 answers RQ1, by investigating possible factors that influence remote AM deployment. In Chapter 4 a discrete-event simulation model is proposed that can be used to assess different options of AM integration through scenario analysis, answering RQ2. Subsequently RQ3 is answered in Chapter 5, by selecting two suitable case studies, based on two different mission locations and deployment types. The selection of input values of the simulation model, RQ4, is discussed in Chapter 6. The results of the simulation study and a sensitivity analysis are presented in Chapter 7, answering RQ5. The thesis ends with a conclusion, research limitations and recommendations in Chapter 8.

3 Influencing factors of remote AM deployment

In order to assess how AM can be integrated in a remote spare part supply chain, the factors influencing AM deployment decisions should be considered. Therefore, in this chapter, the first research question is answered:

RQ1: What factors influence AM deployment options in a remote spare parts supply chain?

In Section 3.1 we start by discussing literature on the topic of AM in spare parts management. This provides insights in the factors that may influence AM deployment in various research contexts and shed light on considerations to include when deploying AM remotely. Hereafter, in Section 3.2, we present the interviewing procedure that is used to identify influencing factors of AM deployment among RNLA experts, to supplement literature. Subsequently, in Section 3.3, we combine the information collected from both sources in Table 3.2 and review the set of influencing factors collected to answer the first research question.

3.1 Literature on AM deployment

In Section 2.1 we already identified that AM can be a way to deal with the difficulties encountered in spare parts inventory control. Various researchers have investigated this. Therefore, this section discusses different streams of literature on the topic of satisfying spare part demand using AM technologies, in order to encounter factors that may influence remote AM deployment. A combination of databases is considered in order to obtain literature, selected based on the relevance of topics within specific databases. As a result, the databases consulted are: GoogleScholar, ProQuest, ScienceDirect and Scopus. Research papers are selected based on their relevance in relation to our research. Selecting studies is initially done based on the title, abstract, introduction and conclusion. Adding to that, forward and backward citation is used on the most promising studies to uncover more relevant sources of literature.

One stream of literature focuses on selecting the best sourcing strategy, AM or CM, for multiple parts, where CM lead times are generally assumed to be long as opposed to short AM lead times. Hereafter we discuss three key examples of this literature stream. Cestana et al. (2019) evaluate AM and CM supply options for slow-moving parts with high required service levels. The focus of the research is on comparison of AM and CM set-up times and production times. Especially when CM set-up times are high relative to their production times, it turns out that using AM instead of CM can reduce the total costs drastically. Furthermore, using AM instead of CM generally reduces the optimal stock levels. Sgarbossa et al. (2021) assess under which conditions transitioning from CM to AM is economically profitable, taking into account various AM techniques and post-processing treatments. The size, complexity, and demand frequency of parts are varied, and limited storage space is assumed. The authors mirror mechanical properties in terms of mean time to failure. The research shows that deploying AM is most attractive for smaller parts, low backorder costs, high lead times for CM, and long review periods. If there is no storage space, for example in remote or offshore environments, AM outperforms CM. When there is limited storage space, the decision to opt for AM or CM parts is mainly based on part complexity. Song and Zhang (2020) determine the optimal source selection strategy that minimizes the long-run average costs. The authors assume a single location hybrid system, where CM parts can be stocked, while AM parts can be produced on demand. The authors consider costs, speed and part reliability of AM and assess how part criticality (cost of equipment outage) and demand frequency (part failure rate) influence the optimal solution. Song and Zhang (2020) find that including AM capability results in significant cost reductions, although it is not frequently utilized.

Whereas the previous papers determine the one best sourcing option, Knofius et al. (2021) consider dual sourcing, whereby one type of component can be both stocked and printed on demand. The authors examine under which conditions printing is a preferable sourcing option compared to a conventional option, and incorporate that AM and CM parts have different failure rates. Knofius et al. (2021) state that solely deploying AM on demand is not suitable for parts that are downtime critical. These parts require some stock to ensure equipment availability. Furthermore, AM seems most promising in instances with high backorder costs and where CM is associated with high holding costs. The authors stress that dual sourcing using AM at remote locations is a topic of future research as it could induce cost savings and improved downtime management of capital goods.

Other studies specifically focus on printing parts in remote locations. Tönissen and Schlicher (2021) investigate whether to bring along AM capabilities to disaster areas, and if so, how many. The research considers which amount of printmaterial to take and which items to bring physically. Tönissen and Schlicher (2021) find that packing AM capability is nearly always beneficial. Meisel et al. (2016) embrace the advantage of deploying AM in remote locations and investigate which type of AM technology to deploy given a specific set of characteristics of the remote location. The research focuses on constraints and objectives of the AM process, the AM machine, the part considered, materials, and environmental and logistics considerations. Busachi et al. (2018) investigate the implementation of applications of AM in defense support services. As defense organizations typically operate in complex and critical environments, the authors discuss the choices in terms of spare parts to stock in relation to the logistics, administrative and procurement delay times, and stress the uncertainties in military logistics. As the context of a mission typically determines the use of equipment, this also influences the failure behavior of equipment. Therefore, the authors state that for assessment of AM implementation in a specific context, the degree of conflict, the type of mission and the criticality of components should be considered. In a qualitative study, Den Boer et al. (2020) focus on the responsiveness, efficiency and sustainability aspects of deploying AM in remote locations. The study was conducted in collaboration with the RNLA and focuses on military and humanitarian missions. Den Boer et al. (2020) discuss that procurement of CM parts often incurs long supplier lead times (6-8 months), which can be shortened by deploying AM as replaceable part, or temporary fix. Temporary fixes are spare parts that can be produced quickly in case of a shortage of regular parts.

Westerweel et al. (2021) combine literature on dual sourcing using AM with deployment of AM in remote locations and assess two types of emergency shipments: printing an AM part and expediting a CM part. The part considered is critical in the sense that part failure causes system downtime. In line with the research of Knofius et al. (2021), Westerweel et al. (2021) consider different failure probabilities for AM and CM parts. Printed parts serve as temporary fix, such that these are replaced by a CM part and disposed once the CM part arrives. The authors specifically model failure costs to reflect the inconvenience of a failure during operations. The results of Westerweel et al. (2021) show when printing, expediting or backordering should be used to satisfy critical part demand. The model is applied to the

RNLA peacekeeping mission in Mali. An on-site general-purpose printer induces great cost reductions for a selection of fourteen printable parts within three vehicle types.

Instead of selecting between AM and CM or combing them, another stream of literature focuses on the choice between centralized and decentralized AM capabilities. Hereafter we discuss two examples. Khajavi et al. (2014) introduces different cost items and uses scenario analysis to determine under what conditions decentralized AM is given preference over centralized AM. The authors show that high automation, low acquisition prices, and short AM production times favor decentralized spare parts production. Liu et al. (2014) evaluate the options of centralized and decentralized AM production and compare them with the conventional as-is situation. Various scenarios are considered to study the effect of AM on safety stocks and stock-out risks, taking into account different demand characteristics. Liu et al. (2014) find that changing the as-is situation reduces the safety stock under various scenarios.

The majority of research papers considered, quantitatively study a specific spare parts supply scenario with AM as sourcing option, either instead of, or in combination with CM spare parts. Due to the quantitative nature, these papers treat how inventory levels, safety stock or base-stock levels are affected by introducing AM. In order to evaluate downtimes, most papers consider printing times of AM parts in relation to leadtimes or production times of CM parts. Additionally, different cost items are included to evaluate the optimal sourcing selection strategy per research paper. The qualitative papers considered complement the quantitative papers by describing factors that may specifically influence remote AM deployment, or AM deployment in a RNLA context.

3.2 Expert interviews on AM deployment

Besides literature, experts may complement or even stress certain factors that, according to their expertise, may not be excluded from the research. Therefore, this section will explain the interviewing procedure, the selection of respondents and results in terms of usable influencing factors these interviews yielded.

3.2.1 Interview procedure

The objective of conducting interviews is to complement literature in answering the first research question. As this question is explorative in nature, an open-ended interviewing procedure is selected (Blumberg et al., 2014). The interviews serve to shed light on the set-up of the as-is remote spare part supply chain. Additionally, the interviews allow for respondents' interpretations of how AM may be integrated in the spare parts supply chain during missions. By allowing in-depth interviewing, respondents may be asked to explain or substantiate their views. Rather than an extensive interviewing guide, a memory list is used by the interviewer to ensure the same issues are addressed in every interview, thereby increasing the comparability of multiple interviews. Appendix C can be consulted for the memory list.

3.2.2 Interview respondents

To ensure a certain degree of information saturation, experts working in various departments touching with our scope are interviewed. Interviewees are selected based on their position as stakeholder throughout the spare part supply chain. First of all, experts who can provide knowledge on the current as-is spare parts supply chain are considered. This ranges from maintenance personnel, performing maintenance activities, to logistics providers, who are in charge of transportation movements and the advisory and supporting body, who coordinates all actions during missions. Additionally, experts in the field of AM should be consulted on their knowledge of remote AM deployment, such as AM users. This leads to a total of 12 interviewees. Table 3.1 gives an overview of the background of each interview respondent. Names of interviewees are excluded for privacy reasons. The table contains two additional columns showing whether the interviewee was selected based on knowledge on the as-is supply chain (SC), additive manufacturing (AM) or both.

Table 3.1: Overview of interviewees

Number	**Respondent background**	**SC**	**AM**
1	Land Maintenance Initiative	X	X
2	Logistics Knowledge Center 1		X
3	Systems & Analysis Department 1	X	
4	Supply & Transport Command	X	
5	Board of Operations	X	
6	AM user	X	X
7	Systems & Analysis Department 2		X
8	11 Supply Command	X	X
9	11 Maintenance Company	X	X
10	13 Maintenance Company	X	
11	13 Armored Infantry	X	
12	11 Combat Logistics	X	

The interview respondents all work within the RNLA. Hereafter we briefly discuss each interviewee's background. Appendix A can be consulted for the organisational structure of the RNLA. *Respondent 1* works for the Land Maintenance Initiative. This is a cooperation between the RNLA and the industry, created to streamline maintenance of RNLA materiel by increasing the operational availability of materiel at lower costs. *Respondent 2* fills a position at the Logistics Knowledge Center of the RNLA. This body aims to collect and retain logistic concepts and experiences and develop these for the future of RNLA logistics, among which logistics of spare parts. Another two of the respondents, *respondent 3* and *respondent 7*, work at the Systems & Analysis department of the Material Logistics Command. This department collects and develops analytics about RNLA (weapon) systems, in order to understand materiel performance. The department plays a role in advising on the use and maintenance of equipment. Besides, one of these interviewees, *respondent 7*, had a previous position at the Land Maintenance Initiative. *Respondent 4* works at the Supply & Transport Command. During military exercises and deployment, the Supply & Transport Command arranges and supervises all road transports of the RNLA. The unit is specialized in moving large quantities of goods and equipment in the Netherlands and abroad. Generally during type two deployment (peacekeeping), this unit coordinates deployed central stock of spares. Yet another respondent, *respondent 5*, fills a seat at the Board of Operations, the body that advises and supports the Chief of Defence on the deployment and readiness of military personnel, and directs, adjusts and monitors military deployment. *Respondent 6* has worked as an AM user with an AM configuration during a pilot in Mali. *Respondent 8* works at the 11 Supply Command. This is a unit that is only reckoned by the 11 Airmobile Brigade due to their logistic operations through air. Prior to this position, this interview respondent has worked for the Logistics Knowledge Center, focusing on AM techniques for spare parts management. *Respondent 9* and *respondent 10* both fill a position at a Maintenance Company. *Respondent 9* works as an engineer and operates an AM configuration for 11 Airmobile Brigade. *Respondent 10* works at the Staff of the Maintenance Company of the 13 Light Brigade. *Respondent 11* has a logistics position within 13 Armored Infantry and has been responsible for acquiring spare parts in Lithuania. The last of our respondents, *respondent 12*, has been approached based on expertise in combat logistics at 11 Airmobile Brigade.

3.2.3 Influencing factors retrieved from interviews

Here we describe the influencing factors retrieved from interviews. In Table 3.2 an overview is presented, including which factors were contributed by which interview respondent. In interviews, various respondents stressed that remote operations are often accompanied by long lead times. Printing could be an option if printing times reduce waiting times for spares. In that sense, AM is mentioned by different respondents as a valuable option in satisfying spare part demand for obsolete parts. A number of respondents mentioned AM part reliability in relation to CM reliability (i.e. failure behavior) as a determining factor for the success of AM as sourcing option. Climatic conditions, machine resources and the type (and robustness) of the printer and print material were often mentioned, as the RNLA usually operates in varying circumstances. Additionally, the experts stressed mission-specific factors that may influence the manner of remote AM deployment, such as: mission aim/type of mission (type one or type two deployment, combat or peacekeeping, respectively), the mission duration, the mission size, level of threat, type of vehicles deployed and supply chain uncertainty. From our interview respondents we learned that the focus of the RNLA is more on system availability, i.e., vehicle readiness, than on specific cost items. Another factor mentioned by experts is prioritisation of potential printables, i.e., which parts may be printed and how should these be scheduled on AM capability. Moreover, interview respondents mentioned the (combination of) various part retrieval options (regular supply, expediting against a high fee, emergency printing) and the option to print temporary fixes rather than part replacements. The location of AM configuration is frequently mentioned in interviews, which is expected as it is one of the topics of the interview memory list.

3.3 Identified factors influencing AM deployment

By combining the results gathered through literature and expert interviews, a number of potentially influencing factors of remote AM deployment remains. Table 3.2 presents an overview of possible influencing factors, whereby the rows represent factors studied by researchers or mentioned by interviewees. The columns refer to the specific research paper or interviewee mentioning the influencing factor. It should be noted that the papers not necessarily study AM deployment in remote locations, except for Busachi et al. (2018), Den Boer et al. (2020), Meisel et al. (2016), Tönissen and Schlicher (2021) and Westerweel et al. (2021). The interviewees were specifically asked to substantiate their view on the topic or AM deployment in a remote spare part supply chain. The factors listed in the table are arranged based on how often these are mentioned.

In essence, the research papers are mainly centered around quantitative considerations, such as costs and lead times or printing times, that may help determine in what way producing spare parts using AM is best utilized. Factors such as backorder/downtime costs, unit production/printing costs and unit order/procurement costs are not, or rarely mentioned in interviews, while these are well represented in literature. Especially Khajavi et al. (2014) study a number of cost items that are are barely shared with interviewees or other literature sources. Some papers study a specific variable, like AM or CM set-up times (Cestana et al., 2019), AM machine automation level (i.e. how many machines one operator can operate) (Khajavi et al., 2014), part variety (number of parts) or part criticality (reflected in terms of varying backorder costs) (Song and Zhang, 2020), or different types of AM configurations combined with post-processing (Sgarbossa et al., 2021). These factors are not specifically mentioned by the interviewees.

The experts consulted, on the other hand, mention factors gathered through their experience, that may influence remote AM deployment specifically, such as climatic conditions, machine resources and skilled personnel. While these influencing factors are mentioned by a number of interviewees, these are only shared with two research papers by Den Boer et al. (2020) and Meisel et al. (2016). It should be emphasized that the main author of Den Boer et al. (2020) is military. However, contrary to the other papers considered, these two papers are concerned with the advantages and challenges of remote AM deployment, and selecting the right AM technology for remote AM deployment, respectively. Interestingly, the factors mission size, type of vehicles deployed, (digital) infrastructure on the base, prioritisation of potential printables, part retrieval options and obsolete parts are only mentioned by interviewees, stressing a literature gap concerning the selection of papers we considered. Mission specific factors, like mission aim/type of mission (type one or type two deployment, combat or peace deployment, respectively) and level of threat, are generally discussed during interviews, which highly influence remote operations, according to RNLA experts.

Some factors are less frequently mentioned by interview respondents and researchers, potentially indicating these are understudied in literature on (remote) AM deployment. Westerweel et al. (2021) introduce unit failure cost as a penalty for failure of a spare part during military operations (unlike backorder or downtime costs for the inconvenience of not having a spare part in stock). Similarly, supply chain uncertainty may be of influence, which is typical for a military context. This factor is mentioned by Busachi et al. (2018) as well as two interview respondents, and stresses the uncertainty in replenishment occurrences and lead times.

In this chapter we presented different factors that may influence remote AM deployment, retrieved from literature and expert interviews. We decide to consider the first ten identified factors to be most important when considering integrating AM remotely. However, since factors eight through thirteen are mentioned equally often, we choose to consider factors up to and including factor thirteen to be most important. In Chapter 4 we eventually discuss which factors we actually include in our research.

Table 3.2: Factors affecting AM deployment according to researchers and interviewees

		Busachi et al. (2018)	Cestana et al. (2019)	Den Boer et al. (2020)	Khajavi et al. (2014)	Knofius et al. (2021)	Liu et al. (2014)	Meisel et al. (2016)	Sgarbossa et al. (2021)	Song and Zhang (2020)	Tönissen and Schlicher (2021)	Westerweel et al. (2021)	**Interviewee 1 (LMI)**	**Interviewee 2 (LKC)**	**Interviewee 3 (S&A 1)**	**Interviewee 4 (S&T Com.)**	**Interviewee 5 (Board of Ops)**	**Interviewee 6 (AM user)**	**Interviewee 7 (S&A 2)**	**Interviewee 8 (11 Supply Com.)**	**Interviewee 9 (11 MaintCoy)**	**Interviewee 10 (13 MaintCoy)**	**Interviewee 11 (13 Ar. Inf.)**	**Interviewee 12 (11 Comb. Log.)**	**Total**
1	**Printing time/rate**	X	X	X	X	X	X		X	X	X			X		X		X		X		X	X	X	16
2	**Lead time**	X		X	X	X	X	X	X	X						X	X			X		X	X		13
3	**Component failure behavior (i.e. spare part demand)**	X	X	X	X	X	X		X	X	X	X							X			X	X		13
4	**Inventory/base-stock level**	X	X	X	X	X	X		X	X	X	X		X			X	X							13
5	**Location of the AM machine**				X		X						X	X		X		X	X	X	X		X		10
6	**Climatic conditions**							X						X			X	X	X	X		X	X	X	9
7	**Skilled personnel**			X				X						X				X	X	X		X	X		8
8	**Unit holding costs**		X		X	X	X		X	X		X													7
9	**Unit production/ printing costs**	X		X		X			X	X		X			X										7
10	**Machine resources (power, gas, water)**			X				X									X	X	X	X				X	7
11	**Type of printmaterial**			X				X					X					X	X			X	X		7
12	**Option of temporary fix**			X								X	X		X			X			X		X		7
13	**Part variety**									X	X		X		X			X	X				X		7
14	**Unit backorder/ downtime costs**		X		X	X			X	X		X													6
15	**Mission aim/ type of mission**	X												X	X		X		X			X			6

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Table 3.2 – continued from previous page

		Busachi et al. (2018)	Cestana et al. (2019)	Den Boer et al. (2020)	Khajavi et al. (2014)	Knofius et al. (2021)	Liu et al. (2014)	Meisel et al. (2016)	Sgarbossa et al. (2021)	Song and Zhang (2020)	Tönissen and Schlicher (2021)	Westerweel et al. (2021)	**Interviewee 1 (LMI)**	**Interviewee 2 (LKC)**	**Interviewee 3 (S&A 1)**	**Interviewee 4 (S&T Com.)**	**Interviewee 5 (Board of Ops)**	**Interviewee 6 (AM user)**	**Interviewee 7 (S&A 2)**	**Interviewee 8 (11 Supply Com.)**	**Interviewee 9 (11 MaintCoy)**	**Interviewee 10 (13 MaintCoy)**	**Interviewee 11 (13 Armored Inf.)**	**Interviewee 12 (11 Comb. Log.)**	**Total**
16	**System availability**	X		X									X			X				X	X				6
17	**Obsolete parts**														X	X	X	X	X	X					6
18	**Level of threat**	X													X		X			X		X			5
19	**Type of printer**								X				X				X					X		X	5
20	**AM machine and material volume**							X			X			X								X		X	5
21	**Part criticality**	X								X	X					X							X		5
22	**Utilization of AM machine**		X		X					X	X														4
23	**Depreciation costs**			X	X	X						X													4
24	**(Supply chain) uncertainty**	X									X				X					X					4
25	**(Unit) order/ procurement costs**					X				X		X													3
26	**Maintenance costs**			X		X		X																	3
27	**Initial AM machine cost**			X				X														X			3
28	**Order cycle/replenishment time intervals**				X				X			X													3
29	**Part retrieval options**													X						X	X				3
30	**AM part quality**										X	X													2
31	**AM or CM set-up time**	X	X																						2
32	**Print chamber size/ number of parts per run**				X			X																	2
33	**Material cost**				X										X										2

Continued on next page

Table 3.2 – continued from previous page

		Busachi et al. (2018)	Cestana et al. (2019)	Den Boer et al. (2020)	Khajavi et al. (2014)	Knofius et al. (2021)	Liu et al. (2014)	Meisel et al. (2016)	Sgarbossa et al. (2021)	Song and Zhang (2020)	Tönissen and Schlicher (2021)	Westerweel et al. (2021)	**Interviewee 1 (LMI)**	**Interviewee 2 (LKC)**	**Interviewee 3 (S&A 1)**	**Interviewee 4 (S&T Com.)**	**Interviewee 5 (Board of Ops)**	**Interviewee 6 (AM user)**	**Interviewee 7 (S&A 2)**	**Interviewee 8 (11 Supply Com.)**	**Interviewee 9 (11 MaintCoy)**	**Interviewee 10 (13 MaintCoy)**	**Interviewee 11 (13 Armored Inf.)**	**Interviewee 12 (11 Comb. Log.)**	**Total**
34	**Transportation cost**			X	X																				2
35	**Mission duration**	X											X												2
36	**Mission size**																X		X						2
37	**Type of vehicles deployed**												X						X						2
38	**(Digital) infrastructure on the base**													X			X								2
39	**Prioritisation of potential printables**																	X					X		2
40	**Automation level**				X																				1
41	**Personnel cost**				X																				1
42	**Unit failure cost**											X													1

4 General model

A model may serve to quantitatively assess different ways of integrating AM in a remote spare parts supply chain. The question remains what type of model this may be and what this model may look like. In this chapter we thus answer the second research question:

RQ2. Which quantitative model can be used to assess different ways of integrating AM as sourcing option in a remote spare parts supply chain?

In this chapter we discuss the quantitative model we use to assess different scenarios of integrating AM remotely. In Section 4.1 we start by discussing what type of model is suitable to apply to the problem we identified in Chapter 2. We find that discrete-event simulation is most appropriate. We proceed by describing some modeling assumptions in Section 4.2. In that discussion, we include the important influencing factors that we identified in Chapter 3. Hereafter we describe the model in Section 4.3. Subsequently, in Section 4.4, we explain the discrete-event simulation procedure and implementation in detail, focusing on events that cause system changes. The model's evaluation procedure is described in Section 4.5, where we present the considered performance measures and subsequently discuss scenario analysis, used to evaluate various ways of AM integration. As we define different SKU base-stock levels per scenario, this section also includes the base-stock level determination procedure.

4.1 Type of model

The goal of this research is to determine means to assess whether or not to include AM capability in a remote spare parts supply chain, and if so, where to locate these. We aim to provide a model that allows quantitative evaluation of a spare parts supply system that includes both CM and AM options. Examples of ways to quantitatively assess an operations management problem are mathematical evaluation or computer simulation.

In literature centered on AM as spare part sourcing option, there are various examples of papers applying a mathematical approach. Cestana et al. (2019) use Markov Chains to model the production and set-up times when assessing whether to source spare parts using CM or AM techniques. Song and Zhang (2020) model a queuing system and present a framework to determine the optimal source selection strategy - CM or AM - that minimizes the long-run average costs in a single location. Results are obtained through Markov Chain models. Knofius et al. (2021) propose a dual-sourcing model, based on a Markov Decision Process, combining a continuous-time Markov Chain with linear programming, examining under which conditions AM is a preferable sourcing options compared to a conventional option. Westerweel et al. (2021) combine dual-sourcing using AM with deployment of AM in remote locations by modeling a discrete-time Markov Decision Process, to assess when printing, expediting or backordering should be used to satisfy critical part demand. Tönissen and Schlicher (2021) present a two-stage stochastic programming (NP-hard integer linear programs) and subsequently reconfigure this to an integer linear program, to decide whether or not to pack AM capability for disaster response operations.

For complex problems, mathematical analysis often requires the problem to be simplified. In these instances, computer simulation may be a better suited approach, allowing incorporation of the problem's complexities (Bertrand and Fransoo, 2002). Ghadge et al. (2018) use a system dynamics simulation approach, to identify the potential of AM in the spare parts supply chain, mitigating supply chain risks. Busachi et al. (2018) investigate the implementation of applications of AM in the defense support services, by applying a system dynamics approach to adapt the as-is situation using various scenarios. Likewise, we aim to provide a quantitative model that captures most of reality's aspects. A distinction can be made between different simulation approaches for queuing models, specifically continuous, discrete and discrete-event simulation (Boon et al., 2020). Continuous simulation, is often used in chemical applications where the state of the system changes continuously. In discrete simulation, the system is reviewed at regular points in time separated by fixed intervals. Discrete-event simulation retains an object-oriented approach, where the system is reviewed when jumping from one event to the next. It allows incorporation of uncertainties encountered in operations of a remote spare parts supply chain and the systems' behavior can be compared over time. Discrete-event simulation is a tool that is often used for decision support purposes in logistics and supply chain management (Tako and Robinson, 2012). As we encounter changes in the system at arbitrary moments in time, i.e., we want to respond to component failure the moment it occurs, we choose to follow a discrete-event simulation (DES) approach.

4.2 Modeling assumptions

In this section various key assumptions regarding integration of AM in the spare parts supply chain are discussed, forming the basis of the model. Therefore, we explain the use of temporary fix, after which we describe the choice for printing spare parts make-to order, i.e., not stocking printed parts. Hereafter, we discuss the choice to focus on downtime critical spare parts, as well as the inventory policy and the different sourcing options included in the model. Lastly, we discuss which cost items captured in the operating costs.

Besides a description of these modeling assumptions, we discuss the most important factors affecting AM in remote areas, identified by literature and interview respondents as discussed in Chapter 3, see Table 3.2. We regard the first thirteen factors as most important (mentioned at least seven times) and specifically discuss how we include these factors in our research in Section 4.2.7.

4.2.1 Temporary fix

In the model we assume AM part quality to be lower than CM part quality. More specifically, we solely consider AM parts as temporary fix rather than an actual part replacement. Temporary fixes can be produced quickly in case of a shortage of regular parts. As the name suggests, a temporary fix bridges the period until replacement by a conventional part. We assume AM as temporary fix for the following reasons. At first, temporary fixes allow a short response time. Although the speed of production may come at the expense of a lower reliability, temporary fixes may be valuable in maintaining or even improving responsiveness, thus increasing asset availability (Westerweel et al., 2021; Zijm et al., 2019). Secondly, due to an increased level of responsiveness, inventory levels may be decreased when using temporary fixes. Thirdly, the use of temporary fixes ensures the OEM's business is not disrupted and may increase the OEM's level of cooperation, as the regular part is still required (Westerweel et al., 2021). Finally, AM technology is still under development. It is rather understudied what effect external factors, such as changes in the production environment, may have on the quality of the print, stressing a temporary part is favored over a replacement.

4.2.2 Print to stock or to order?

AM can be used to print on demand, in literature often reckoned as make-to-order (MTO), or print to stock, which is generally referred to as make-to-stock (MTS). In our model we assume printing on demand to complement CM inventories, for several reasons. Firstly, printing on demand can reduce large emergency stocks required for modern warfare (Den Boer et al., 2020), in turn, decreasing storage liability and the logistics drag of the units in the field (Antill and Smith, 2017). MTO may thus reduce the inventory holding costs for spare parts that are rarely demanded (Walter et al., 2004; Chekurov et al., 2018). Westerweel et al. (2021) state that operating at remote locations is paired with storage space restrictions, implying holding costs are higher than usual in inventory management. However, solely printing on demand and not keeping stock is not suitable for downtime critical parts, as this may induce high downtime costs (Knofius et al., 2021). Thus, we consider CM stock to absorb initial shortages. While MTS, using AM to replenish stock, may be beneficial in case CM supply options are restricted or when CM supply options carry high supply risks, we dot not include it in our model.

4.2.3 Type of spare parts

In this model, we only focus on spare parts that are downtime critical. This means absence of these parts causes system failure and, consequently, these systems cannot be used in operations. We choose to only consider downtime critical parts, as these affect the vehicle readiness of the installed base, our objective function. Additionally, the model only considers SKUs that can be produced using both CM and AM techniques, since we study the effect on the overall vehicle readiness of sourcing AM parts next to regular CM part supply. The parts included are treated as consumables, while in practice parts may be sent to the Netherlands for repair after component failure.

4.2.4 Inventory policy

In our model we assume that spare parts are replenished via an $(S-1, S)$ policy in every stocking location. This implies that a new spare part is ordered, every time one is take from stock. This is reasonable, since we value an inventory policy that allows quick response to shortages as equipment downtime is costly.

4.2.5 Supply options

There exist various spare part sourcing options of conventional spare parts: regular supply, expediting, retrieval through partner organisations and cannibalisation. In the model we solely consider regular CM spare part supply, complemented by local emergency AM supply in the form of a temporary fix. Regular supply occurs on the basis of scheduled replenishments to the area of deployment in order to prevent out-of-stock situations or satisfy outstanding spare part demand (i.e., backorders). Regular supply may, for instance, occur on a weekly basis. We complement regular supply by local AM to produce a temporary fixes when we have a backorder, to assess how inclusion of AM may affect to vehicle readiness in a deployment area. However, when out-of-stock situations occur of critical spare parts, there are some other sourcing options that may be called upon. In practice it is possible to expedite spare parts, meaning speeding up the delivery against a high fee. This is an emergency option which, in a most extreme case, would mean an aircraft is sent to the area to deliver the spare part. In practice, this opportunity is hardly ever used due to the high fee (Westerweel et al., 2021). Therefore, this sourcing option is not considered in the model. Retrieval through partner organisations is not considered either, as the RNLA aims for supply chain resilience. Finally, cannibalisation is a sourcing strategy sometimes utilized by the RNLA. This is generally an unfavorable option as the part probably already degraded through the use in another vehicle. These final two sourcing options may be utilized in exceptional cases and not structurally (Board of Operations).

4.2.6 Operating costs

The operating costs we regard in this model are: holding costs, downtime costs, failure costs and print costs. Holding costs reflect storage space restrictions in a remote environment, incurred over the period of time an item is transit or physically in stock in every stocking location. Downtime costs are costs reflecting the unavailability of material, incurred for every unit of time a system is not available. Failure costs reflect the inconvenience of system failure during operations, including the cost of recovery (Westerweel et al., 2021). These costs are only incurred once, when a part failure occurs. We include failure costs for both CM and AM parts, to stress that every failure is equally important and undesirable, so also AM part failures before replacement by a more reliable CM counterpart. Similar to Westerweel et al. (2021), we include print costs consisting of material costs and machine depreciation costs, found by Atzeni et al. (2010) to be the largest cost factors of 3D thermoplastics printing. For every print order we thus consider print costs that are SKU specific and AM capability specific, because of the differences in material quantities.

4.2.7 Factors affecting AM deployment

In Chapter 3 we discussed the factors affecting AM deployment according to researchers and interview respondents, which are summarized in Table 3.2. We identify the first ten factors as most important. However, as factors eight through thirteen are mentioned equally often (seven times), we consider the first thirteen factors as most important. We consider the trade-off between print time (factor 1) and lead time (factor 2) in our model when deciding when to use the emergency AM option, which is further discussed in Section 4.3. Component failure behavior (factor 3) is included in the model, triggering spare part demand and a change in the inventory levels (factor 4). We consider a system with multiple locations (factor 5) that can be used as AM hosting locations reflecting the supply chain recognized by the RNLA. Climatic conditions (factor 6) are not specifically included in the model, but can be regarded as external factors affecting the quality of the printed part or shipment continuation. We eventually consider two case studies in different regions under different climatic conditions, explained in Section 5.1. Skilled personnel (factor 7) and machine resources (factor 10) are factors especially mentioned by interviewees that we assume are conditions that are met prior to deploying AM capability. We consider general-purpose AM capabilities, which are not particularly difficult to operate. Prior to deployment, we have to ensure there are enough operators who can control an AM capability. Similarly, machine resources simply have to be arranged prior to deployment. Two of our interview respondents in charge of logistics justify this (Supply & Transport Command; Board of Operations). As mentioned in Section 4.2.6 we consider unit holding costs (factor 8) and unit print costs (factor 9). The type of print material (factor 11) is considered through the choice for temporary fix, allowing us to include a selection of general-printer print materials. In Section 4.5.2 we describe how we asses different AM capability types with different print materials, included through spare part specific print times and print costs. The use of temporary fix (factor 12) is discussed in Section 4.2.1. Part variety (factor 13) is included by allowing us to print a selection of spare parts, which is discussed in Section 4.3.

4.3 Model description

We consider a multi-echelon, multi-item serial supply chain for spare parts, as presented in Figure 4.1. Our goal is to decide on the location of an AM production facility, by evaluating vehicle readiness and operating costs over time for various scenarios. We denote any specific moment in time by $t \in \mathbb{R}_+$ and the evaluation period $[0, T]$. We model three echelon levels near or in the country of deployment, of which every echelon level can keep spare part inventories. We refer to the set of echelons, or locations, as $J = \{1, 2, 3\}$. Location 3 denotes the most downstream location.

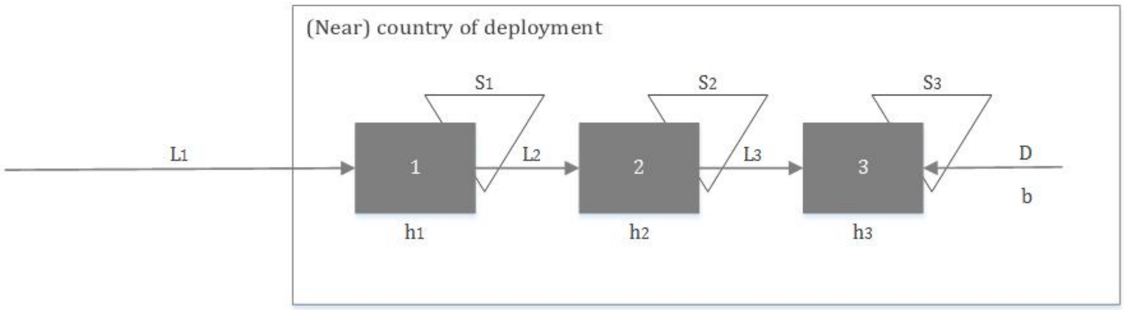

Figure 4.1: General model

In the deployment area, we consider a set of vehicles $\mathcal{N}$ as our installed base. Each vehicle consists of components that may fail. We consider the set $\mathcal{M}$ of downtime critical components. Each location $j \in J$ may keep stock of SKU $m \in \mathcal{M}$. The base-stock level at location $j \in J$ for SKU $m \in \mathcal{M}$ is denoted by $S_{j,m} \in \mathbb{N}$.

AM capability
We consider AM capability in location 2 or 3, or not at all. Local AM can be used as an emergency option to satisfy backorders. That is, we rely on CM spare parts and only consider AM whenever we have no spare part inventory on hand of the requested SKU. We assume that AM is used to manufacture temporary fixes that bridge the period until replacement by a CM alternative. We consider infinite printing capacity when including AM capability. We only consider stocking AM parts in the instance that a CM part overtakes an AM part.

Spare part demand
Only in the most downstream location, location 3, spare part demand may occur. Spare part demand arises when a functioning SKU $m \in \mathcal{M}$ in one of the deployed vehicles fails. The time between failures of both CM and AM SKUs is assumed to follow an exponential distribution, with parameters $\lambda_{CM,m} \in \mathbb{R}_+$ and $\lambda_{AM,m} \in \mathbb{R}_+$, respectively. Failures are assumed to occur mutually independent. We assume that, when a vehicle is down due to an outstanding spare

part demand, the other SKUs cannot fail. This assumption is made as the power of down vehicles is off and component failure is assumed to happen through wear during intensive vehicle usage. Since we choose to consider AM to solely produce temporary fixes, we assume $\lambda_{CM,m} \geq \lambda_{AM,m}$.

If available, SKU $m \in \mathcal{M}$ requested at location 3 is immediately delivered from stock; it is backordered otherwise. When a spare part is delivered from stock, location 3 simultaneously orders a part from location 2 to restock inventories. This demand of location 3 triggers an inventory check at location 2. If a spare part of the requested SKU is in stock, it is queued for shipment to location 3. Immediately a spare part is ordered from location 1 to restock inventories. If the requested part is not in stock in location 2, it is backordered from location 1. Location 1 operates in a similar manner as location 2. Location 1 orders from an external supplier that has ample stock, to which we refer as location 0. This means that SKU requests of location 1 are simply queued for shipment.

Print order release
We consider AM capability whenever we do not have CM spare part inventory on hand of SKU $m \in \mathcal{M}$, i.e., when we have a backorder. Printing time of part $m \in \mathcal{M}$ is SKU specific and denoted by $P_m \in \mathbb{R}_+$. A print order is released whenever the expected AM delivery time is (non-strictly) smaller than the expected CM delivery time. We further explain this rule in Section 4.4. We model uncertainty to reflect that AM parts may fail during the printing process. With probability $0 < q_j \leq 1$, $j \in J$, the print is finished and turns out successful. This means that with probability $(1 - q_j)$ the print may fail prematurely, before it is finished. The time at which the print fails is assumed to be uniformly distributed on the printing time P_m. When a print is rejected, a new print order is released if the expected AM delivery time is (non-strictly) smaller than the CM delivery time. This rule is explained in Section 4.4.

Spare part replenishment
Spare part supply between consecutive locations occurs through scheduled shipments. The SKUs requested by location j, queued by location $j - 1$, are put in transit for every location $j \in J$. Replenishments to each of the locations occur periodically. We refer to the number of periods between two consecutive shipments as the order cycle, which we denote by $O_j \in \mathbb{R}_+$ for location $j \in J$. To reflect the uncertainty in supply occurrences we consider a probability that any shipment may be cancelled due to unforeseen, exogenous circumstances. With a certain probability $0 < p_j \leq 1$, scheduled replenishments take place to location $j \in J$. This means that with probability $(1 - p_j)$ a scheduled replenishment is cancelled. When a replenishment occurrence is cancelled, the queued parts remain in queue. The next possible shipment occurrence from location $j - 1$ to location j occurs O_j time units later, for every location $j \in J$. If there are no queued SKUs, there is no shipment. SKUs spend $L_j \in \mathbb{R}_+$ time units in transit, to which we refer as the lead time to location j for every location $j \in J$.

Spare part receipt
Spare part receipt at location $j \in J$ either occurs through regular replenishment, or through successful delivery of a print order. A regular replenishment from location $j - 1$ to location $j \in J$ takes L_j time units to arrive, provided that the shipment occurrence was successful. For successful delivery of a print order, P_m time units after a successful print order an AM SKU $m \in \mathcal{M}$ is delivered. AM spare parts can only be received by the location hosting AM

capability, thus either location 2 or location 3. In location 3 an AM SKU is used to replace a failed SKU in a down vehicle immediately when the SKU is received, without taking additional time. This means the vehicle is available again, driving with a temporary fix until arrival of a CM SKU or component failure. In location 2 an AM SKU still requires shipment to location 3. Therefore, spare part receipt means the SKU is queued for shipment. We only consider stocking AM parts in the instance that a CM SKU is received before an AM SKU is received.

CM SKUs received by location $j \in J$ can either be used to restock inventories, or to satisfy backorders. Thus, upon arrival, we check if there are backorders of SKU $m \in \mathcal{M}$ in location $j \in J$. For location $j \in \{1, 2\}$, a backorder means we queue the part for shipment to location $j+1$. For location 3, satisfying a backorder means replacing a failed component (or temporary fix) in a vehicle. Whenever a shipment arrives in location 3, we prioritize replacing a failed component in a down vehicle over replacing an AM temporary fix within an available vehicle, i.e., we choose to replace a failed CM SKU in a down vehicle before replacing an AM SKU in a driving vehicle. After replacing an AM SKU by a CM SKU, we dispose the AM SKU. In any location $j \in J$, if there are no backorders, we stock the SKU $m \in \mathcal{M}$.

Vehicle readiness and operating costs

The performance measures we consider are vehicle readiness and operating costs. Vehicle readiness denotes the percentage of vehicles available over the entire evaluation period. Operating costs are made up of holding costs, downtime costs, print costs and failure costs. Holding costs in location $j \in J$, for SKU $m \in \mathcal{M}$ are denoted by $h_{j,m} \in \mathbb{R}_+$ per part per unit time. Stocking spare parts is costly as storage space is often limited in remote, isolated areas. These space restrictions generally imply higher holding costs than usual in inventory management. Therefore, holding costs are modeled as a fraction of the SKUs regular unit order costs (Westerweel et al., 2021). To reflect that storage capacity becomes even more tight when moving downstream the supply chain, we assume $h_{j,m} \geq h_{j-1,m}$. Holding costs at location $j \in J$ are incurred over the SKUs in the location's inventory system, i.e., SKUs physically on hand (and in queue) at location j and the SKUs in transit to location j, for all locations $j \in J$, as presented in Figure 4.2. We incur holding costs whenever the quantity of SKUs in the inventory system of location $j \in J$ changes, over the time period these SKUs were in stock: just after a shipment occurrence, when SKUs are put in transit from location $j-1$ to location j for every location $j \in J$, or when location $|J|$ uses an SKU from stock.

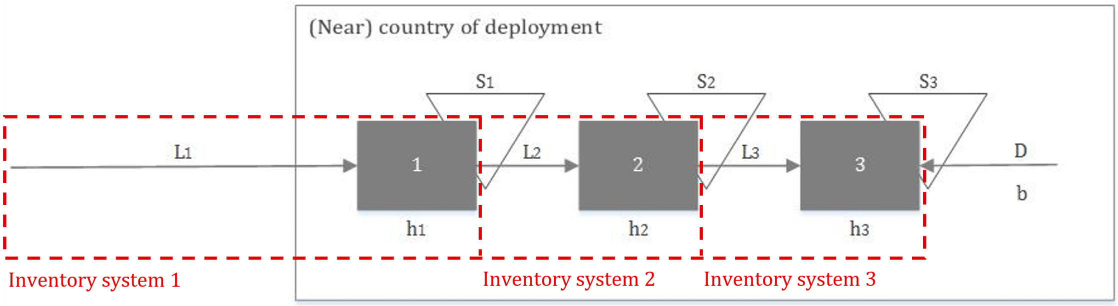

Figure 4.2: Inventory system per location $j \in J$

For every down vehicle waiting for a spare part we incur fixed downtime cost $b \in \mathbb{R}_+$ per unit time. This reflects the inconvenience of an unavailable vehicle. For every component failure, we thus register the total downtime of a vehicle $n \in \mathcal{N}$ and multiply this by downtime costs b. For every print order of SKU $m \in \mathcal{M}$, print costs $c_m \in \mathbb{R}_+$ are incurred. This represents the price of quickly satisfying a backorder. Print costs are SKU specific and fixed, based on the quantity and type of material used for the printed part. To reflect the inconvenience of a failure during operations, we model fixed failure costs $f \in \mathbb{R}_+$, representing the costs of vehicle recovery. Failure costs are incurred every time a CM or AM component fails.

Overview of model notation

Set	*Description*
J	Set of locations in the mission area
$\mathcal{M}$	Set of downtime critical components
$\mathcal{N}$	Set of vehicles

Parameter	*Domain*	*Description*
$S_{j,m}$	$\mathbb{N}$	Base-stock level in location $j \in J$ of SKU $m \in \mathcal{M}$
O_j	$\mathbb{R}_+$	Order cycle of shipment occurrences to location $j \in J$
L_j	$\mathbb{R}_+$	Shipment lead time of location $j - 1$ to location j, for location $j \in J$
P_m	$\mathbb{R}_+$	Print time of SKU $m \in \mathcal{M}$
$\lambda_{CM,m}$	$\mathbb{R}_+$	Failure rate of CM SKU $m \in \mathcal{M}$
$\lambda_{AM,m}$	$\mathbb{R}_+$	Failure rate of AM SKU $m \in \mathcal{M}$
p_j	$0 < p_j \leq 1$	Probability of shipment continuation
q_j	$0 < q_j \leq 1$	Probability of print success
$h_{j,m}$	$\mathbb{R}_+$	Unit holding costs at location $j \in J$ of SKU $m \in \mathcal{M}$ per unit of time
b	$\mathbb{R}_+$	Downtime cost per unit of time
c_m	$\mathbb{R}_+$	Unit print costs of SKU $m \in \mathcal{M}$
f	$\mathbb{R}_+$	Componentailure costs

4.4 Discrete-event simulation

In this section we discuss how we apply discrete-event simulation to retrieve information on the performance of different printer type-location combinations. The simulation starts at $t = 0$ and ends at $t = T$, where time is denoted in hours. We evaluate a continuous time system with discrete events. That is, the events that change the state of the system are countable and predetermined. The set of events is denoted $\mathcal{E} \subseteq \mathbb{N}$. The actions that make up an event happen instantly, at the event time $t \in \mathbb{R}_+$.

We first discuss the notation we use in the simulation model in Section 4.4.1. We thoroughly explain the structure of the DES model in Section 4.4.2. This is followed by a description of the implementation of the simulation model in Section 4.4.3 and a verification of the simulation model in Section 4.4.4.

4.4.1 Simulation variables

We use specific notation to track the distribution of SKU quantities throughout the model over time and to register information on our performance measures. The notation is introduced here, as it is used in describing the DES model in Section 4.4.2. Note that in Section 4.5.1 we discuss how we calculate the performance measures over simulation time $[0, T]$.

Serial supply chain notation

The notation we use to register SKU quantities in the DES model is based on multi-echelon inventory management literature of an echelon base-stock policy, i.e., a centralized control scheme. The following measures are introduced:

- $IOH_{j,m}(t)$ inventory on hand of SKU m in location j at time t,
- $B_{j,m}(t)$ backorders of SKU m in location j at time t,
- $IO_{j,m}(t)$ inventory on order of SKU m by location j from location $j-1$ at time t,
- $IT_{j,m}(t)$ inventory in transit of SKU m to location j from location $j-1$ at time t,
- $Q_{j,m}(t)$ inventory in queue of SKU m at location j to location $j+1$ at time t,

where $t \in \mathbb{R}_+$. $m \in \mathcal{M}$ and $j \in J$ for $IOH_{j,m}(t)$, $B_{j,m}(t)$, $IO_{j,m}(t)$ and $IT_{j,m}(t)$. For $Q_{j,m}(t)$, $m \in \mathcal{M}$ and $j \in J$, $j \in \{1,2\}$, as the final location does not reckon a queue. Note that $IO_{j,m}(t)$ is not necessarily the same as $IT_{j,m}(t)$, since any previous location (i.e. $j-1$) may have outstanding backorders for SKU $m \in \mathcal{M}$. Initially, the system starts with $IOH_{j,m}(0) = S_{j,m}$, $B_{j,m}(0) = 0$, $IO_{j,m}(0) = 0$, $IT_{j,m}(0) = 0$ and $Q_{j,m}(0) = 0$ at $t = 0$. Each of these measures may change whenever a spare part request occurs.

Vehicle readiness and operating cost notation

Here we introduce specific notation used in the DES model for variables later used to calculate our performance measures (Section 4.5.1). A vehicle is available when all considered SKUs are fully functioning according to their purpose. The availability of vehicle $n \in \mathcal{N}$ at a random point in time is given by $A_n(t) = \{0,1\}$, whereby 1 denotes an available vehicle and 0 expresses that the vehicle is down. Component failure triggers a spare part order of SKU $m \in \mathcal{M}$. We refer to x_i as the i^{th} order, $i \in \mathbb{N}$. The set of orders is denoted $\mathcal{I}$, thus $x_i \in \mathcal{I}$. We specify downtime $D_{x_i,n} \in \mathbb{R}_+$ for every spare part order, i.e., the period a vehicle $n \in \mathcal{N}$ has availability $A_n = 0$ and is waiting for an SKU $m \in \mathcal{M}$. Note that downtime $D_{x_i,n} = 0$ of order $x_i \in \mathcal{I}$ applies when an SKU $m \in \mathcal{M}$ is delivered directly from stock, $D_{x_i,n} > 0$ when we have a backorder. We specifically register the total number of print orders of SKU $m \in \mathcal{M}$ over simulation time $[0,T]$ and denote this by $Y_m \in \mathbb{N}$. The following measures for costs items are introduced:

- $H_j[t_{-1},t]$ holding costs over time $[t_{-1},t]$, where t is the time holding costs are updated and t_{-1} is the previous time holding costs were updated at location $j \in J$,
- $H_j[0,T]$ total holding costs of location $j \in J$ over time $[0,T]$,
- $H_{total}[0,T]$ total holding costs of location 1, 2 and 3 over time $[0,T]$,
- $B[0,T]$ total downtime costs over time $[0,T]$,
- $C[0,T]$ total print costs over time $[0,T]$,
- $F[0,T]$ total failure costs over time $[0,T]$.

Location specific holding costs $H_j[t_{-1}, t]$, over period $[t_{-1}, t]$ are calculated during the simulation when the quantity of SKUs in the inventory system of location $j \in J$ changes. These costs are determined using Equation 4.1.

$$H_j[t_{-1}, t] = (t - t_{-1}) * \sum_{m \in \mathcal{M}} h_{j,m} * (IOH_{j,m}(t) + Q_{j,m}(t) + IT_{j,m}(t)), \tag{4.1}$$

where $t \in \mathbb{R}_+$ in hours denotes the time at which we calculate the holding costs for location $j \in J$, $t_{-1} \in \mathbb{R}_+$ the previous time in hours we calculated the holding costs for location $j \in J$, with $t > t_{-1}$. $h_{j,m}$ denotes the unit holding costs, $IOH_{j,m}(t)$ the inventory on hand at time t, $Q_{j,m}(t)$ the items queued for shipment to location $j+1, j \neq |J|$ at time t, and $IT_{j,m}(t)$ the items in transit to location j of SKU $m \in \mathcal{M}$ at location $j \in J$ at time t. To obtain $H_j[0, T]$ we sum over all $H_j[t_{-1}, t]$ for every t that the quantity of SKUs in the inventory system of $j \in J$ changes. We describe how we obtain the values of the total individual cost items, and in turn, the total operating costs over simulation time $[0, T]$ in Section 4.5.1.

Overview of simulation notation

Set	*Description*
$\mathcal{E}$	Set of events included in the discrete-event simulation
$\mathcal{I}$	Set of orders $\{x_1, x_2, ..., x_i\}, i \in \mathbb{N}$

Variable	*Domain*	*Description*
$A_n(t)$	$\{0, 1\}$	Availability of vehicle $n \in \mathcal{N}$ at time t
$D_{x_i,n}$	$\mathbb{R}_+$	Downtime incurred for order $x_i \in \mathcal{I}$ of vehicle $n \in \mathcal{N}$
Y_m	$\mathbb{N}$	Number of print orders for SKU $m \in \mathcal{M}$
$H_j[t_{-1}, t]$	$\mathbb{R}_+$	Holding costs at location $j \in J$ over time $[t_{-1}, t]$
$H_j[0, T]$	$\mathbb{R}_+$	Total holding costs of location $j \in J$ over time $[0, T]$
$H_{total}[0, T]$	$\mathbb{R}_+$	Sum of total holding costs $\forall\ j \in J$ over time $[0, T]$
$B[0, T]$	$\mathbb{R}_+$	Total downtime costs over time $[0, T]$
$C[0, T]$	$\mathbb{R}_+$	Total print costs over time $[0, T]$
$F[0, T]$	$\mathbb{R}_+$	Total failure costs over time $[0, T]$
$IOH_{j,m}(t)$	$\mathbb{N}$	Inventory on hand of SKU $m \in \mathcal{M}$ at location $j \in J$ at time t
$B_{j,m}(t)$	$\mathbb{N}$	Backorders of SKU $m \in \mathcal{M}$ in location $j \in J$ at time t
$IO_{j,m}(t)$	$\mathbb{N}$	Inventory on order of SKU $m \in \mathcal{M}$ to location j from location $j-1$, $j \in J$, at time t
$IT_{j,m}(t)$	$\mathbb{N}$	Inventory in transit of SKU $m \in \mathcal{M}$ to location j from location $j-1$, $j \in J$, at time t
$Q_{j,m}(t)$	$\mathbb{N}$	Inventory in queue of SKU $m \in \mathcal{M}$ at location j to location $j+1$ at time t

4.4.2 Simulation description

We distinguish $|\mathcal{E}| = 12$ event types. Here we describe in detail what each event entails, accompanied by visualisations of the actions in each event. In these visualisations we model start and end events (circular shape) actions (rectangular shape) and choices (diamond shape). Light grey is used to denote an update in a cost item. Dark grey is used to distinguish which actions are only considered when including AM capability.

Hereafter, in Table 4.1, we provide an overview of all simulation's events and consecutive events, showing how the quantities of spare parts move through the echelons. We denote $t \in \mathbb{R}_+$ the time of the event occurrence. Actions in the events happen immediately, without taking additional time. In column "Sequential Event" we denote the consecutive event $e \in \mathcal{E}$ and the time this event e occurs. We review the system during moments in time that an event occurs and the system changes. To track the upcoming events, the simulation model is centered around a Future Event Set (FES), in which we chronologically order all future events based on the event time. We further describe this in Section 4.4.3.

Spare part request (events 1, 2, 3 and 4)
Events 1 through 3 represent a spare part request in location 3, 2 and 1, respectively. The process of a spare part request at location 3, event 1, is presented in Figure 4.3. A similar process is mapped for a request at location 2 and 1, events 2 and 3, in Figure 4.4. Event 1 occurs through component failure at time $t_{x_i} \in \mathbb{R}_+$, where x_i denotes failure $i \in \mathbb{N}$, i.e., t_{x_1} denotes the time of the first component failure. The concerning location $j \in J$ checks whether SKU $m \in \mathcal{M}$ can be delivered from stock, i.e., $IOH_{j,m} \geq 1$. If so, for location $j \in \{1, 2\}$ this means the SKU is queued for the next scheduled replenishment, i.e., $IOH_{j,m} - 1$, $Q_{j,m} + 1$. We do not update holding costs, as the number of SKUs in the inventory system of location $j \in \{1, 2\}$ does not change. In location $j = 3$ the part immediately replaces the failed component at time t_{x_i}. There is no queue, thus only $IOH_{j,m} - 1$, after which we update holding costs to obtain $H_{|J|}[0, t_{x_i}]$. In any case, we order a new part from one location upstream, location $j - 1$, thus $IO_{j,m} + 1$. Only in event 1, if there is no spare of SKU $m \in \mathcal{M}$ directly available, i.e. $IOH_{|J|,m} = 0$, the vehicle availability A_n of vehicle $n \in \mathcal{N}$ is adjusted from 1 to 0. Additionally the printing option is considered, which is explained hereafter. Event 4 indicates a spare part request at the external supplier, presented in Figure 4.5. Since we consider an external supplier with ample stock, inventories do not have to be checked. The requested SKU is simply queued for the next scheduled replenishment.

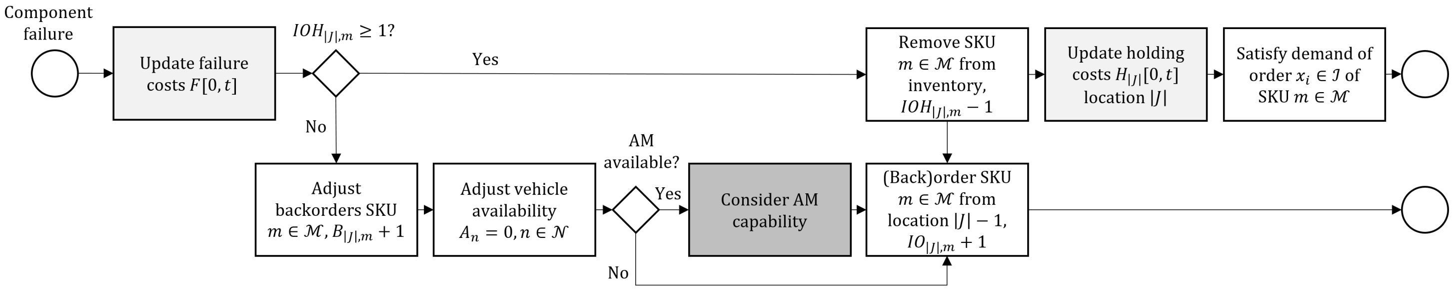

Figure 4.3: Spare part request location $|J| = 3$

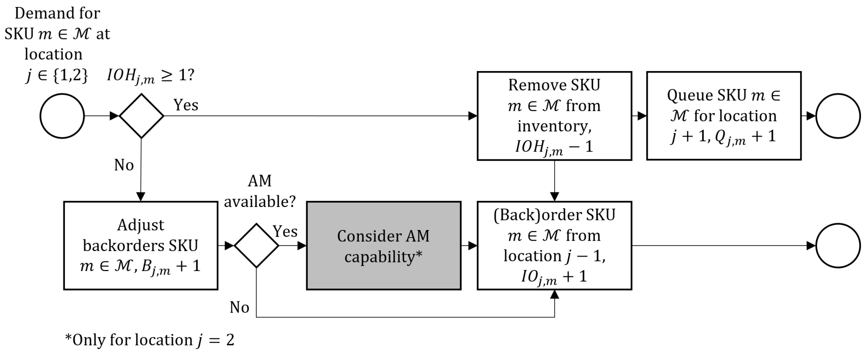

Figure 4.4: Spare part request location $j \in \{1,2\}$

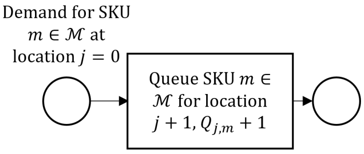

Figure 4.5: Spare part request location 0

Consider AM capability
AM capability located in the most downstream location, $j = |J|$, may be called upon when there is no inventory on hand of SKU $m \in \mathcal{M}$ in this location, i.e. $IOH_{|J|,m} = 0$. When locating AM capabilities one location upstream, $j = |J| - 1$, AM capabilities may be called upon when there is no inventory on hand of SKU $m \in \mathcal{M}$ in the two most downstream locations, i.e. $IOH_{|J|,m} + IOH_{|J|-1,m} = 0$. When we review whether to release a print order for SKU $m \in \mathcal{M}$ at time t_{x_i} for order $x_i \in \mathcal{I}$ to temporarily satisfy a backorder, we walk through the steps of the decision rule below. If the inequality holds, we terminate:

1. *If* $IT_{j,m}(t_{x_i}) \geq B_{j,m}(t_{x_i})$
   If $t_{delivery,j} \geq t_{AMdelivery,j}$: release print order
   Otherwise: wait for CM part, which is already in transit
2. *If* $IOH_{j-1,m}(t_{x_i}) + Q_{j-1,m}(t_{x_i}) + IT_{j,m}(t_{x_i}) \geq B_{j,m}(t_{x_i})$
   If j $t_{shipment,j} + L_j \geq t_{AMdelivery,j}$: release print order
   Otherwise: wait for CM part, which can be put on next shipment from location $j-1$ to location j
3. *Release print order anyway*

$t_{AMdelivery,j} = t + P_m$, $t_{AMdelivery,j} \in \mathbb{R}_+$, denotes the expected AM delivery time if we start the print process at time t_{x_i}. $t_{delivery,j} \in \mathbb{R}_+$ represents the next expected delivery time of SKUs in transit from location $j-1$ to location j for every location $j \in J$. $t_{shipment,j} \in \mathbb{R}_+$ represents the next expected shipment time from location $j-1$ to location j for every location $j \in J$. A print order is thus released whenever the expected print time is (non-strictly) smaller than the expected delivery time of a CM part. In Step 1 we check if there are SKUs in transit to the location hosting AM capabilities, that were initially meant to restock inventories (up to base-stock level). If so, we compare the expected delivery time of this in-transit conventional part to the expected AM delivery time. In the slightest possibility of reducing downtime using AM, we start the printing process. If not, we proceed to Step 2 and check inventories of the location upstream of the AM hosting location. If this upstream location has the concerning SKU in stock, we compare the expected delivery time of a conventional spare part from one location upstream to the expected AM delivery time. Again, in the slightest possibility of reducing downtime using AM, we release a print order. Otherwise, we print the part anyway, in Step 3. We choose to limit our AM print order decision rule to only consider checking inventory physically in stock at locations j and $j-1$. SKUs considered in the model are manufactured on a general-purpose AM machine, taking at most one day of production. SKU retrieval through regular shipment from locations more upstream are accompanied by leadtimes exceeding one day, meaning AM production is beneficial in all cases.

Shipment release (event 5, 6 and 7)
Events 5, 6 and 7 indicate a shipment release from the external supplier to location 1, from location 1 to 2 and from location 2 to location 3, respectively. The event is visualized in Figure 4.6. Shipment releases occur at repetitive moments in time, based on the order cycle O_j of location $j \in J$. Initially, the continuation of the planned shipment is checked. With probability p_j shipment to location $j \in J$ occurs. If the shipment continues, all queued SKUs from location $j-1$ are put in transit to location j.

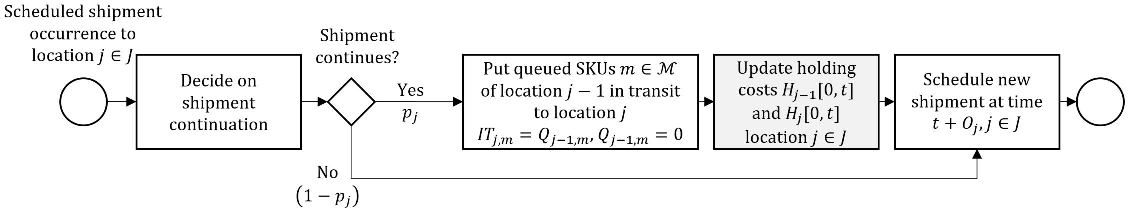

Figure 4.6: Shipment occurrence from location $j-1$ to location $j, j \in J$

Spare part receipt (event 8, 9 and 10)
Events 8, 9 and 10 imply SKU receipt at location 1, 2 and 3, respectively. Figure 4.8 visualises spare part receipt in location 1 and 2, and Figure 4.9 shows spare part receipt in location 3. The SKU is used to satisfy a backorder, or to restock inventories if there are no backorders. In location 1 and 2 ($j \in J$, $j \neq |J|$) satisfying a backorder means the part is queued to be shipped to the next consecutive location. In location 3 ($j = |J|$) the SKU is used to satisfy outstanding spare part demand. Vehicles are served based on a first come, first served (FCFS) scheduling algorithm, meaning the vehicle waiting longest for the concerning SKU will receive the spare part. We distinguish between AM an CM part receipts. Figure 4.7 is meant to clarify the backorder prioritization choices. In case an AM part is received, we check vehicles with availability $A_n = 0$ and FCFS replace the failed component that matches the incoming SKU type $m \in \mathcal{M}$, such that the vehicle availability can be adjusted from 0 to 1. We only consider path 1 of Figure 4.7 for AM part receipts. Whenever a CM part comes in, down vehicles are prioritized over available vehicles with AM parts as the objective of our research is to improve vehicle readiness. Thus, we first check the vehicles with availability $A_n = 0$ (path 1, Figure 4.7). If there are no vehicles waiting for SKU $m \in \mathcal{M}$ with availability 0, we review whether there are vehicles with availability $A_n = 1$, driving with an AM part. If so, we replace the AM part by a CM part (path 2, Figure 4.7) and dispose the used AM part.

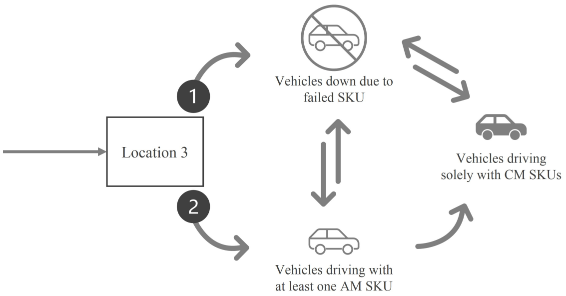

Figure 4.7: Prioritization of backorders

These prioritization choices imply that a CM part that was initially meant to replace an AM part in a vehicle with availability 1, may instead be used to satisfy spare part demand of a vehicle with availability 0. Consequently, instead of one vehicle with a CM part and availability 1 and another vehicle with availability 0, we have two vehicles with availability 1, one with CM part and one with an AM part. The vehicle with the AM part retains the AM part until the next CM spare part is delivered. An instance may occur that a CM part overtakes an AM part. This means a temporary fix was ordered, but a CM part was delivered sooner. When the AM part is not used for the concerning vehicle, we make the exception of stocking the single AM part rather than disposing it. We charge holding costs for stocked AM parts, similar to CM parts. A stocked AM part is used whenever a spare part $m \in \mathcal{M}$ is requested and there is no CM part of the concerning type in stock.

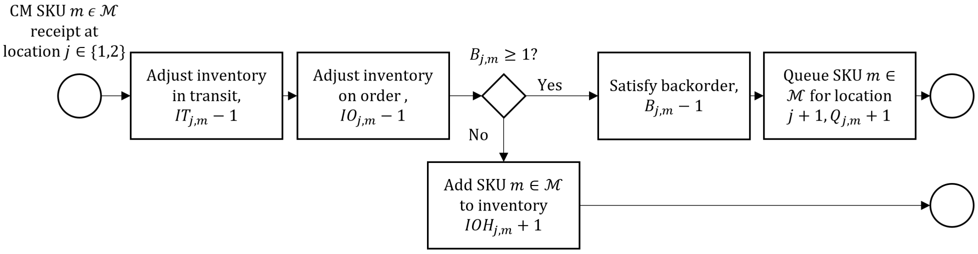

Figure 4.8: Spare part receipt location $j \in \{1, 2\}$

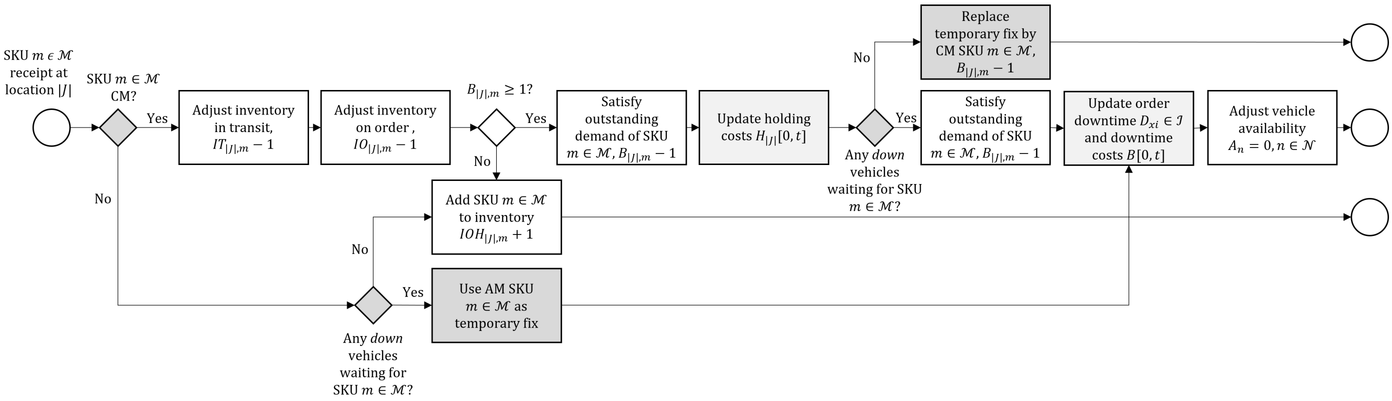

Figure 4.9: Spare part receipt location $|J| = 3$

Release print order (event 11 and 12)

Events 11 and 12 denote the release of a print order, when AM capability is located in location 3 ($j = |J|$) and location 2 ($j = |J| - 1$), respectively. Figure 4.10 visualizes the print order release event. With a certain probability q_j, $j \in J$, the order is manufactured uninterruptedly. With a probability $(1 - q_j)$ the print is interrupted during the print process. This triggers a review whether or not to restart the print process for the concerning order. We review whether the expected AM delivery time is (non-strictly) smaller than the expected CM delivery time. If so, we restart the print process, otherwise we wait for the CM part (see *Consider AM capability*, p. 32). The interruption time is uniformly distributed on the print time P_m, $m \in \mathcal{M}$. The location of AM capability determines the consecutive event: whether the AM part is received by location 2 (AM capability in location 2), or location 3 (AM capability in location 3).

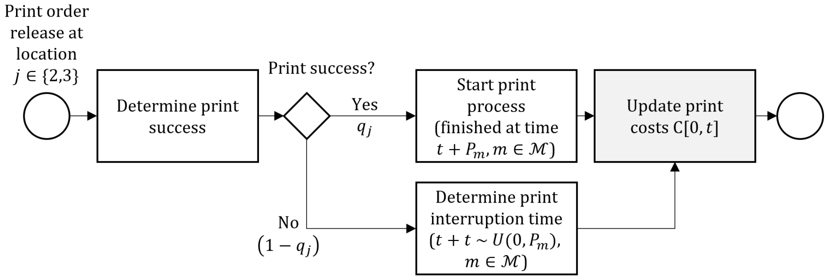

Figure 4.10: Print order release at location $j \in \{2, 3\}$

Table 4.1: Overview of events and consecutive actions

Event	**Description**	**Consecutive action**	**Sequential event**
1	Spare part request location 3, (component failure)	Update failure costs $F[0,t]+f$ If $IOH_{3,m}(t)>0$: Satisfy demand from stock and order a new spare for inventory $IOH_{3,m}(t)-1$, $IO_{3,m}(t)+1$ holding costs $H_3[0,t]+H_{3,m}[t_{-1},t]$ If $IOH_{3,m}(t)=0$: Backorder spare part from location 2 Availability A_n of vehicle $n\in\mathcal{N}$ from 1 to 0 $B_{3,m}(t)+1$, $IO_{3,m}(t)+1$ If AM capability in location 3: Consider AM (p. 32)	Event 2 (t) Event 2 (t) If we use AM: Event 11 (t)
2	Spare part request location 2	If $IOH_{2,m}(t)>0$: Queue demanded part and order a new spare for inventory $IOH_{2,m}(t)-1$, $Q_{2,m}(t)+1$, $IO_{2,m}(t)+1$ If $IOH_{2,m}(t)=0$: Backorder spare part from location 1 $B_{2,m}(t)+1$, $IO_{2,m}(t)+1$ If AM capability in location 2 and $IOH_{3,m}(t)+IT_{3,m}(t)+IOH_{2,m}=0$: Consider AM (p. 32)	Event 3 (t) Event 3 (t) If we use AM: Event 12 (t)
3	Spare part request location 1	If $IOH_{1,m}(t)>0$: Queue demanded part and order a new spare for inventory $IOH_{1,m}(t)-1$, $Q_{1,m}(t)+1$, $IO_{1,m}(t)+1$ If $IOH_{1,m}(t)=0$: Backorder spare part from location 0 $B_{1,m}(t)+1$, $IO_{1,m}(t)+1$	Event 4 (t) Event 4 (t)
4	Spare part request location 0	Queue demanded part $Q_{0,m}(t)+1$	
5	Shipment release to location 1	Schedule next shipment occurrence to location 1, $t_{shipment,1}=t+O_1$ If shipment continues: Update holding costs $H_1[0,t]+H_{1,m}[t_{-1},t]$ Put all queued spare parts of location 0 in transit to location 1 $t_{delivery,1}=t+L_1$ For all $m\in\mathcal{M}$: $IT_{1,m}(t)=Q_{0,m}(t)$ Clear $Q_{0,m}(t)$	Event 5 ($t+O_1$) For every item: Event 8 ($t+L_1$)

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Table 4.1 – continued from previous page

Event	Description	Consecutive action	Sequential event
6	Shipment release to location 2	Schedule next shipment occurrence to location 2, $t_{shipment,2} = t + O_2$ If shipment continues: Update holding costs $H_1[0,t] + H_{1,m}[t_{-1},t]$ $H_2[0,t] + H_{2,m}[t_{-1},t]$ Put all queued spare parts of location 1 in transit to location 2 $t_{delivery,2} = t + L_2$ For all $m \in \mathcal{M}$: $IT_{2,m}(t) = Q_{1,m}(t)$ Clear $Q_{1,m}(t)$	Event 6 $(t + O_2)$ For every item: Event 9 $(t + L_2)$
7	Shipment release to location 3	Schedule next shipment occurrence to location 3, $t_{shipment,3} = t + O_3$ If shipment continues: Update holding costs $H_2[0,t] + H_{2,m}[t_{-1},t]$ $H_3[0,t] + H_{3,m}[t_{-1},t]$ Put all queued spare parts of location 2 in transit to location 3 $t_{delivery,3} = t + L_3$ For all $m \in \mathcal{M}$: $IT_{3,m}(t) = Q_{2,m}(t)$ Clear $Q_{2,m}(t)$	Event 7 $(t + O_3)$ For every item: Event 10 $(t + L_3)$
8	Part receipt location 1	$IO_{1,m}(t) - 1$, $IT_{1,m}(t) - 1$ If $B_{1,m}(t) = 0$: Add spare part to inventory $IOH_{1,m}(t) + 1$ If $B_{1,m}(t) > 0$: Queue demanded spare part $Q_{1,m}(t) + 1$, $B_{1,m}(t) - 1$	
9	Part receipt location 2	If incoming part $m \in \mathcal{M}$ is CM: $IO_{2,m}(t) - 1$, $IT_{2,m}(t) - 1$ If $B_{2,m}(t) = 0$: Add spare part to inventory $IOH_{2,m}(t) + 1$ If $B_{2,m}(t) > 0$: Queue demanded spare part $Q_{2,m}(t) + 1$, $B_{2,m}(t) - 1$ If incoming part $m \in \mathcal{M}$ is AM: If $B_{2,m}(t) > 0$: Queue demanded spare part $Q_{2,m} + 1$ If $B_{2,m}(t) = 0$: $IOH_{2,m} + 1$	

Continued on next page

Table 4.1 – continued from previous page

Event	Description	Consecutive action	Sequential event
10	Part receipt location 3	If incoming part $m \in \mathcal{M}$ is CM: $IO_{3,m}(t) - 1$, $IT_{3,m}(t) - 1$ If $B_{3,m}(t) = 0$: Add spare part to inventory $IOH_{3,m}(t) + 1$ If $B_{3,m}(t) > 0$: Satisfy outstanding spare part demand for order $x_i \in \mathcal{I}$ $B_{3,m}(t) - 1$ $H_3[0,t] + H_{3,m}[t_{-1}, t]$ Specify order downtime $D_{x_i,n}$ Update downtime costs $B[0,t] + b * D_{x_i,n}$ Availability A_n of vehicle $n \in \mathcal{N}$ from 0 to 1 (except for an instance when we replace AM by CM) If incoming part $m \in \mathcal{M}$ is AM: If there are any down vehicles $n \in \mathcal{N}$, with $A_n = 0$ waiting for incoming SKU type $m \in \mathcal{M}$: Satisfy outstanding spare part demand using temporary fix Specify order downtime $D_{x_i,n}$ Update downtime costs $B[0,t] + b * D_{x_i,n}$ Availability A_n of vehicle $n \in \mathcal{N}$ from 0 to 1 Otherwise, $IOH_{3,m} + 1$	If we satisfy an order: Event 1 $(t + t \sim exp(\lambda_m))$ (where $\lambda_m \in \{\lambda_{AM,m}, \lambda_{CM,m}\}$)
11	Release print order location 3	Determine print success or failure and start print process of requested spare part Update print costs $C[0,t] + P_m$	If success: Event 10 $(t + P_m)$ If failure and choice to restart: Event 11 $(t + t \sim U(0, P_m))$
12	Release print order location 2	Determine print success or failure and start print process of requested spare part Update print costs $C[0,t] + P_m$	If success: Event 9 $(t + P_m)$ If failure and choice to restart: Event 12 $(t + t \sim U(0, P_m))$

4.4.3 Implementation of the simulation model

The DES model is implemented using Python 3.6. We identify various class objects: SKU (set $\mathcal{M}$), vehicle (set $\mathcal{N}$), order (set $\mathcal{I}$), event (set $\mathcal{E}$), FES and simulation results. The first few class objects correspond to the sets we identified in the model, denoting the objects that can experience change in the system. The FES denotes the future event set, ordering all our future events $e \in \mathcal{E}$ over time. This set changes at various moments in time as events take place, and new events are added. New events are ordered based on time of occurrence. If two events have the same time in the FES, the new event is added prior to the event that is already in place in the FES. The last class object, simulation results, is used to store our simulation results to obtain the performance measures.

It should be noted that certain events trigger sequential events. There are four events that ensure continuation of our DES model that may start a change in the system: component failure (event 1) and shipment release (events 5, 6 and 7). Figure 4.11 denotes a timeline and shows the times $t_{x_i} \in \mathbb{R}_+$ at which a component in one of the $\mathcal{N}$ vehicles fails and an order $x_i \in \mathcal{I}$ is created. Figure 4.12 shows the possible shipment times $t_{shipment,j}$ to location $j \in J$. Every shipment occurrence is an order cycle O_j in hours apart.

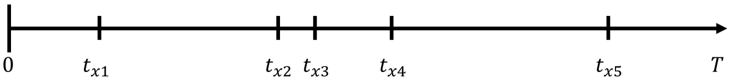

Figure 4.11: Timeline with failure times t_{x_i}, $x_i \in \mathcal{I}$ (event 1)

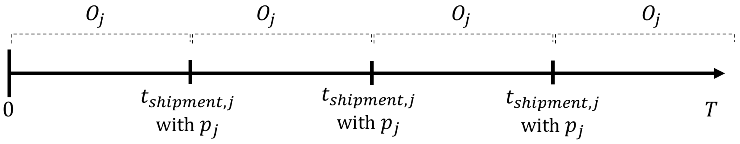

Figure 4.12: Timeline with possible shipment occurrences to location $j \in J$ (events 5, 6, 7)

Prior to the start of the simulation, at $t = 0$, we create initial events and add these to the FES: an event 5, 6 and 7 and an event 1 for every vehicle $n \in \mathcal{N}$. At time $t = 0$ we determine the failure times of every SKU $m \in \mathcal{M}$ and create an event 1 for the first SKU to fail in every vehicle $n \in \mathcal{N}$. Every time t a failed SKU is replaced by a new component - either AM or CM - we identify the next SKU $m \in \mathcal{M}$ to fail in the concerning vehicle $n \in \mathcal{N}$ and add an event 1 for this failure. Every time we encounter an event 1 occurrence we check whether the failed SKU $m \in \mathcal{M}$ is still present in the vehicle, as for an AM SKU, it could have already been replaced by a CM counterpart. The simulation model runs until time T (in hours). At the end of the simulation time, we calculate the performance measures over time $[0, T]$ to obtain the simulation's performance measures, described in Section 4.5.1.

4.4.4 Verification of simulation model

After implementation of the DES model, the model is verified using various test cases. Here we describe the test cases we used to verify the correctness of the model.

- We tested if the right sequential event was added to the FES after an event occurrence and whether events occurred in the right order. For example, we first encounter event 1, component failure and thus demand for SKU $m \in \mathcal{M}$ in location 3 prior to event 2, demand for this SKU in location 2.

- We checked if events occurred at the right time. For example, when we put queued SKUs from location $j-1$ in transit to location j at time t, these should arrive in location j at time $t + L_j$, for every $j \in J$. Similarly we tested the timing of new shipment releases created at time t, planned to occur at time $t + O_j$ for every $j \in J$.
- We reviewed that the number of SKUs of type $m \in \mathcal{M}$ put in transit from location $j-1$ to location j, for every $j \in J$, is never larger than the number of SKUs physically in stock at location $j-1$, i.e., $IOH_{j-1,m} + Q_{j-1,m} \geq IT_{j,m}$ at time t.
- We assessed that the number of items of SKU $m \in \mathcal{M}$ put in transit from location $j-1$ to location j, for every $j \in J$, is never larger than the quantity ordered by location j, i.e., $IO_{j,m} \geq IT_{j,m}$.
- We reviewed that no SKUs were put in transit whenever a shipment occurrence got cancelled. When we set $p_j = 0$ we reviewed that shipments do not occur.
- We confirmed that SKUs in vehicles solely fail when the vehicle is available, i.e., $A_n = 1$ for $n \in \mathcal{N}$. We specifically checked that AM parts, replaced by CM parts do not have a component failure event (event 1).
- We set base-stock levels of every SKU in every location equal to 0, i.e., $S_{j,m} = 0 \ \forall \ j \in J, \ \forall \ m \in \mathcal{M}$. We confirmed that in this instance, we always backorder.

4.5 Evaluation

In this section, we explain how we calculate the performance measures for every scenario. We describe how we apply scenario analysis to compare different ways of integrating AM capability in the remote spare part supply chain. Furthermore, we describe how we determine the base-stock levels per scenario.

4.5.1 Performance measures

Using the DES model we obtain values for our performance measures vehicle readiness and operating costs, i.e., total holding costs, total downtime costs, total print costs and total failure costs. While the notation is already introduced in Section 4.4.1, here we explain how we calculate each performance measure at the end of the simulation time T.

Vehicle readiness

The vehicle readiness of installed base $\mathcal{N}$ over time $[0, T]$ is a percentage, considering the downtime $D_{x_i,n}$ in hours of every order $x_i \in \mathcal{I}$, vehicle $n \in \mathcal{N}$, using Equation 4.2:

$$\text{Vehicle readiness } [0, T] = \left(1 - \frac{\sum_{x_i \in \mathcal{I}} D_{x_i,n}}{|\mathcal{N}| * T}\right) * 100. \tag{4.2}$$

Total holding costs
In Section 4.4.2 we discuss how we update location specific holding costs $H_j[0,T]$ during the simulation. We calculate total holding costs $H_{total}[0,T]$ over all locations over simulation time $[0,T]$ using Equation 4.3.

$$H_{total}[0,T] = \sum_{j \in J} H_j[0,T]. \tag{4.3}$$

Total downtime costs
Downtime costs b are incurred for every vehicle that has availability $A_n = 0$ for every unit of time, reflecting the inconvenience of an unavailable vehicle. We calculate total downtime costs $B[0,T]$ over simulation time $[0,T]$, by considering the downtime $D_{x_i,n}$ of every order $x_i \in \mathcal{I}$ of vehicle $n \in \mathcal{N}$, using Equation 4.4:

$$B[0,T] = b * \sum_{x_i \in \mathcal{I}} D_{x_i,n}. \tag{4.4}$$

Total print costs
Print costs c_m are SKU $m \in \mathcal{M}$ specific and are incurred for every print order. Recall that Y_m denotes the number of print orders for SKU $m \in \mathcal{M}$. The total print costs $C[0,T]$ over simulation time $[0,T]$, by Equation 4.5:

$$C[0,T] = \sum_{m \in \mathcal{M}} c_m * Y_m. \tag{4.5}$$

Total failure costs
Failure costs f are incurred for every SKU that fails, to reflect the costs of discontinuing a planned operation for which the vehicle was scheduled. We do not distinguish different failure costs for AM or CM parts. The total failure costs $F[0,T]$ over the simulation time $[0,T]$ are calulated by considerig the total number of failures $|\mathcal{I}|$, using Equation 4.6:

$$F[0,T] = f * |\mathcal{I}|. \tag{4.6}$$

Total operating costs
Finally, we calculate the total operating costs over simulation time $[0,T]$ by adding the individual cost items, using Equation 4.7:

$$\text{Total operating costs}[0,T] = H_{total}[0,T] + B[0,T] + C[0,T] + F[0,T]. \tag{4.7}$$

4.5.2 Scenario analysis

Scenario analysis is a tool that is often used in decision-making, especially in instances with uncertainty (Varum and Melo, 2010). Scenarios allows us to identify various settings and compare these. We use scenario analysis with the scenarios being not installing AM capabilities or installing AM capabilities at one of $j \in \{2, 3\}$, locations. We can choose from $A \in \mathbb{N}$ different types of AM capabilities, meaning that we consider $2 * A + 1$ scenarios. An AM capability implies a certain AM technology type, material type, printing time, etc. In practice, we test two locations and about two to five printer types, leaving us with at most eleven scenarios.

Table 4.2: Scenarios of remote AM integration

AM capability types	1			
	2			
	...			
	$A-1$			
	A			
		2	3	
	AM locations			**No AM**

Every scenario, with a specific AM capability type in a predetermined location, can be evaluated used the simulation model presented in Section 4.4. After running the simulation model, we obtain the scenario specific performance measures as described in Section 4.5.1. In turn, the performance measures of different scenarios can be compared to assess different ways of AM integration.

4.5.3 Base-stock level determination

Literature provides us with the insight that, when including AM as additional sourcing option, base-stock levels may be adjusted downwards without affecting the availability of vehicles, due to the quick response time of AM capability close to the location where demand arises (Den Boer et al., 2020; Cestana et al., 2019; Liu et al., 2014; Ghadge et al., 2018). We aim to use this advantage to determine scenario specific base-stock levels for every SKU $m \in \mathcal{M}$, in every location $j \in J$, based on the type and location of AM capability. A way to determine a scenario's optimal base-stock levels is enumeration. This implies running the simulation model with all possible combinations of base-stock levels in locations $j \in J$ for every single SKU $m \in \mathcal{M}$, i.e., $S_{1,m}, S_{2,m}, S_{3,m}$. Suppose we want to assess all combinations of base-stock levels ranging from 0 to 10 in every location for example, this requires at most $11^3 = 1.331$ simulations per SKU $m \in \mathcal{M}$, per scenario. This may become a time-intensive operation as we expand the set of SKUs $\mathcal{M}$ and the number of scenarios. We thus desire to implement a "smart" approach to estimate the base-stock levels more quickly. We introduce an approach to determine the base-stock levels in every location $j \in J$, inspired by a heuristic by Shang and Song (2003). The approach is based on solving a newsvendor problem for a serial supply chain with linear costs and stationary demand. Hereby, we aim to stock SKUs in sufficient quantities to balance downtime costs and holding costs.

The base-stock levels for every SKU $m \in \mathcal{M}$ in the final location $|J|$ are established by considering a classical newsvendor problem, making a trade-off between holding costs and backorder costs. For the locations upstream, i.e. $j \in J, j \neq |J|$, we define an upper and lower bound for the base-stock level $S_{j,m}$, take the average and round down to find the base-stock level for every SKU $m \in \mathcal{M}$. Eq. 4.8 shows how to determine the base-stock level of SKU $m \in \mathcal{M}$ of the final location, $S_{|J|}$. Eq. 4.9 and Eq. 4.10 show how to determine the lower bound and upper bound of the base-stock level in location $j \in J, j \neq |J|$, denoted by S_j^l and S_j^u, respectively. The base-stock levels in these locations is then approximated using Equation 4.11. Note that F_j denotes the cumulative distribution function of the total lead time demand of location $j \in J$.

$$S_{|J|,m} = F^{-1}\left(\frac{b + \sum_{i=1}^{J-1} h_{i,m}}{b + \sum_{i=1}^{J} h_{i,m}}\right) \tag{4.8}$$

$$S_{j,m}^l = F_j^{-1}\left(\frac{b + \sum_{i=1}^{j-1} h_{i,m}}{b + \sum_{i=1}^{J} h_{i,m}}\right) \tag{4.9}$$

$$S_{j,m}^u = F_j^{-1}\left(\frac{b + \sum_{i=1}^{j-1} h_{i,m}}{b + \sum_{i=1}^{j} h_{i,m}}\right) \tag{4.10}$$

$$S_{j,m}^a = \lfloor \frac{S_{j,m}^l + S_{J,m}^u}{2} \rfloor \tag{4.11}$$

Demand is assumed to follow a Poisson distribution, which is characterized by exponential inter-arrival times. In calculating the base-stock levels, the lead time demand of SKU $m \in \mathcal{M}$ in location $j \in J$ is determined based on the failure rate $\lambda_{CM,m}$ over the lead time to the concerning location, over the entire fleet, i.e. $|\mathcal{N}|$. We correct for the order cycle of location $j \in J$ by incorporating the mean waiting time for a scheduled shipment in the lead time, i.e. $\frac{O_j}{2}$. As an example, the lead time demand in location 3 of SKU $m \in \mathcal{M}$ for a scenario without AM capabilities is calculated as follows: lead time demand $= \lambda_{CM,m} * |\mathcal{N}| * (L_3 + \frac{O_3}{2})$. Whenever printing capabilities are included, we instead consider $min((L_j + \frac{O_j}{2}), P_m)$ when location $j \in J$ is equipped with an AM capability. For example, the lead time demand in location 3 of SKU $m \in \mathcal{M}$ for a scenario with AM capability in location 3 is calculated as follows: as $min((L_3 + \frac{O_3}{2}), P_m) = P_m$, lead time demand $= \lambda_{CM,m} * |\mathcal{N}| * P_m$.

Usage of this approach allows us to adjust the base-stock levels to the scenario specific circumstances. We take into account that we are working with a serial supply chain. We also consider that the expected lead time is shortened when using AM capabilities. By incorporating different types of AM capabilities, with different print times per SKU $m \in \mathcal{M}$, base-stock levels can be adjusted downwards in locations that host AM capabilities and upstream, as we use $min((L_j + \frac{O_j}{2}), P_m)$ to correct the lead time demand of SKU $m \in \mathcal{M}$ in location $j \in J$.

We assess the effect of the base-stock levels obtained through this approach on the in Section 4.5.1 introduced performance measures of the model, by running the simulation model with the approximated base-stock levels. We use case study input, as described in Chapter 6, to assess how the performance measures of the model change when we adjust base-stock levels using print times P_m for every SKU $m \in \mathcal{M}$ in the lead time demand, opposed to running the model with base-stock levels based on lead time demand over $(L_j + \frac{O_j}{2})$, thus without incorporating SKU specific print times. These test case results are provided in Appendix D. The test cases show that adapting the lead time demand using print time P_m of SKU $m \in \mathcal{M}$, results in similar or increased vehicle readiness, under lower total operating costs.

5 Case Study

A case study can be used to gain insights in the vehicle readiness and operating costs of scenarios containing different types of AM capability in different locations. However, a case study should be carefully selected based on the available context and data. Thus, in this chapter we answer the following research question:

RQ3. What is an interesting case study to evaluate using the proposed model?

In this chapter we discuss which case study contexts are valuable to substantiate in order to assess whether to integrate AM capability in the remote spare part supply chain, and if so, where and of what type. We start by discussing a general mission context and select two case study contexts in Section 5.1. We proceed by introducing the materiel that we will base our case studies on, and discuss the AM capability types we consider, in Section 5.2 and Section 5.3, respectively. Section 5.4 finalizes the chapter by presenting the case study scenarios.

5.1 Mission context

The setting of military operations is considerably different during different deployments. In Chapter 3 we already concluded that military experts generally describe the missions' context to be of influence on the way AM is integrated in the remote spare part supply chain. We use "mission context" as an umbrella concept to describe the mission aim, the level of threat, climatic conditions and the different operating locations, with their supply modes and resupply times in mission areas. In turn, we use the mission context to describe our case study's settings, explained here and summarized in Table 5.1.

The mission's aim is generally linked to the type of deployment. In Sections 1.1.1 and 1.1.2 we describe the main tasks of the RNLA and subsequently the deployment types. The type of deployment influences the level of threat and the degree to which military operations need to be static or dynamic. As AM technologies are not yet mature enough to deliver reliable products when moving (i.e. during dynamic operations) AM capability may only be used when units remain in one place. This means the probability of successfully delivering AM parts is lower for highly dynamic units, i.e. type 1 deployment (combat), than type 2 deployment (peacekeeping). Climatic conditions were mentioned by many RNLA experts as influential on the location of AM capability. Due to the main tasks of Defence, RNLA units can be deployed anywhere in the world. Generally, the past decades, military units have mainly been deployed in dry and dusty climates, like Iraq, Afghanistan and Mali. However, currently a NATO mission is carried out in Lithuania, to which Dutch military units contribute. From experience, the RNLA learned that different kinds of climates affect the vehicles in a way that cannot be forecasted based on spare part failure behavior data gathered in the Netherlands. Movements in the Netherlands generally occur over fixed infrastructure, while this is often not the case in mission areas. Dust or mud ends up all over the vehicle, speeding up the wear process of individual parts. Prior to every deployment, the various stocking and operating locations are determined. In Section 1.3.1 we discussed that the number of locations is mission specific. While the RNLA operates protocols for the set-up of the remote supply chain, i.e. maximum distance between two consecutive locations, the lead times between two locations varies during different deployments. Additionally, the area of deployment determines the possible transportation modes that can be used to resupply deployed units. Desert areas are difficult to reach with transportation modes other than aircraft, for example, while countries within Europe can be reached through many modes, such as road, rail and air. The location of the mission and the chosen resupply modes, affect the total resupply times. Missions progressing on different continents are characterized by less frequent strategic supply moments, due to the distance, the limited number of possible supply modes and possibly the difficulty to reach the area.

We thus remark that the mission contexts of different deployments can vary greatly from each other. Therefore, two case study contexts are selected: Lithuania, centered around type 1 deployment (combat), and Afghanistan, focusing on type 2 deployment (peacekeeping). It should be noted that Lithuania is not an actual type 1 mission. However, we use the current deployment in Lithuania as an inspiration of a type 1 (combat) mission, to be able to test the model based on two deployment types. Table 5.1 presents the characteristics and differences between the two considered case studies.

Table 5.1: Context of case studies

	Case study 1	**Case study 2**
Deployment area	Lithuania	Afghanistan
Mission aim	Type 1 deployment (combat)	Type 2 deployment (peacekeeping)
Locations (1, 2, 3)	Warschau, Lithuanian border, Rukla	Kandahar, Tarin Koot, Dehrawood
Operations	Dynamic	Static
Level of threat	High	Low
Climatic conditions	Moist and muddy	Dry and dusty
Transportation modes (to 1, to 2, to 3)	Air, Road, Road	Air, Air, Air

The main motivation for these two specific locations lays in the fact that the RNLA has been deployed to both these areas, meaning there is information available on these two missions. Additionally, these missions are reckoned by a sufficiently large military presence allowing a three-echelon supply chain in the mission area. The choice for these two missions is further substantiated by differences in mission purpose, as the RNLA was supposed to keep order in Afghanistan, while deployment in Lithuania serves to demonstrate increased military NATO presence against Russia. Additionally, both case studies are centered around a different deployment type (hypothetically), enabling obtainment of results on a rather static setting as compared to a dynamic setting. Moreover, both locations differ in terms of climate conditions. Furthermore, both missions reckon different transportation modes and supply frequencies. Where strategic and operational movement to and in Lithuania is mainly done by air and road, Afghanistan is solely supplied through air. Figure 5.1 presents the supply chain considered for *Case study 1*, while Figure 5.2 shows the supply chain considered for *Case study 2*.

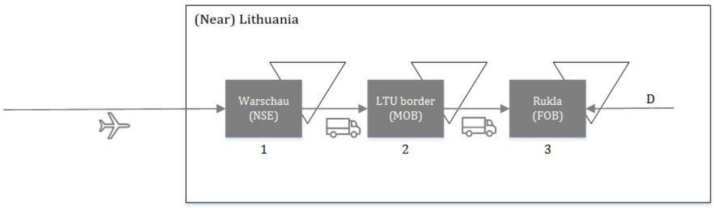

Figure 5.1: Supply chain *Case study 1: Lithuania*

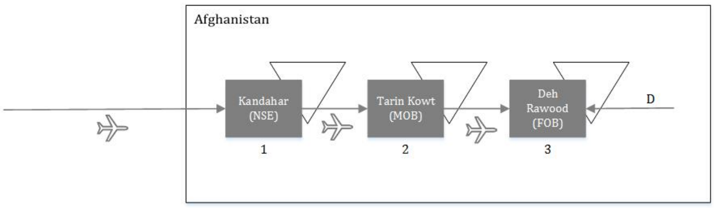

Figure 5.2: Supply chain *Case study 2: Afghanistan*

5.2 Deployed materiel

We aim to assist in determining a suitable AM capability type-AM location combination when integrating AM capability as additional sourcing option, depending on the mission's context. To increase comparability between the two case studies, we choose to test the same installed base for *Case study 1* as well as *Case study 2*. In essence, the model can be applied to different vehicle types, in order to study the effect of integrating a print option on the availability and costs over different vehicle types. However, the purpose of this study is to gain insight if and where to locate AM capability in the remote spare part supply chain and how the vehicle readiness is affected by comparing lead times of regular supply with print times of an emergency AM option. Therefore, we choose to simply study an installed base of $|\mathcal{N}|$ vehicles of a single type. The installed base should be sufficiently large to generalize the models' findings over the chosen vehicle type. The vehicles tested using the model all contain the same set of $\mathcal{M}$ SKUs, where $\mathcal{M}$ is large enough to study the effect of print choices throughout different SKUs.

Figure 5.3: Fennek reconnaissance vehicle, from Ministerie van Defensie (2022b)

As we aim to provide realistic case study results, the chosen vehicle type should be managed and deployed adequately in both case studies. For both case studies we choose to adopt the Fennek reconnaissance vehicle, also studied by Westerweel et al. (2021). Figure 5.3 shows the Fennek vehicle. This vehicle is mainly used for observation and guarding purposes, which is suitable in both *Case study 1* and *Case study 2*. Furthermore, the installed base of this vehicle type during deployments is generally large enough to obtain meaningful results. In Chapter 6 we describe the complete set of SKUs and their characteristics.

5.3 AM capabilities

The parts produced using AM only serve to bridge the time until a CM spare part becomes available, as AM serves as an emergency option. Therefore, we solely consider general-purpose printers in the case studies. Note that every scenario only considers one AM capability type in one location, to be able to assess the preferred AM capability type-location combination. The RNLA aims to deploy AM capability in a remote area, which may be anywhere in the world. Thus, AM capability and print material must be able to withstand different climatic conditions, and should be robust enough to be transported to isolated locations without fixed infrastructure. A selection of two AM capability types is included in this study, based on the AM capability and material types the RNLA favors to deploy (Additive Manufacturing Expertise Center). For *Case study 1* and *Case study 2*, we consider the same set of possible AM capability types with a single material type per AM capability, presented in Table 5.2. From here on the AM capabilities will be listed Type A and Type B.

Table 5.2: AM capabilities

Name	**AM capability type**	**Material type**
Type A	Ultimaker S5	Nylon
Type B	Markforged Mark 2	Onyx

5.4 Case study scenarios

In Section 4.5.2 we show that we use scenario analysis in order to compare different ways of integrating AM in a remote spare parts supply chain, besides a situation without AM integration. For *Case study 1*, as well as *Case study 2*, we review the same number of test scenarios. We consider $J = 2$ print locations and $A = 2$ types of AM capabilities, leaving $2 * 2 + 1 = 5$ scenarios for both case study contexts. Table 5.3 and 5.4 present the case study scenarios, i.e., no AM and different combinations of AM location and AM capability type, of *Case study 1* and *Case study 2*, respectively.

Table 5.3: Scenarios *Case study 1*

<table>
<tr><td rowspan="3">AM capability types</td><td>A</td><td>1</td><td>2</td><td rowspan="3">5</td></tr>
<tr><td>B</td><td>3</td><td>4</td></tr>
<tr><td></td><td>2</td><td>3</td></tr>
<tr><td></td><td colspan="3">AM locations</td><td>No AM</td></tr>
</table>

Table 5.4: Scenarios *Case study 2*

<table>
<tr><td rowspan="3">AM capability types</td><td>A</td><td>6</td><td>7</td><td rowspan="3">10</td></tr>
<tr><td>B</td><td>8</td><td>9</td></tr>
<tr><td></td><td>2</td><td>3</td></tr>
<tr><td></td><td colspan="3">AM locations</td><td>No AM</td></tr>
</table>

6 Simulation Study

After selecting two suitable case studies, model input can be collected. This allows running the simulation model, in order to obtain realistic case study results on different ways of AM integration. In this chapter we answer the fourth research question:

RQ4. What are the model input values for the AM and CM sourcing options?

In Section 6.1 we describe the generic model input parameters for both *Case study 1* and *Case study 2*. This includes cost parameters and SKU specific parameters. In Section 6.2, we describe the case study specific parameters, such as lead times and order cycles. The approach to determine the scenario-specific base-stock levels is presented in Section 6.3. The chapter concludes by presenting the simulation's run parameters in Section 6.4.

6.1 Generic model input parameters

To allow comparison between the two specific mission contexts, we consider the same set of vehicles, $\mathcal{N}$, with the same set of SKUs, $\mathcal{M}$, through the two proposed case studies. Despite considering two separate case study contexts, we also consider similar cost values for both case studies, in order to increase comparability. In the simulation model holding costs, downtime costs, printcosts and failure costs are considered. Hereafter we describe the parameter values for the installed base, the set of SKUs, and the different cost components.

As described in Section 5.2 the case study is tested for the Fennek reconnaissance vehicle. The set of SKUs considered therefore solely contains parts of this vehicle type. The total size of the Fennek fleet, i.e. the installed base, during both case studies is set at $|\mathcal{N}| = 50$. According to a RNLA operations expert, this is a suitable number of Fenneks to deploy in a mission context with a magnitude like we consider in *Case study 1* and *Case study 2* (Logistics Knowledge Center 2). Table 6.1 provides an overview of the set of $|\mathcal{M}| = 14$ SKUs tested using the simulation model and their parameter values. The print times are given in hours, costs are given in euros, failure rates are given in failures/hour and material volumes are given in cubic centimeters. We adopt the set of 8 Fennek SKUs considered by Westerweel et al. (2021) (SKUs 1 through 8) and expand this with another 6 SKUs retrieved from RNLA Fennek maintenance experts (SKUs 9 through 14) (Instructor Armored Vehicles). All parts considered are downtime critical, and can be procured as CM spare part and can be produced using AM.

The model requires SKU specific failure rates (λ_{CM}) and holding costs ($h_{j,m}, j \in J, m \in \mathcal{M}$), which are adopted from Westerweel et al. (2021). The regular unit order costs for SKU $m \in \mathcal{M}$ can be used to determine the holding costs over different locations for the concerning SKU. Like Westerweel et al. (2021), we assume the annual inventory holding costs per SKU to be 100% of the regular unit order costs in location 1 and location 2. In turn, in location 3 we assume annual inventory holding costs to be 150% ($h_{3,m} = 1.5h_{1,m} = 1.5h_{2,m}$) of the regular unit order costs, to reflect limited stocking space and the unfavorability of keeping stock in location 3. For the SKUs identified by RNLA maintenance experts, we obtain the SKUs' regular unit order costs through the use of SAP, the RNLA's enterprise resource planning (ERP) system. The failure rates for SKUs 9 through 14 are calculated based on the average number of orders of the concerning SKU over the entire Fennek fleet over the past four years, given that the SAP data of these parts over this period is complete. The

Table 6.1: SKU specific input parameters

SKU	$h_{j,m}$(100%) (€/year)	$\lambda_{CM,m}$ (failures/hour)	v_m (cm^3)		P_m (hours)		c_m (€)	
			A	**B**	**A**	**B**	**A**	**B**
1	2.80	0.000029	1.00	0.60	0.08	0.15	0.10	0.13
2	235.28	0.000058	108.87	110.49	6.18	8.18	11.16	25.64
3	3.01	0.000029	2.00	1.20	0.12	0.22	0.19	0.28
4	131.28	0.000113	237.35	255.34	13.12	17.60	24.29	59.26
5	10.12	0.000029	2.08	1.70	0.15	0.25	0.19	0.39
6	3.21	0.000113	2.00	1.20	0.12	0.22	0.19	0.28
7	1.11	0.000258	35.81	34.60	2.10	2.93	3.66	8.03
8	11.87	0.000229	29.05	26.67	1.73	2.38	2.37	6.19
9	121.45	0.000024	6.46	5.63	0.47	0.47	0.66	1.30
10	141.09	0.000003	14.30	12.40	1.00	1.22	1.49	2.86
11	31.10	0.000002	9.00	7.80	0.67	0.83	0.94	1.80
12	71.15	0.000002	21.78	20.15	1.50	1.83	2.25	4.66
13	354.89	0.000001	31.81	30.38	2.18	2.60	3.28	7.02
14	229.60	0.000010	7.94	6.92	0.57	0.75	0.84	1.60

failure rate calculations are presented in Appendix E. The calculations are verified by a RNLA life cycle analyst (Systems & Analysis department 3). The failure rate of AM parts (λ_{AM}) manufactured on different general-purpose printer types is assumed to be a factor larger than the failure rate of a CM counterpart (λ_{CM}). Thus, the failure rate of AM parts manufactured on printer Type A is assumed to be twenty times that of the conventional part ($\lambda_{AM} = 20\lambda_{CM}$), the failure rate of AM parts manufactured on printer Type B is assumed to be thirty times that of the conventional part ($\lambda_{AM} = 30\lambda_{CM}$). We assume the failure rate of AM parts to be a lot higher than those of CM counterparts, because we do not want to overestimate the quality of AM-produced parts in a remote environment. The time between failures (both CM and AM) is assumed to be exponentially distributed with rate parameter λ, which is constant, implying the distribution's memoryless property.

Furthermore, Table 6.1 contains the SKU specific part print volumes, print times and print costs. The SKU print volume (v_m) influences the print time (P_m) and print costs (c_m) of each SKU $m \in \mathcal{M}$. Print volumes and print times are determined using slicing software, by considering an SKU 3D model and performing the steps preparing the actual printing process. The software then determines the print volume and print time based on specific printer settings and the volume of the conventional part (Additive Manufacturing Expertise Center). In turn, the print costs are determined by considering machine depreciation, the SKU print volume, print speed and raw material costs. The printer settings and calculation of print costs can be viewed in Appendix F. Besides SKU specific holding and print costs, we consider downtime costs and failure costs, like Westerweel et al. (2021) and we adopt the values from their research. The researchers identified downtime costs to be €400 per Fennek vehicle per day. As we review time in hours, downtime costs (b) equal €16.67 ($\approx \frac{\text{€}400}{24}$) per down vehicle per hour, and the failure costs (f) equal one-time €400 ($\approx 12 * b + 200$). According to Westerweel et al. (2021) the failure costs represent the inconvenience of vehicle failure during operations. These costs include vehicle recovery and are therefore estimated to be the downtime costs of a vehicle for half a day ($12 * b$) plus additional costs (€200) for vehicle recovery.

6.2 Case study specific input parameters

Besides the general input parameters, we consider case study specific input parameters. This includes lead time between subsequent locations, order cycles to locations, probabilities of shipment cancellation and probability of print failure per AM capability type. The case study specific input values are presented in Table 6.2, where lead times and order cycles are given in hours and probabilities of print failure are AM capability specific. *Case study 1: Lithuania* is characterized by frequent shipments (once a day) to every location $j \in J$ ($O_1 = 24$, $O_2 = 24$, $O_3 = 24$). The lead time to location 1 is shortest as this is the only air movement, other shipments take place by road ($L_1 = 2$, $L_2 = 5$, $L_3 = 4$). The probability that shipment continues is rather high, since the RNLA prioritizes supporting logistics at all cost as discontinuity of logistics means that the operational units at the front line suffer from shortages ($p_1 = 0.9$, $p_2 = 0.9$, $p_3 = 0.9$). *Case study 2: Afghanistan* is characterized by less frequent supply occurrences (weekly, half-weekly) as operations are less intensive and critical ($O_1 = 168$, $O_2 = 168$, $O_3 = 84$). The lead time to location 1 is rather long, as this is an inter-continental operation. Lead times to location 2 and 3 are short, as supply occurs through air ($L_1 = 15$, $L_2 = 1$, $L_3 = 1$). Supply disruptions cancelling a replenishment occurrence during type 2 deployment (peacekeeping) are generally ignored ($p_1 = 0.7$, $p_2 = 0.7$, $p_3 = 0.9$), opposed to type 1 deployment (combat). For type 2 deployment (peacekeeping) equipment failure is perceived as less important as it has less major consequences for the operational units than when they are in an actual steel-on-steel conflict situation. For the type 1 deployment (combat) a (costly) solution of supply continuation is generally sought, resulting in a higher probability of shipment continuation (i.e., Lithuania $p_1 = 0.9$ opposed to Afghanistan $p_1 = 0.7$). The input values are provided by a RNLA operations expert and a RNLA AM expert (Logistics Knowledge Center 2; Additive Manufacturing Expertise Center). The parameters of *Case study 1* are inspired by deployment in Lithuania and do not represent the actual current deployment values. The parameters of *Case study 2* are based on RNLA expert experience in Afghanistan. We emphasize that all these parameters are estimated based on experience, as there is no clean data available that can be used in determining these input parameters.

Table 6.2: Case study specific input parameters

Case study	O_1 (hours)	O_2 (hours)	O_3 (hours)	L_1 (hours)	L_2 (hours)	L_3 (hours)	p_1	p_2	p_3	q_j	
										A	B
1. Lithuania	24	24	24	2	5	4	0.9	0.9	0.9	0.7	0.9
2. Afghanistan	168	168	84	15	1	1	0.7	0.7	0.9	0.7	0.9

6.3 Scenario specific base-stock levels

The base-stock levels of every SKU $m \in \mathcal{M}$ in every location $j \in J$, for each case study and every scenario are determined based on the approach described in Section 4.5.3. We recall that, in calculating the base-stock levels, the lead time demand of SKU $m \in \mathcal{M}$ is determined based on the failure rate ($\lambda_{CM,m}$) over the lead time to the concerning location, over the entire fleet, i.e. $|\mathcal{N}| = 50$. We incorporate the waiting time prior to shipment based on the order cycle ($\frac{O_j}{2}$), the actual lead time and (L_j), and if AM capability is available, we include SKU print time (P_m). Appendix G provides the base-stock levels for *Case study 1* and *Case study 2*, for every SKU $m \in M$, for every location $j \in J$, for every scenario.

6.4 Run parameters of simulation model

In order to obtain meaningful results, prior to running the simulation model various run parameters have to be determined. Hence, we discuss the warm-up period, the simulation length and the number of replications.

6.4.1 Warm-up period

Generally, prior to running an actual simulation model, the warm-up period is determined (Boon et al., 2020). This accounts for correction of system bias caused by the initial system's parameters, as the system does not start in steady state. However, we aim to model a real world mission context and specifically choose to exclude any warm-up period from the simulation. This study is centered around an ad-hoc remote supply chain. Our initial inventory on hand reflects the inventory that is carried along to remote locations in mission areas during the start of military deployment. We are aware that this represents the real world and not a system that has reached steady state. The time between failures follows an exponential distribution with rate parameter λ, which is constant and carries a memoryless property, meaning we do not have a higher probability of SKU failure during a later moment in time.

6.4.2 Simulation length

Similar to the choice to disregard a warm-up period, we base the simulation length on actual duration of a mission. *Case study 1* is inspired by current NATO deployment in Lithuania, which is still an ongoing mission. *Case study 2* is based on Afghanistan deployment, which has terminated. This deployment was rather long (20 years), opposed to other terminated missions. We follow an RNLA operations expert (Logistics Knowledge Center 2) and choose a simulation length that equals the complete mission duration of another deployment: Mali, for both *Case study 1* and *Case study 2*. The simulation is thus run for a total of six years, based the total period of the Netherlands' military presence in Mali.

6.4.3 Number of replications

The number of simulation replications is chosen to gain insightful results within a reasonable computation time. We use the central limit theorem to determine the number of runs and choose to accept an error of 0.25 over a 95%-confidence interval. While we ideally desire a smaller error, we aim to balance computation time with error and note that Python is rather slow compared to languages like Java and C^{++} (Boon et al., 2020). We accept an error of 0.25 as this will already provide us with meaningful insights on the preferred AM location. Eq. 6.1 allows us to determine the minimal number of runs, which can be rewritten to Eq. 6.2. Note that $z_{\alpha/2}$ is the $(\alpha/2)$ quantile of the standard normal distribution, σ is the standard deviation of the mean order waiting time (i.e., downtime incurred per component failure) and n is the number of simulation runs. We run the simulation model without AM capability based on *Case Study 1* input for 100 times over six years to obtain the standard deviation, $\sigma = 11.19$ hours, of the mean order downtime, $E[D] = 1.77$ hours. Hence, we plug in the values in Eq. 6.2 to obtain $n > 7,699$. Thus, we choose $n = 10,000$ runs for every scenario.

$$z_{\alpha/2} * \frac{\sigma}{\sqrt{n}} < \epsilon \qquad (6.1)$$

$$n > (\frac{z_{\alpha/2} * \sigma}{\epsilon})^2 \qquad (6.2)$$

7 Results

Combining the answers of RQ1 through RQ4, allows us to run the simulation model and to evaluate the simulation results. Therefore, in this chapter, the final research question is answered:

RQ5. How is vehicle readiness affected by the integration of AM compared to the base situation and how sensitive is the performance of the proposed model to the model parameters?

In Sections 7.1 and 7.2 we discuss the simulation's results in terms of vehicle readiness and operating costs of both case studies. In Section 7.3, we identify how AM capabilities are used throughout the case-studies' scenarios. We conclude this chapter by presenting sensitivity analysis on various parameters of the model to assess the model's robustness in Section 7.4.

7.1 Vehicle readiness

From both case studies we obtain the performance measures presented in Table 7.1. Note that scenarios 1 through 5 belong to *Case study 1: Lithuania* and scenarios 6 through 10 are from *Case study 2: Afghanistan.* The results are presented over the entire period of a six year deployment ($T = 52560$ hours). The mean order downtime per scenario and the 95%-confidence intervals are presented in Appendix H. We use "Cheap AM" to refer to AM capability Type A and "Costly AM" to describe AM capability Type B, since the machine purchase price and material costs are lower for Type A than Type B, while the reliability of Type B is higher than Type A in terms of both failure rate and probability of print failure.

In both case studies we find costly, more reliable AM capability in location 3 results in the highest vehicle readiness. In *Case study 1* a slight increase in vehicle readiness is found in all scenarios including AM capabilities, opposed to the scenario without AM capabilities. In *Case study 2* we only find an increase in vehicle readiness in scenario 9. Noticeably, the vehicle readiness is high for all scenarios 1 through 10 (> 99%). These high values for vehicle readiness arise as we determine our base-stock levels based on a classical newsvendor problem, meaning we weigh inventory costs against downtime costs. As the hourly downtime cost largely outweigh the hourly holding costs, spares are stocked in sufficient quantities to avoid that these high costs are incurred.

Table 7.1: Simulation results of *Case study 1* (1-5) and *Case study 2* (6-10)

Scenario	**Vehicle readiness (%)**	$H_{total}[0,T]$ **(€)**	$F[0,T]$ **(€)**	$B[0,T]$ **(€)**	$C[0,T]$ **(€)**	**Total operating costs (€)**
1. Cheap AM, loc. 2	99.89	33,106	680,178	49,426	27	761,736
2. Cheap AM, loc. 3	99.95	19,108	681,127	22,593	630	723,458
3. Costly AM, loc. 2	99.89	33,494	680,727	49,508	46	763,775
4. Costly AM, loc. 3	99.97	20,489	681,312	13,285	1,053	716,138
5. No AM	99.88	27,544	680,306	50,400	0	758,249
6. Cheap AM, loc. 2	99.23	47,411	675,368	338,776	65	1,061,620
7. Cheap AM, loc. 3	99.78	30,644	681,047	98,177	1,086	810,954
8. Costly AM, loc. 2	99.23	47,829	675,451	338,080	119	1,061,479
9. Costly AM, loc. 3	99.90	30,619	681,489	43,891	1,913	757,912
10. No AM	99.82	45,406	679,852	80,777	0	806,035

7.2 Operating costs

The results show that including AM capabilities may result in a reduction in total operating costs. Operating costs are lowest when locating costly, more reliable AM capability in location 3. In *Case study 1*'s most favorable scenario, scenario 4, a cost reduction of 5.6% is reached opposed to scenario 5 (no AM capabilities). In *Case study 2* we find a similar cost reduction of 6.0% of scenario 9 opposed to scenario 10 (no AM capabilities).

7.2.1 Downtime costs

The results show that downtime costs ($B[0,T]$) are lowest when installing more costly, but more reliable AM capabilities in location 3. We find differences in downtime costs over both case studies. In *Case study 1* locating AM capability in location 3 results in lower downtime costs than not including AM capability, regardless of the AM capability type. In *Case study 2* only installing costly AM in location 3 results in lower downtime costs than not installing AM capability. All other scenarios include higher downtime costs opposed to the scenario without AM capabilities. *Case study 2* is characterized by large order cycles (i.e. long waiting times for a next shipment to location 3) and high shipment uncertainties. We stress that we do not include the probability of shipment cancellation in calculating base-stock levels, which might result in an underestimation of the base-stock levels. Consequently, as overall supply times are long, less reliable AM SKUs may fail before replacement by a CM SKU, causing more downtime. Moreover, we find that downtime costs in both case studies are higher for a cheaper, less reliable AM capability type. The less reliable AM capability type has a higher probability of printfailure during manufacturing and a lower final product quality opposed to the other AM capability type.

7.2.2 Holding costs

We find that the total holding costs ($H_{total}[0,T]$) can be significantly reduced when including AM capability in location 3, compared to not including AM capabilities. This occurs through the reduction of base-stock levels. In scenario 4 opposed to scenario 5 of *Case study 1* we find: $S_{1,\mathcal{M}} = -3.0\%$, $S_{2,\mathcal{M}} = -6.8\%$ and $S_{3,\mathcal{M}} = -57.1\%$. In scenario 9 opposed to scenario 10 of *Case study 2* we find: $S_{1,\mathcal{M}} = -6.7\%$, $S_{2,\mathcal{M}} = -5.4\%$ and $S_{3,\mathcal{M}} = -69.2\%$. Remarkably, including AM capabilities in location 2 is associated with higher holding costs than not including AM capability, while the base-stock levels are generally lower than in scenarios without AM capabilities (on average *Case study 1*: $S_{1,\mathcal{M}} = -4.8\%, S_{2,\mathcal{M}} = -6.8\%$, *Case study 2*: $S_{1,\mathcal{M}} = -14.6\%, S_{2,\mathcal{M}} = -22.2\%$). This happens for two reasons: in these scenarios we do not reduce base-stock levels location 3, and location 3 also incurs holding costs over the parts in transit, thus also for AM parts, which later have to be replaced by CM parts.

7.2.3 Failure costs and printcosts

The failure costs ($F[0,T]$) are fairly stable, denoting the number of failures multiplied by the failure costs. We observe that these are slightly lower for scenarios with lower vehicle readiness, as SKUs cannot fail when the vehicle is down. The printcosts ($C[0,T]$) are generally higher for *Case study 2* than *Case study 1*. Due to the case study's longer supply times, the AM capability is used more frequently. Installing AM capabilities in location 3, ensures it is called upon more frequently than in location 2, resulting in higher printcosts.

7.3 Type of AM orders

In Appendix I we present the mean number of AM orders per SKU type, for every scenario 1 through 10. We find that, in both case studies, AM capabilities are largely used when these are installed in location 3 (on average 389.39 times in *Case study 1*, 496.99 times in *Case study 2*), while these are barely used when these are located in location 2 (on average 6.55 times in *Case study 1*, 15.16 times in *Case study 2*). By installing AM capabilities in location 2, we only reduce base-stock levels in location 2 and upstream. We initially aim to stock SKUs in location 3 in sufficient quantities, avoiding out-of-stock situations. Installing AM capabilities in location 3 allows base-stock level reduction through all echelons.

Overall, AM capability is mostly used for SKUs 9 through 14. These SKUs are generally stocked in little quantities due to the relatively high unit holding costs and infrequent demand (Appendix G can be consulted for SKU specific base-stock levels). This may imply that AM capabilities may be especially useful for unexpected or infrequent failures of expensive parts. Furthermore, we find that AM capabilities are used more often in *Case study 2*, opposed to *Case study 1*, due to the larger order cycles, implying more waiting time between supply occurrences and thus more potential time savings by on-site AM production options.

7.4 Sensitivity Analysis

The case studies provide us with initial insights on the most suitable AM capability type-location combination. However, we identify some parameters that may largely influence the model's outcomes. We argue that the failure rates may be underestimated, similar to the holding costs that are largely outweighed by the downtime costs. We also note that an increased level of threat may influence the preferred AM hosting location and the probability of shipment cancellation and the base-stock level optimization procedure may influence the model's outcomes. In this section we use sensitivity analysis on these variables to test the robustness of the simulation model to these parameters. We specifically choose not to rerun all scenarios for both case studies, instead we assess the most suitable AM scenarios. We provide a motivation for each parameter we apply sensitivity analysis to, and for the case studies we use. The 95%-confidence bounds can be found in Appendix K.

7.4.1 Failure rates

Vehicle use is generally more frequent and intensive in remote areas, than during operations in the Netherlands, and we thus expect more wear on the individual vehicle's parts. It is reasonable that the failure rates in our model are an underestimated representation of reality, as failure rate calculations are centered around usage in the Netherlands. Therefore, we test the model's sensitivity to higher SKU failure rates. We choose to include two variations: with base-stock adjustment, as if we are aware that the failure rates of the considered SKUs are generally a factor higher, and without base-stock adjustment, as if SKU failures occur more frequent than forecasted. We test varying failure rates on scenarios 9 and 10 of *Case study 1: Afghanistan*, as this mission takes place under completely different climatic conditions than those we know in the Netherlands. The results are presented in Table 7.2 (with base-stock level adjustment) and Table 7.3 (no base-stock level adjustment). Column λ_{CM}, λ_{AM} denotes the failure rate multiplication factor. Base-stock levels are presented in Appendix J.

Table 7.2: Simulation results, under varying failure rates and base-stock level adjustment

	λ_{CM}, λ_{AM}	**Vehicle readiness (%)**	**Number of orders**	$H_{total}[0,T]$ **(€)**	$F[0,T]$ **(€)**	$B[0,T]$ **(€)**	$C[0,T]$ **(€)**	**Total operating costs (€)**	**Costs/ order (€)**
Scenario 9	$*10$	88.96	19,485	95,695	8,956,575	4,837,431	103,264	13,992,966	718
AM in loc. 3	$*20$	76.66	33,218	143,969	17,096,996	10,223,916	229,416	27,694,299	833
Scenario 10	$*10$	92.38	20,987	128,659	8,396,734	3,338,409	0	11,863,802	565
No AM	$*20$	83.95	38,839	198,136	15,538,763	7,029,533	0	22,766,434	586

Table 7.3: Simulation results, under higher failure rate and no base-stock level adjustment

	λ_{CM}, λ_{AM}	**Vehicle readiness (%)**	**Number of orders**	$H_{total}[0,T]$ **(€)**	$F[0,T]$ **(€)**	$B[0,T]$ **(€)**	$C[0,T]$ **(€)**	**Total operating costs (€)**	**Costs/ order (€)**
Scenario 9 AM in loc. 3	$*10$	62.70	12,913	32,994	7,200,536	16,336,595	149,779	23,719,904	1,837
Scenario 10 No AM	$*10$	53.86	11,864	41,324	4,755,298	20,213,275	0	25,009,896	2,108

The results presented in Table 7.2 show that including AM capability in a situation with higher failures rates and adjusted base-stock levels, results in lower vehicle readiness and higher operational costs. The adjusted base-stock levels may be reduced too much, resulting in higher downtime costs ($B[0,T]$) in scenario 9 compared to scenario 10. Furthermore, as we prioritize down vehicles over vehicles driving with an AM SKU, we find that slow advance of CM parts, which are then used for down vehicles, often causes AM parts to fail before replacement by a CM part. In turn, this causes a vast increase in failure costs ($F[0,T]$). This effect becomes even larger when the failure rate increases from a factor 10 to a factor 20. Table 7.3 shows that, when we are not expecting an increase in failure rates by a factor 10 (no base-stock level adjustment), vehicle readiness is higher and operating costs are lower when including AM capability. The AM capability improves the ability to respond quickly to uncertainties in spare part demand. We note that the simulation was run over a period of 6 years. Realistically, the RNLA would adjust base-stock levels upwards if the failure rate turns out to be a lot higher than initially forecasted.

7.4.2 Unit holding costs

The results of both case studies show that the hourly unit holding costs are largely outweighed by the hourly downtime costs. As we consider a classical newsvendor problem, we therefore stock CM SKUs in sufficient quantities to prevent high downtime costs (up to vehicle readiness $> 99\%$). However, the RNLA struggles with increasing space restrictions when moving downstream towards the conflict area. This is already taken into account by differentiating between the unit holding costs in locations 1, 2 and 3 (100% of regular unit order costs of SKU $m \in \mathcal{M}$ for locations 1 and 2, opposed to 150% in location 3). Especially in a type 1 deployment (combat), units are required to relocate quickly, we cannot keep infinite inventories. For that reason, we test the model with higher inventory costs on scenarios 4 and 5 of *Case study 1* and adjust the base-stock levels accordingly, provided in Appendix J. Table 7.4 shows the simulation's results of under varying unit holding costs. Column $h_{j,m}$ ($j \in J, m \in \mathcal{M}$) denotes the unit holding cost multiplication factor.

Table 7.4: Simulation results, under varying holding costs

	$h_{j,m}$	**Vehicle readiness (%)**	**Number of orders**	$H_{total}[0,T]$ **(€)**	$F[0,T]$ **(€)**	$B[0,T]$ **(€)**	$C[0,T]$ **(€)**	**Total operating costs (€)**	**Costs/ order (€)**
Scenario 4	$*10$	99.91	1,702	110,265	681,381	38,413	1,460	831,520	489
AM in loc. 3	$*20$	99.83	1,699	107,764	680,710	70,575	4,281	863,330	508
Scenario 5	$*10$	99.39	1,691	116,434	676,462	267,816	0	1,060,711	627
No AM	$*20$	99.20	1,687	182,897	674,727	349,880	0	1,207,505	716

The results show that, including AM capabilities (scenario 4) still outperforms a situation without AM capabilities (scenario 5) in terms of vehicle readiness and total operating costs. We find that the insurance of CM stock is more expensive than being able to respond quickly through AM. In essence, unit print costs for one SKU ($P_m, m \in \mathcal{M}$) are significantly smaller than the unit holding costs over a longer period of time of the same SKU ($h_{j,m}, j \in J, m \in \mathcal{M}$), although taking some production time, implying some downtime costs (b). However, as we use a general-purpose printer to ensure quick part supply, often within hours, this is negligible.

7.4.3 Probability of print failure

RNLA operations experts provided us with the insight that, during type 1 deployment (combat), the level of threat can be very high, requiring dynamic operations in location 3 (13 Maintenance Company). As the current AM technologies are not yet mature enough to produce AM parts while driving, AM capability may be interrupted more frequently, than solely the printer's error. We evaluate the simulation's results according to the guidelines described in the RNLA's doctrines. In the run-up to combat phase - the competition phase - units in the most downstream location should relocate every 12 hours. In the actual combat phase, these units should relocate every 6 hours. In the (near) future, the RNLA aims to adjust this to 2 hours (Logistics Knowledge Center 2). We use scenario 4 of *Case study 1* to test if the desired AM location remains location 3, or changes to location 2 as the level of threat in location 3 increases. We evaluate the influence of the probability of print failure on a reliable AM capability, to assess how the level of threat may influence AM location decisions. The probability of print success is multiplied by $\frac{11}{12}$, $\frac{5}{6}$ and $\frac{1}{2}$ in scenario 4. We use scenario 3 with fixed $q_2 = q_3 = 0.9$ for comparison. Table 7.5 shows the simulation's results. Column q_2, q_3 denotes the probability of print success' multiplication factor.

Table 7.5: Simulation results, under increasing level of threat

	q_2, q_3	**Vehicle readiness (%)**	**Number of orders**	$H_{total}[0,T]$ **(€)**	$F[0,T]$ **(€)**	$B[0,T]$ **(€)**	$C[0,T]$ **(€)**	**Total operating costs (€)**	**Costs/ order (€)**
Scenario 3 AM in loc. 2	$*1$	99.89	1,701	36,742	680,421	49,413	46	766,621	451
Scenario 4 AM in loc. 3	$*1$	99.97	1,703	20,489	681,312	13,285	1,053	716,138	421
	$*\frac{11}{12}$	99.96	1,704	20,503	681,838	17,275	1,122	720,738	423
	$*\frac{5}{6}$	99.95	1,704	20,517	681,641	21,605	1,202	724,965	426
	$*\frac{1}{2}$	99.91	1,702	20,558	681,119	39,858	1,758	743,293	437

From the results it can be concluded that, using the presented multiplication factors, location 3 remains the preferred AM production location in terms of vehicle readiness and operating costs. AM capabilities in location 3 provide the benefit that AM parts can be build in once the part is finished, unlike location 2, where the AM still requires shipment. Despite the frequent shipments and short lead times, these logistics times increase the mean order downtime. We stress that we do not yet incorporate the time the operational units spend on relocating. In that sense, location 2 may become the preferred printing location when the total time spent on relocating exceeds the total time available for AM part production.

7.4.4 Probability of shipment cancellation

During type 1 deployment (combat), RNLA logistics experts do everything in their power to allow shipments to continue, despite possible risks they run into while doing so, as operational units require supplies in order to continue battling. AM capabilities may ensure more supply chain resilience as spare parts can be produced on demand where these are requested. We therefore test the simulation model's performance of *Case study 1* when the probability of shipment cancellation increases to the same degree as *Case study 2*. Note that we initially use $p_1 = p_2 = p_3 = 0.9$ in *Case study 1*. We consider *Case study 1* with $p_2 = p_3 = 0.8$ and $p_2 = p_3 = 0.7$, keeping all other parameters equal. We choose to evaluate scenario 4 of *Case study 1* as this showed most promising results. We also evaluate scenario 5 to compare the results to. Table 7.6 shows the simulation's results. Column p_2, p_3 denotes the new value for probability of shipment continuation.

Table 7.6: Simulation results, under higher probability of shipment cancellation

	p_2, p_3	**Vehicle readiness (%)**	**Number of orders**	$H_{total}[0,T]$ **(€)**	$F[0,T]$ **(€)**	$B[0,T]$ **(€)**	$C[0,T]$ **(€)**	**Total operating costs (€)**	**Costs/ order (€)**
Scenario 4 AM in loc. 3	0.9	99.97	1,703	20,489	681,312	13,285	1,053	716,138	421
	0.8	99.97	1,703	20,502	681,450	14,105	1,109	717,166	421
	0.7	99.96	1,702	20,517	681,067	15,772	1,187	718,544	422
Scenario 5 No AM	0.9	99.88	1,701	27,544	680,306	50,400	0	758,249	446
	0.8	99.87	1,702	27,540	680,631	56,365	0	764,535	449
	0.7	99.85	1,700	27,535	680,087	64,075	0	771,697	454

The results show that the performance measures of our scenario with AM capability remain relatively stable when the probability of shipment cancellation increases, while the performance measures in the scenario without AM capability degrade. AM capability is called upon more frequently as p_2 and p_3 decrease, which can be read from the increasing total printcosts ($C[0,T]$). We also find the total holding costs ($H_{total}[0,T]$) and total downtime costs ($B[0,T]$) in scenario 4 remain significantly lower than scenario 5. Especially the total downtime costs in scenario 5 amount up to four times those of scenario 4. The total operating costs are incrementally increased by approximately €10,000 in scenario whenever the probability of shipment continuation decreases by 0.1, while the increase of scenario 4 is about €1,000. An additional advantage is that we can still achieve the same level of vehicle readiness, while fewer shipments take place. This means that, whenever supply risks are very high, the RNLA may choose to cancel a delivery in the interest of personnel safety. These results imply that on-site AM capabilities may indeed increase supply chain resilience.

7.4.5 Base-stock levels

The scenario-specific base-stock levels may be underestimated, because of the infrequent supply occurrences and high probability of shipment cancellation not taken into account in base-stock level calculations. Therefore, we revise the base-stock levels of one SKU type by iteratively adjusting these. We use one SKU type, as failures occur mutually independent and SKUs cannot fail whenever a vehicle is down. We choose to assess base-stock levels for SKU $7 \in \mathcal{M}$, for which we obtained large base-stock level reductions after including AM capability. Starting in the most downstream stage, we incrementally increase $S_{j,m},\ j \in J, m \in \mathcal{M}$, until the base-stock levels including AM capability equal the benchmark base-stock levels. We perform this analysis on *Case study 2*, as this is characterized by more uncertainty in shipment occurrences and longer order cycles. The full procedure and results are discussed in Appendix L. Table 7.7 shows scenarios 6 through 10, with the lowest base-stock levels resulting in similar or improved performance measures opposed to the benchmark scenario.

Table 7.7: Simulation results of *Case study 2* for SKU 7, with adapted base-stock levels

Scenario	S_3, S_2, S_1	**Vehicle readiness (%)**	$H_{total}[0,T]$ **(€)**	$F[0,T]$ **(€)**	$B[0,T]$ **(€)**	$C[0,T]$ **(€)**	**Total operating costs (€)**	**Costs/ order (€)**
6. Cheap AM, loc. 2	**6, 8, 9**	99.99	974	272,416	4,953	10	278,352	409
7. Costly AM, loc. 3	**5, 8, 11**	99.99	1,142	272,628	4,819	38	278,628	409
8. Cheap AM, loc. 2	**6, 8, 9**	99.99	975	270,072	3,924	18	274,989	408
9. Costly AM, loc. 3	**5, 8, 11**	99.99	1,143	270,812	2,820	75	274,850	406
10. No AM	**6, 9, 12**	99.99	1,255	270,904	5,046	0	277,205	409

The results show that the base-stock level determination procedure discussed in Section 4.5.3 may have provided underestimated base-stock levels, at least for SKU 7 in *Case study 2*. After slightly increasing the initially determined ones for scenarios 6 through 9, we find that including AM capability results in similar vehicle readiness at similar or lower operating costs per order in every scenario, opposed to not including AM capabilities (benchmark scenario). These results are obtained through lower base-stock levels opposed to not installing AM capabilities. We stress that we solely adapted the procedure for one SKU type.

7.4.6 Conclusions sensitivity analysis

After performing sensitivity analysis on various of the model's input parameters, we find that AM is very suitable when we are not armed against higher spare part failure rates than forecasted. In line with this, when stocking spares becomes more costly, i.e. when we cope with volume restrictions, integrating AM capabilities in the remote spare parts supply chain allows quick response to out-of-stock situations. However, we also find that our base-stock level optimization procedure may provide underestimated base-stock levels. Analysis on the base-stock levels of certain SKU showed that base-stock levels can be reduced when including AM capability, but these should be sufficiently high in instances that cope with uncertainty in supply occurrences and long order cycles. Additionally, when the print failure increases due to an increasing level of threat or other exogenous circumstances, we still find the most downstream location to be the preferred AM hosting location. This may change whenever including actual times operational units are relocating and AM capabilities cannot be used. Finally, we find AM to contribute to more supply chain resilience, as the vehicle readiness is barely affected when the probability of shipment cancellation increases.

8 Conclusions and discussion

In this chapter we conclude our research by answering the main research question in Section 8.1. Besides, we identify the research' limitations in Section 8.2 and provide recommendations in Section 8.3.

8.1 Conclusions

The objective of this research has been to answer the main research question on how to integrate AM capabilities in a remote spare part supply chain:

How can AM capability be deployed in mission areas to improve the trade-off between vehicle readiness and relevant operating costs?

In this research, we considered different locations to place AM capability and different AM capability types, and assessed the effect on vehicle readiness and operating costs in remote operations. We developed a discrete-event simulation model to quantitatively assess different scenarios. The model was subsequently tested using two case studies, *Case study 1* based on type 1 deployment (combat) and *Case study 2* based on type 2 deployment (peacekeeping).

Our results show that on-site AM capability to produce temporary fixes may in various scenarios increase vehicle readiness and reduce the total operating costs, depending on the selected combination of AM location-AM capability type. An additional sourcing option reducing mean order downtime (i.e., increasing responsiveness) and increasing in vehicle readiness (i.e., asset availability) through the use of temporary fixes, opposed to a situation without AM integration, is in line with the findings of Westerweel et al. (2021) and Zijm et al. (2019). In general, the most downstream location, closest to where demand arises, is also found to be the preferred hosting location of AM capability. Locating AM capability in the most downstream location ensures a cost reduction for three reasons: firstly, the base-stock levels in all echelons may be adjusted downwards according to our base-stock determination procedure, causing a reduction in holding costs. When locating AM capability more upstream, we only adjust base-stock levels in this location and upstream. Secondly, when locating AM capability where demand arises, AM capability is frequently utilized, contrary to locating AM capability more upstream. The printing process may be started whenever demand occurs and the most downstream location has no CM spare part inventories. When locating AM capability more upstream, we only start the printing process whenever demand arises and all locations from the AM hosting location and downstream are out-of-stock, a less likely occurrence. Thirdly, in out-of stock situations with AM capability in the most downstream location, printed parts are delivered whenever the printing process is finished, i.e., we do not have to wait for a shipment occurrence, unlike scenarios with AM capability more upstream. This allows quick response to out-of-stock situations and does not increase vehicle downtime through waiting times. Subsequently, this ensures a higher degree of supply resilience as we are less dependent on lead times and long order cycles of the regular supply lines. Similar to Den Boer et al. (2020), Cestana et al. (2019), Liu et al. (2014) and Ghadge et al. (2018), we find that base-stock levels can be reduced when including AM capability, while retaining the same or increased degree of vehicle readiness, under lower operating costs. Base-stock level reduction is largest when locating AM capabilities in the most downstream location, as this allows base-stock level adjustment through all echelons.

The results also provide us with the insight that a more expensive, slower, but more reliable AM capability is preferred over a cheaper, faster, but less reliable AM capability. The more reliable AM capability type is characterized by a smaller probability of print failure and is able to deliver more reliable parts. This becomes more evident when the mission is characterized by long lead times and infrequent, uncertain supply moments. This is in line with the general findings mapped by Svoboda et al. (2021) on multiple sourcing literature: the benefit of a more expensive, reliable sourcing option increases as the yield uncertainty and the penalty for shortages increases and the value of sourcing from a reliable backup supplier increases as the frequency of supply disruptions grows. When a mission is characterized by a stable supply chain with frequent resupply, a cheap AM capability may already induce improvements opposed to not installing AM capability. In a study on multiple sourcing by Xin et al. (2017), reckoned by a rather unreliable fast supply option and a less responsive but reliable supply option, similar results are found: combining such supply sources outperforms single supply sources. We do stress that, when using temporary parts, we do not fully adopt a dual-sourcing model. We find AM capabilities to be specifically useful for parts with a low failure rate and relatively high holding costs, for which stocking spare parts is generally expensive. This aligns with the findings of Knofius et al. (2021).

Finally, we consider a similar research context as Westerweel et al. (2021) and obtain similar findings: RNLA operations may benefit from on-site AM capability. While we do not find similarly large operating cost reductions, we stress this may be subject to base-stock level determination procedure, as we keep large inventories, which is discussed in Section 8.2. We extend the research of Westerweel et al. (2021) and contribute to literature by proposing a model to evaluate different ways of integrating AM in a remote spare part supply chain, in terms of AM hosting location and AM capability type. We hereby include uncertainties and take SKU specific print times into account. Furthermore, we contribute to literature by evaluating two case studies based on empirical field research.

8.2 Limitations

In performing this research, we acknowledge a number of limitations. The first limitation is the methodology to determine the base-stock levels throughout the scenarios. We attempt to approximate base-stock levels of the different SKUs after including AM capability, while we do not yet fully optimize these. The modified heuristic used in this thesis is intuitive and allows echelon base-stock calculations that provide us with the insight that base-stocks can be adjusted downwards, decreasing holding costs and the required stocking space. In both case studies, we find certain scenarios in which base-stock adjustment improves the vehicle readiness, under reduced total operating cots. However, in performing sensitivity analysis on the base-stock levels, we find that these may be underestimated. Better results in terms of vehicle readiness and operating costs can be obtained throughout all scenarios when slightly increasing base-stock levels. The heuristic is adapted such that we correct the lead time demand by the minimum of print time and lead time, as if we attempt to use AM capability for MTS rather than MTO purposes. Furthermore, we do not correct the base-stock levels for the uncertainties in the model: probability of print failure and probability of shipment cancellation. These supply uncertainties not considered in base-stock level calculations thus largely affect the model's outcomes. Similar findings are emphasized by Snyder and Shen (2006), who state that supply uncertainties may largely affect operating costs.

Another limitation of the research is the unavailability of data. We emphasize that the case studies presented in this work purely serve to demonstrate how the vehicle readiness may be affected when adding AM capability and that the location and type of AM capability matters, depending on the situation considered.

Finally, various assumptions are made to create the model, which can be regarded as limitations. We assume that the SKUs considered in this research are all downtime critical and spare part failure causes system downtime. In essence, this is not necessarily the case: some of the SKUs we consider may cause just part of the vehicle to fail. This does not necessarily mean that the vehicle can no longer be used at all, it may still be able perform part of it functionalities. Various of these failures may in practice temporarily be fixed using BDR, affecting the mean order downtime, which we disregard. We also assume that we are allowed to use AM to temporarily satisfy outstanding spare part demand of a critical SKU. AM technologies may not be used yet to supply critical spare parts, as there are no licenses of the OEM that allow AM of parts and there is no AM part certification yet. Furthermore, we assume that the external supplier in the model, the Netherlands, has ample stock. On the contrary, this is often not the case and the RNLA copes with obsolescence of many spare parts.

8.3 Recommendations

From this research a number of recommendations can be deduced. Firstly, we acknowledge that we made first attempts to optimize base-stock levels based on the availability of onsite AM capability. However, we find that there is more potential in optimizing base-stock levels throughout the different echelons in a remote environment. We recommend future research aiming to explore ways in which to optimize base-stock levels throughout all echelons when including AM capability, i.e., consider enough stock to obtain a desired level of vehicle readiness when sourcing spare parts through regular supply complemented by an emergency AM option supplying temporary fixes. When optimizing these base-stock levels, uncertainties in supply occurrences should be considered, as well as uncertainties in spare part delivery by an additional AM sourcing option, i.e. the probability of print failure we consider in this research. To our knowledge, contrary to demand uncertainty, determination of optimal base-stock levels under supply disruptions in multi-echelon supply chains remains a topic rather understudied. We therefore suggest one way of incorporating this is by performing enumeration using computational applications, maintaining a service level constraint, such as vehicle readiness, and evaluating total operating costs. In the sensitivity analysis we used a similar approach between certain base-stock level bounds for one SKU type, but this was not computed for all possible values of base-stock levels and it was performed manually, which is more time intensive.

Also, we recommend follow-up research to include methods or models suitable to identify parts that have print potential as temporary fix (specifically remotely), in line with Knofius et al. (2016). In this research we adapted the SKU dataset of Westerweel et al. (2021) and expanded this by identifying additional printables in collaboration with RNLA maintenance and AM experts. These experts identified Fennek parts that can be retrieved conventionally and through AM, that are downtime critical and show printpotential as these may be manufactured using both nylon and onyx. However, we stress that we simply include a subset of the Fennek parts that may be printable using AM capability and material we considered. There may be many more SKUs suitable for AM. In turn, we do not consider which SKUs have most potential to be printed, i.e., some parts may be quick to manufacture using AM, but costly to produce. Similarly, we do not consider obsolete spare parts, as the model considers parts that may be retrieved through CM and AM. However, we recommend studying the effect of deploying AM for obsolete parts, as AM may particularly be useful in reducing system downtime caused by these parts that are hard to obtain conventionally.

Additionally, specifically for the RNLA, we recommend better data registration, allowing future studies to assess more realistic case studies and their results. A number of the parameter values in this study are either estimated by RNLA operations, AM and maintenance experts, or based on primitive data. We are a aware that data registration on supply occurrences and lead times remains a challenge due to the RNLA's specific business operations, and procedures that can be deviated from. In terms of spare part failure behavior, vehicle usage is generally more intensive in mission areas. During operations in the Netherlands, vehicles require to be operationally ready, while this does not necessarily mean all these vehicles are utilized on a daily basis. In this study we do not correct failure rates for usage intensity as there is no data available on the failure rates in mission areas relative to operations in the Netherlands. A suggestion is a well-organized procedure for spare part requests in SAP whereby the applicant registers which specific SKUs have failed and for what reason, under which conditions.

Moreover, specifically for RNLA missions, during type 1 deployment (combat) operational units in the most downstream location operate dynamically, opposed to type 2 deployment (peacekeeping). In this study we do assess AM location decisions when the print failure increases due to exogenous circumstances, but we do not consider the time we are not able to operate the AM capability as units are relocating. In essence, this may be included by evaluating whether or not to restart the print process after a certain time spend on relocating, instead of directly when a print order has failed. However, this requires differentiation between print failure subject to print error and print failure or interruption caused by the need to relocate. This may result in more incentive to utilize location 2 for AM capabilities. We thus encourage future research to incorporate this. Besides, it is interesting to investigate how AM integration choices would be affected when the quality of AM increases to approach the quality of CM parts, or even exceed it. In the latter case it means SKUs no longer serve to temporarily satisfy spare part demand. The model rather changes to a pure dual-sourcing model. This may improve supply chain resilience and further reduce base-stock levels.

Finally, we recommend attempts to collaborate with OEMs to license on-site AM production of parts, and certifications to be able to actually use manufactured parts. As of now, a lack of standards largely prevents the RNLA from deploying AM in the Netherlands and remotely. As industry is currently facing similar burdens, partnership with OEMs may already be useful in designing spare part supply structure whenever these industry-wide limitations are bridged.

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A RNLA Organisation

Removed due to confidentiality reasons.

B RNLA Materiel

Removed due to confidentiality reasons.

C Interview memory list

Hereafter the memory list is provided that serves to guide the interviews. Different types of questions are asked, to uncover the as-is business processes regarding spare parts management, in the Netherlands as well as during deployment. However, as the interviews are explorative in nature, the main focus lays on asking further questions based on the answers given by the interviewees. Questions of various types, as discussed by Blumberg et al. (2014), can be used throughout the interviews. Some questions are prepared to steer the interview, however, some of these questions may be skipped or asked in a different form.

Each interview starts with a brief explanation of the research context, like: "The RNLA is interested in integrating AM in the remote spare parts supply chain (during deployment of type one and type two). Through this research we aim to deliver a model that may assist in determining if and where printers may be deployed during remote deployment."

Introductory question:

- Could you tell something about the department you work for and your role in it?

Indirect questions are not directed at the interviewee, rather at the general processes:

- What does the remote spare part supply chain generally look like?
- How are spare parts, that are out of stock, requested on a mission?
- How are the parts selected that are brought along during deployment?
- What are the different part retrieval options on a mission?
- How are spare parts handled that are generally difficult to retrieve (i.e. due to spare part obsolesce, or long lead times)?
- What are the facilities on each of the different remote locations that are set up during deployment?
- What steps are taken during preparation of a new mission?
- Could you explain how logistics operations are arranged during remote deployment?
- Could you explain how spare part inventory levels are determined (in the Netherlands and in remote locations)?

Direct questions serve to uncover more on the respondents viewpoint:

- Could you explain what factors you believe may influence remote AM deployment?
- Could you explain in what way you feel AM should be integrated in the remote spare parts supply chain of the RNLA?
- Could you explain which locations you believe are suitable to locate an AM production configuration?

- Which parties do you think may be involved in the printing process?
- What factors would you consider important to include in a model on remote AM integration?
- When do you think an additional AM sourcing option has most value (i.e. stock printed parts for regular supply, print parts solely as emergency option)?
- Do you feel there are restrictions regarding remote AM production?

Besides the predefined questions, *follow-up questions* are used throughout the interview to ensure the answers are understood correctly. These questions serve to ask the respondent to elaborate further on a specific topic or question. *Probing questions* may be used to learn more about a specific part of the interviewees answer, i.e. how certain decisions are made. *Specifying questions* can be used to steer the respondent to elaborate on the entire answer, in order to gain more information, i.e. consequences of certain decisions. *Structuring questions* may be used to steer the interviewee to a next topic after reaching a certain level of information saturation, i.e. change the topic form spare parts management in the Netherlands, to remote spare parts management. *Interpreting questions* are used to ensure that the information was interpreted correctly, by repeating and summarizing the interviewees answers in questions.

D Calculation and assessment of base-stock levels

This appendix serves to justify the base-stock determination procedure. We are specifically interested if the base-stock levels can be adjusted downwards when including AM capability without affecting the simulation's performance measures: vehicle readiness and operating costs. In Section 4.5.3 the approach used to determine the scenario-specific base stock levels is introduced. We benchmark the approach for the scenarios without AM integration, by considering lead time demand over the lead time and mean shipment waiting time $((L_j + \frac{O_j}{2})$, with $j \in J$ and $m \in \mathcal{M}$). Hereafter we provide an example of how the base-stock levels through echelon 1, 2 and 3 can be determined for SKU $1 \in \mathcal{M}$. Base-stock levels of the other SKUs in $\mathcal{M}$ are determined in a similar manner. Table D.1 shows the case study and SKU specific input parameters used in the base-stock calculations.

Table D.1: Input parameters for base-stock calculation of *Case study 1*, SKU 1

λ_{CM} (failures/hour)	$\lvert\mathcal{N}\rvert$	$\lambda_{CM,fleet}$ (failures/hour)	o_m (€)	b (€/hour)	h_1, h_2, h_3 (€/hour)	O_1, O_2, O_3 (hours)	L_1, L_2, L_3 (hours)
0.000029	50	0.001450	2.80	16.67	0.000320, 0.000320, 0.000480	24,24,24	2,5,4

In Table D.1 $\lambda_{CM,fleet}$ is obtained by multiplying λ_{CM} by the number of vehicles that together make-up the Fennek vehicle fleet for this case study ($\lvert\mathcal{N}\rvert$). In every location $j \in J$ we assess the lead time demand, that is, demand over the lead time. With our adaption, for location 3 this is demand over $(L_3 + \frac{O_3}{2}) = (4 + \frac{24}{2}) = 16$ hours. For location 2 we encounter lead time demand over $(L_2 + \frac{O_2}{2}) + (L_3 + \frac{O_3}{2}) = (5 + \frac{24}{2}) + (4 + \frac{24}{2}) = 33$ hours, and similar for location 1 we calculate lead time demand over $(L_1 + \frac{O_1}{2}) + (L_2 + \frac{O_2}{2}) + (L_3 + \frac{O_3}{2}) = (2 + \frac{24}{2}) + (5 + \frac{24}{2}) + (4 + \frac{24}{2}) = 47$ hours. These values are multiplied by λ_{fleet} in order to calculate the lead time demand. Lead time demand of location 3, location 2 and location 1 is 0.023200, 0.047850 and 0.068150 failures per hour, respectively.

For location 3, the base-stock level of SKU 1 can be determined using Eq. 4.8 with $j = 3$ and $m = 1$. For locations 2 and 1 we use Eq. 4.9 and Eq. 4.10 to obtain the base-stock level's lower and upper bounds. Subsequently, Eq. 4.11 is used to obtain the base-stock level values. Hereafter, in Table D.2 we provide the calculations to obtain the base-stock levels of SKU 1 in locations 3, 2 and 1. Note that F_j denotes the cumulative distribution function of the total lead time demand of the concerning location $j \in J$. Base-stock levels of all SKUs in $\mathcal{M}$ are calculated in a similar manner.

After calculating the base-stock levels for every location $j \in J$, for every location $m \in \mathcal{M}$, we obtain a vector for every location including all SKUs' base-stock levels for the benchmark situation:
$S_3 = [2, 1, 2, 2, 2, 3, 4, 3, 1, 1, 1, 1, 0, 1]$,
$S_2 = [2, 2, 2, 2, 2, 3, 5, 4, 1, 1, 1, 1, 0, 1]$,
$S_1 = [2, 2, 2, 2, 2, 4, 6, 4, 1, 1, 1, 1, 0, 1]$.

Table D.2: Benchmark base-stock level calculations per location of SKU 1

Location 3	**Location 2**	**Location 1**
$S_{\vert J\vert,m} = F^{-1}(\frac{b+\sum_{i=1}^{J-1} h_{i,m}}{b+\sum_{i=1}^{J} h_{i,m}})$	$S^l_{j,m} = F_j^{-1}(\frac{b+\sum_{i=1}^{j-1} h_{i,m}}{b+\sum_{i=1}^{J} h_{i,m}})$ $S^u_{j,m} = F_j^{-1}(\frac{b+\sum_{i=1}^{j-1} h_{i,m}}{b+\sum_{i=1}^{j} h_{i,m}})$	$S^l_{j,m} = F_j^{-1}(\frac{b+\sum_{i=1}^{j-1} h_{i,m}}{b+\sum_{i=1}^{J} h_{i,m}})$ $S^u_{j,m} = F_j^{-1}(\frac{b+\sum_{i=1}^{j-1} h_{i,m}}{b+\sum_{i=1}^{j} h_{i,m}})$
$S_{3,1} = F^{-1}(\frac{b+\sum_{i=1}^{2} h_{i,1}}{b+\sum_{i=1}^{3} h_{i,1}})$	$S^l_{2,1} = F_2^{-1}(\frac{b+\sum_{i=1}^{1} h_{i,1}}{b+\sum_{i=1}^{3} h_{i,1}})$ $S^u_{2,1} = F_2^{-1}(\frac{b+\sum_{i=1}^{1} h_{i,1}}{b+\sum_{i=1}^{2} h_{i,1}})$	$S^l_{1,1} = F_1^{-1}(\frac{b}{b+\sum_{i=1}^{3} h_{i,1}})$ $S^u_{1,1} = F_1^{-1}(\frac{b}{b+\sum_{i=1}^{1} h_{i,1}})$
$S_{3,1} = F^{-1}(0.999971)$	$S^l_{2,1} = F_2^{-1}(0.999952)$ $S^u_{2,1} = F_2^{-1}(0.999981)$ $S^l_{2,1} = 2$ $S^u_{2,1} = 2$	$S^l_{1,1} = F_1^{-1}(0.999933)$ $S^u_{1,1} = F_1^{-1}(0.999981)$ $S^l_{1,1} = 3$ $S^u_{1,1} = 2$
$S_{3,1} = 2$	$S^a_{2,1} = \lfloor\frac{2+2}{2}\rfloor = 2$	$S^a_{1,1} = \lfloor\frac{2+3}{2}\rfloor = 2$

We run all five scenarios of *Case study 1*, for a period of 6 years (= 52560 hours) with these fixed base-stock levels. That is, we keep the base-stock levels in all three echelons the same as our benchmark situation and vary the AM capability type and AM hosting location. We find vehicle readiness to be 99.89%, 99.96%, 99.89%, 99.98% and 99.89% in scenarios 1 through 5, respectively. Total operating costs are presented in Figure D.1.

After this, we adapt the base-stock levels for scenarios including AM capabilities, by incorporating print times. We expect base-stock levels can be adjusted downwards in locations that host AM capabilities and upstream. We therefore use $min((L_j + \frac{O_j}{2}), P_m)$ to correct the lead time demand of SKU $m \in \mathcal{M}$ in location $j \in J$. We thus only reduce the lead time of the location hosting AM capabilities. We show the base stock calculations of scenario 1 of *Case study 1*: AM capability type A in location 2. This means lead time of location 2 changes to P_m, instead of $(L_2 + \frac{O_2}{2})$. In turn, lead time demand in this scenario adapted. For location 3 lead time demand is still calculated over $(L_3 + \frac{O_3}{2}) = (4 + \frac{24}{2}) = 16$ hours, as it does not host AM capabilities. For location 2 we encounter adapted lead time demand over $P_m + (L_3 + \frac{O_3}{2}) = 0.08 + (4 + \frac{24}{2}) = 16.08$ hours, and similar for location 1 we calculate lead time demand over $(L_1 + \frac{O_1}{2}) + P_m + (L_3 + \frac{O_3}{2}) = (2 + \frac{24}{2}) + 0.08 + (4 + \frac{24}{2}) = 30.08$ hours. These values are multiplied by $\lambda_{CM,fleet}$ in order to calculate the lead time demand. Lead time demand of location 3, location 2 and location 1 is 0.023200, 0.023316 and 0.043616 failures per hour, respectively.

Similar to calculations provided in Table D.2, we obtain $S_{3,1} = 2$, $S^a_{2,1} = \lfloor\frac{2+2}{2}\rfloor = 2$, $S^a_{1,1} = \lfloor\frac{2+2}{2}\rfloor = 2$ for locations 3, 2 and 1, respectively, in scenario 1. We obtain the base-stock levels in a similar way for scenarios 2 through 4, for all SKUs in $\mathcal{M}$. Note that we do not recalculate the base-stock levels of scenario 5, as this is our benchmark scenario without AM capabilities. Note that we use these base-stock levels in *Case study 1* and their respective values can be found in Appendix H. With these adapted base-stock levels, we rerun scenarios 1 through 4, for a period of 6 years (= 52560 hours). We find the vehicle readiness to be 99.89%, 99.95%, 99.89% and 99.97%in scenarios 1 through 4, respectively. Total operating costs are presented in Figure D.1.

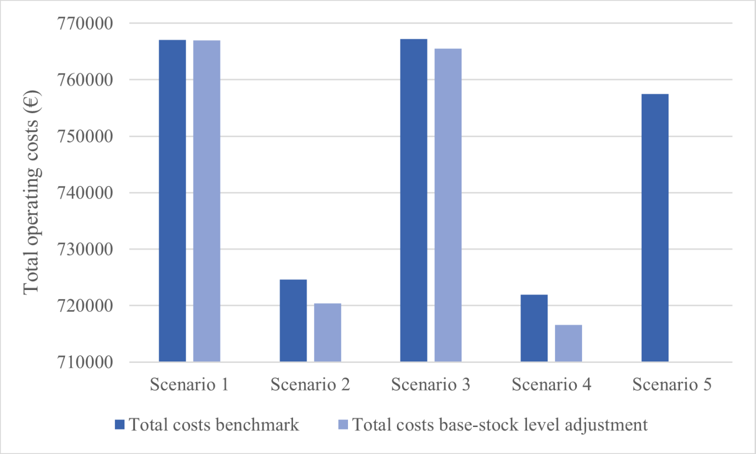

Figure D.1: Total operating costs of benchmark versus adjusted base-stock level scenarios

The results of the benchmark base-stock levels opposed to the adapted base-stock levels show that base-stock levels can be reduced when using the proposed heuristic, barely affecting vehicle readiness, showing improvements in terms of operating costs. We stress that for this test case, base-stock levels in the most optimistic scenario, scenario 4, can be reduced by, on average, 3.0% in location 1, 6.8% in location 2 and 57.1% in location 3, compared to scenario 5.

E Calculation of SKU failure rates

Removed due to confidentiality reasons.

F Calculation of AM parameters and print settings

The print times and print costs for every SKU $m \in \mathcal{M}$ can be determined using a set of print settings. We first present the print settings per AM capability and proceed by discussing how the print times and print costs per SKU are determined.

Print settings

The simulation model is tested for two different AM capabilities: an Ultimaker S5 and a Markforged Mark Two. These AM capabilities and accompanying material types are selected by an RNLA AM expert (Additive Manufacturing Expertise Center) as potential printer types that may be deployed remotely. For every single AM capability we consider a set of print settings, presented in Table F.1. These include the material type, the diameter of the nozzle, the print speed, the layer height and the percentage infill. The printer settings are determined by a RNLA AM expert (Additive Manufacturing Expertise Center). The table also shows the current machine purchase price.

Table F.1: Printer settings per AM capability

AM capbility	**Material type**	**Nozzle diameter (mm)**	**Printspeed (mm/s)**	**Layer height (mm)**	**Infill (%)**	**Purchase price (€)**
Ultimaker S5	Nylon	0.8	30	0.2	20	7,000
Markforged Mark Two	Onyx	0.4	30	0.2	28	24,000

The SKU specific print times are based on the print settings. To determine the actual print times per SKU, a 3D model is inserted in CAD software, adapting the print settings from Table F.1 and slicing the 3D model as if it were to be printed. The software program accurately determines the print time of every SKU $m \in \mathcal{M}$. We assume pre- and post-processing is included in the print time per SKU.

Print costs

Westerweel et al. (2021) introduced Equation F.1 to determine the print costs (c_m) in euros for SKU $m \in \mathcal{M}$, based on the print volume (v_m), print speed (s) and machine depreciation costs (d) of the selected AM capability:

$$c_m(v_m) = \frac{v_m}{s} * d + v_m * r. \tag{F.1}$$

Print volume of part $m \in \mathcal{M}$ is given in cm^3, speed s is given in cm^3/h, cost of raw material r in €/cm^3. Depreciation costs d in €/hour are assumed to be linear over the number of machine operating years, considering a certain machine utilization. Depreciation of the AM capability is calculated using Equation F.2:

$$d = \left(\frac{\text{machine purchase price}}{\text{operating years} * \text{hours/year} * \text{utilization}}\right) \tag{F.2}$$

Using Equation F.2, and subsequently Equation F.1, the print costs c_m for every SKU $m \in \mathcal{M}$ can be calculated. The volume v_m of every SKU $m \in \mathcal{M}$ can be retrieved from Table 6.1. The print speed s and the cost of raw material r are given in Table F.1. The depreciation costs d for the Ultimaker S5 and Markforged Mark Two are presented below. The printcosts c_m, $m \in \mathcal{M}$, for both AM capability types are presented in Table 6.1.

Ultimaker S5: $d = \frac{7000}{(5*24*365*0.5)} =$ €0.32

Markforged Mark Two: $d = \frac{24000}{(5*24*365*0.5)} =$ €1.10

G Scenario specific base-stock levels

This appendix provides the base-stock for *Case study 1* and *Case study 2*, for every SKU $m \in M$, for every location $j \in J$, for every scenario. Base-stock levels are determined using the approach discussed in Section 4.5.3. Table G.1 shows the base-stock levels of *Case study 1*, while Table G.2 presents the base-stock levels of *Case study 2*. Note that scenarios 5 and 10 denote situations without AM integration. Whenever AM integration allows base-stock level reduction for SKU $m \in \mathcal{M}$ in location $j \in J$ the cell is colored green.

Table G.1: Base-stock levels for every scenario of *Case study 1*

		Scenario														
		1			**2**			**3**			**4**			**5**		
		S_3	S_2	S_1	S_3	S_2	S_1	S_3	S_2	S_1	S_3	S_2	S_1	S_3	S_2	S_1
SKU	**1**	2	2	2	1	2	2	2	2	2	1	2	2	2	2	2
	2	1	1	1	1	1	1	1	1	2	1	1	2	1	2	2
	3	2	2	2	1	2	2	2	2	2	1	2	2	2	2	2
	4	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
	5	2	2	2	1	2	2	2	2	2	1	2	2	2	2	2
	6	3	3	3	1	3	3	3	3	3	1	3	3	3	3	4
	7	4	4	5	2	4	5	4	4	5	2	4	5	4	5	6
	8	3	3	4	2	3	4	3	3	4	2	3	4	3	4	4
	9	1	1	1	0	1	1	1	1	1	0	1	1	1	1	1
	10	1	1	1	0	1	1	1	1	1	0	1	1	1	1	1
	11	1	1	1	0	1	1	1	1	1	0	1	1	1	1	1
	12	1	1	1	0	1	1	1	1	1	0	1	1	1	1	1
	13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	14	1	1	1	0	1	1	1	1	1	0	1	1	1	1	1

Table G.2: Base-stock levels for every scenario of *Case study 2*

		Scenario														
		6			**7**			**8**			**9**			**10**		
		S_3	S_2	S_1	S_3	S_2	S_1	S_3	S_2	S_1	S_3	S_2	S_1	S_3	S_2	S_1
SKU	**1**	3	2	3	1	3	4	3	2	3	1	3	4	3	3	4
	2	2	2	3	1	2	3	2	2	3	1	2	3	2	3	3
	3	3	2	3	1	3	4	3	2	3	1	3	4	3	3	4
	4	3	3	4	2	4	5	3	3	4	2	4	5	3	4	5
	5	2	2	3	1	3	3	2	2	3	1	3	3	2	3	4
	6	4	4	6	1	5	7	4	4	6	1	5	7	4	6	7
	7	6	6	9	2	8	11	6	6	9	2	8	11	6	9	12
	8	5	4	8	2	6	9	5	5	8	2	6	9	5	7	10
	9	2	1	2	0	2	2	2	1	2	0	2	2	2	2	2
	10	1	1	1	0	1	1	1	1	1	0	1	1	1	1	1
	11	1	1	1	0	1	1	1	1	1	0	1	1	1	1	1
	12	1	1	1	0	1	1	1	1	1	0	1	1	1	1	1
	13	0	0	0	0	0	1	0	0	0	0	0	1	0	1	1
	14	1	1	1	0	1	1	1	1	1	0	1	1	1	1	2

H Confidence bounds of case studies' scenarios

This appendix provides the case studies' mean order downtime ($E[D]$) and the 95-% confidence bounds in Table H.1. By mean order downtime we mean the average downtime incurred when satisfying an order of a failed CM SKU. Note that scenarios 1 thorugh 5 belong to *Case study 1: Lithuania*, while scenarios 6 through 10 are part of *Case study 2: Afghanistan*.

Table H.1: 95%-confidence intervals of *Case study 1* (1-5) and *Case study 2* (6-10)

Scenario	**CI lower bound (hours)**	$E[D]$ **(hours)**	**CI upper bound (hours)**
1. Cheap AM, loc. 2	1.53	1.96	1.96
2. Cheap AM, loc. 3	0.59	0.71	0.82
3. Costly AM, loc. 2	1.53	1.75	1.97
4. Costly AM, loc. 3	0.33	0.40	0.47
5. No AM	1.56	1.78	2.00
6. Cheap AM, loc. 2	10.47	12.03	13.59
7. Cheap AM, loc. 3	2.77	3.35	3.94
8. Costly AM, loc. 2	10.44	12.00	13.57
9. Costly AM, loc. 3	1.13	1.47	1.81
10. No AM	2.36	2.85	3.35

I Scenario specific mean number of AM orders

Table I.1 reveals the total number of AM printorders for every SKU $m \in \mathcal{M}$, for scenarios 1 through 5 of *Case study 1* and scenarios 6 through 10 of *Case study 2* over 6 year deployment.

Table I.1: Mean number of AM orders per SKU, per scenario

		Scenario									
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
SKU	**1**	0.0007	2.9493	0.0009	2.2495	0	0.0709	7.9916	0.0617	6.2394	0
	2	1.4352	4.3675	1.1062	2.9917	0	1.3508	17.0990	1.1302	13.5482	0
	3	0.0006	2.8995	0.0003	2.2400	0	0.0678	7.9622	0.0723	6.1480	0
	4	0.0093	0.1838	0.0031	0.0922	0	1.0040	4.7851	0.8475	3.6046	0
	5	0.0012	2.9113	0.0006	2.2483	0	0.4083	7.9545	0.3648	6.2193	0
	6	0.0002	17.5342	0.0001	13.5532	0	0.1841	45.3383	0.1516	35.0898	0
	7	0.0002	5.9109	0.0002	4.3733	0	0.6364	43.2212	0.5557	33.3646	0
	8	0.0015	4.4682	0.0020	3.3890	0	1.8574	34.9718	0.9216	27.2906	0
	9	1.1540	98.5914	0.9219	77.0842	0	1.2875	98.6617	1.1001	77.0143	0
	10	0.7079	60.2907	0.5642	47.1389	0	2.0038	57.9382	1.5793	46.4334	0
	11	0.7064	58.3805	0.5526	45.6405	0	1.9928	56.2909	1.5628	45.1237	0
	12	0.6790	59.5519	0.5310	46.4889	0	1.9832	56.7701	1.5669	45.4692	0
	13	1.7639	40.7431	1.3705	40.2360	0	1.9606	40.8163	1.5295	40.2839	0
	14	0.8878	74.3227	0.7056	57.9498	0	2.2807	71.1069	1.7782	57.2454	0
Total printorders		7.3479	433.1050	5.7592	345.6755	0	17.0883	550.9078	13.2222	443.0744	0

J Base-stock levels sensitivity analysis

To perform sensitivity analysis, we choose to vary a number of parameters. In some instances, we adapted scenario-specific base-stock levels, which are presented in this appendix.

Table J.1 shows the base-stock levels of scenarios 9 and 10 when failure rates are a multiplication factor 10 or 20 higher and base-stock levels are adjusted accordingly. Note that columns $10 * \lambda$ and $20 * \lambda$ denote the multiplication factor used in the concerning scenario. We stress that both λ_{CM} and λ_{AM} are adapted in these scenarios. The green cells represent a base-stock level reduction opposed to a scenario without AM capabilities.

Table J.1: Scenario specific base-stock levels under varying failure rates

		Scenario 9						**Scenario 10**					
		$10 * \lambda$			$20 * \lambda$			$10 * \lambda$			$20 * \lambda$		
		S_3	S_2	S_1	S_3	S_2	S_1	S_3	S_2	S_1	S_3	S_2	S_1
SKU	**1**	1	7	11	1	11	16	6	9	12	8	13	18
	2	2	8	13	3	12	21	5	10	14	8	16	24
	3	1	7	11	1	11	16	6	9	12	8	13	18
	4	5	14	22	7	23	38	8	16	24	13	27	42
	5	1	7	10	1	10	15	5	8	11	7	12	17
	6	2	15	25	2	24	41	11	20	29	16	31	48
	7	5	28	47	7	45	80	18	36	54	28	60	93
	8	4	23	40	5	38	68	15	30	46	23	51	80
	9	1	5	7	1	7	11	4	6	8	5	9	13
	10	1	2	2	1	2	3	2	2	3	2	3	4
	11	1	2	3	1	3	3	2	2	3	2	3	4
	12	1	2	2	1	2	3	2	2	3	2	3	4
	13	0	1	1	0	1	2	1	1	1	1	2	2
	14	1	3	4	1	4	6	2	4	5	3	5	7

In Table J.2 we present the base-stock levels of scenarios 4 and 5 under varying unit holding costs ($h_{j,m}$, where $j \in J, m \in \mathcal{M}$), i.e. unit holding costs of *Case study 1* multiplied by a factor 10 and 20. The green cells represent a base-stock level reduction.

Table J.2: Scenario specific base-stock levels under varying unit holding costs

		Scenario 4						**Scenario 5**					
		$10 * h_{j,m}$			$20 * h_{j,m}$			$10 * h_{j,m}$			$20 * h_{j,m}$		
		S_3	S_2	S_1	S_3	S_2	S_1	S_3	S_2	S_1	S_3	S_2	S_1
SKU	**1**	0	1	2	0	1	1	1	2	2	1	2	2
	2	1	1	1	0	0	1	1	1	1	1	1	1
	3	1	1	2	0	1	1	1	2	2	1	2	2
	4	1	1	2	1	1	1	1	1	1	1	1	1
	5	0	1	1	0	1	1	1	1	1	1	1	1
	6	1	2	3	1	2	2	2	3	3	2	2	3
	7	2	3	4	2	3	4	3	4	5	3	4	4
	8	1	2	3	1	2	3	2	3	3	2	3	3
	9	0	1	1	0	0	0	1	1	1	0	0	0
	10	0	0	0	0	0	0	0	0	0	0	0	0
	11	0	0	0	0	0	0	0	0	0	0	0	0
	12	0	0	0	0	0	0	0	0	0	0	0	0
	13	0	0	0	0	0	0	0	0	0	0	0	0
	14	0	0	0	0	0	0	0	0	0	0	0	0

K Confidence bounds of sensitivity analysis

In this appendix we provide the mean order downtimes ($E[D]$) and their 95%-confidence bounds for the various test scenarios of the sensitivity analysis performed in Section 7.4.

Failure rate

Table K.1 shows the mean order downtimes ($E[D]$) and their 95%-confidence bounds for scenarios 9 and 10 where we adjusted the base-stock levels according to a higher failure rate. Table K.2 displays these for scenarios 9 and 10 in which we do not correct the base-stock levels. The column λ_{CM}, λ_{AM} shows the failure rate multiplication factor.

Table K.1: 95%-confidence intervals under higher failure rates (base-stock level adjustment)

	λ_{CM}, λ_{AM}	**CI lower bound (hours)**	$E[D]$ **(hours)**	**CI upper bound (hours)**
Scenario 9	$*10$	14.39	15.44	16.48
	$*20$	18.54	19.76	20.98
Scenario 10	$*10$	8.55	9.54	10.54
	$*20$	9.81	10.86	11.91

Table K.2: 95%-confidence intervals of higher failure rate (no base-stock level adjustment)

	λ_{CM}, λ_{AM}	**CI lower bound (hours)**	$E[D]$ **(hours)**	**CI upper bound (hours)**
Scenario 9	$*10$	77.33	79.89	82.45
Scenario 10	$*10$	98.79	102.00	105.21

Holding costs

In Table K.3 we display the mean order downtimes ($E[D]$) and their 95%-confidence bounds for scenarios 4 and 5, under increased unit holding costs ($h_{j,m}$, with $j \in J, m \in \mathcal{M}$). The column $h_{j,m}$ denotes the unit order cost multiplication factor.

Table K.3: 95%-confidence intervals under higher unit holding costs

	$h_{j,m}$	**CI lower bound (hours)**	$E[D]$ **(hours)**	**CI upper bound (hours)**
Scenario 9	$*10$	1.10	1.26	1.41
	$*20$	2.11	2.31	2.51
Scenario 10	$*10$	9.02	9.51	10.00
	$*20$	11.91	12.46	13.00

Probability of printfailure

Table K.3 shows the mean order downtimes ($E[D]$) and their 95%-confidence bounds for scenarios 4 and 5, under decreased probability of printsuccess (q_2, q_3). The column q_2, q_3 denotes the probability of printsuccess multiplication factor.

Table K.4: 95%-confidence intervals under increasing level of threat

	q_2, q_3	**CI lower bound (hours)**	$E[D]$ **(hours)**	**CI upper bound (hours)**
Scenario 10	$*\frac{11}{12}$	0.44	0.53	0.62
	$*\frac{5}{6}$	0.55	0.66	0.77
	$*\frac{1}{2}$	1.08	1.24	1.40

Probability of shipment cancellation

Table K.5 shows the mean order downtimes ($E[D]$) and their 95%-confidence bounds for scenarios 4 and 5, under decreased probability of shipment continuation (p_2, p_3). The column p_2, p_3 denotes the value adapted for probability of shipment continuation.

Table K.5: 95%-confidence intervals under higher probability of shipment cancellation

	p_2, p_3	**CI lower bound (hours)**	$E[D]$ **(hours)**	**CI upper bound (hours)**
Scenario 4	0.8	0.36	0.44	0.52
	0.7	0.40	0.49	0.58
Scenario 5	0.8	1.74	1.99	2.24
	0.7	1.98	2.26	2.54

L Base-stock level assessment sensitivity analysis

In this appendix we present the results on the base-stock level assessment procedure, performed as part of the sensitivity analysis, to evaluate whether the base-stock levels used in the case studies are underestimated. We use *Case study 2* to perform the analysis to, because this case study includes more uncertainties than *Case study 1.* The procedure is as follows: we select one SKU type, SKU 7 $\in \mathcal{M}$, to perform the analysis. We can apply it to solely one SKU type, since all failures happen independent of each other and SKUs cannot fail while a vehicle is already down due to failure of another SKU. We benchmark the base-stock levels of the scenario without AM capability (scenario 10) as the maximum base-stock levels. Subsequently, we run the simulation model for every scenario including AM capabilities, starting with the base-stock levels determined using the adapted heuristic, as presented in Section 4.5.3. Starting from the most downstream location, we incrementally increase the base-stock level $S_{j,m}$ ($j \in J, m \in \mathcal{M}$) by 1, until we reach the same base-stock level as our benchmark scenario without AM capabilities. The benchmark scenario results are presented in Table L.1. The results of scenarios 6, 7, 8 and 9 are presented in Tables L.2, L.3, L.4 and L.5, respectively. The columns show the various simulation model performance measures, plus the costs per order and the mean number of parts we manufacture using AM techniques. The red color shows which base-stock levels lead to lower vehicle readiness and/or higher operating costs when integrating AM. The green color indicates which adapted base-stock levels lead to similar or increased vehicle readiness compared to our benchmark scenario, at similar or lower total operating costs per order.

We can conclude that we indeed underestimated the base-stock levels. The base-stock levels of SKU 7 are reduced too much, resulting in lower vehicle readiness and higher operating costs. These results show that the total operating costs (also reflected through costs per order) can be reduced when including AM capability in every scenario, under (slightly) decreased base-stock levels, compared to the benchmark scenario. Note that the base-stock levels in the benchmark scenario are $S_3, S_2, S_1 = [6, 9, 12]$. When integrating AM in location 2, base-stock levels can be reduced to $S_3, S_2, S_1 = [6, 8, 9]$ (we initially used $S_3, S_2, S_1 = [6, 6, 9]$), regardless of the AM capability type. When locating AM capabilities in location 3, base-stock levels can be adjusted to $S_3, S_2, S_1 = [5, 8, 11]$ (we initially used $S_3, S_2, S_1 = [2, 8, 11]$), regardless of the AM capability type.

Note that, when including AM capability, slightly higher base-stock levels than we initially considered in our simulation scenarios yields even more relative cost savings per order, under similar or higher vehicle readiness. This phenomenon occurs as the downtime costs largely outweigh the unit holding costs. Now we solely consider one SKU type of one vehicle type. When including AM capability, base-stock levels may be reduced over multiple SKU types, over multiple vehicle types potentially inducing large (stocking) space gains.

Table L.1: Performance measures of scenario 10, benchmark scenario

S_3, S_2, S_1	**Vehicle readiness (%)**	$H_{total}[0,T]$ **(€)**	$F[0,T]$ **(€)**	$B[0,T]$ **(€)**	$C[0,T]$ **(€)**	**Total operating costs (€)**	**Costs/ order (€)**	**Mean number of AM parts**
6, 9, 12	99.99	1,255	270,904	5,046	0	277,205	409	0

Table L.2: Performance measures of scenario 6, under varying base-stock levels

S_3, S_2, S_1	**Vehicle readiness** (%)	$H_{total}[0,T]$ (€)	$F[0,T]$ (€)	$B[0,T]$ (€)	$C[0,T]$ (€)	**Total operating costs** (€)	**Costs/ order** (€)	**Mean number of AM parts**
6, 6, 9	99.97	977	273,544	12,449	22	286,992	420	6.05
6, 7, 9	99.98	976	273,152	7,766	15	281,909	413	4.01
6, 8, 9	99.99	974	272,416	4,953	10	278,352	409	2.65
6, 9, 9	99.99	977	270,832	3,140	7	274,956	406	1.87
6, 9, 10	99.99	1,073	271,244	2,290	7	274,614	405	1.79
6, 9, 11	99.99	1,170	272,560	3,619	7	277,356	407	2.00
6, 9, 12	99.99	1,265	273,560	2,908	8	277,742	406	2.24

Table L.3: Performance measures of scenario 7, under varying base-stock levels

S_3, S_2, S_1	**Vehicle readiness** (%)	$H_{total}[0,T]$ (€)	$F[0,T]$ (€)	$B[0,T]$ (€)	$C[0,T]$ (€)	**Total operating costs** (€)	**Costs/ order** (€)	**Mean number of AM parts**
2, 8, 11	99.92	1,113	274,028	36,935	592	312,667	461	161.64
3, 8, 11	99.97	1,123	273,172	14,891	223	289,409	426	60.87
4, 8, 11	99.97	1,133	272,668	12,992	85	286,878	422	23.31
5, 8, 11	99.99	1,142	272,628	4,819	38	278,628	409	10.48
6, 8, 11	99.99	1,153	274,712	3,221	23	279,108	407	6.18
6, 9, 11	100	1,160	271,876	1,951	12	274,999	405	3.39
6, 9, 12	100	1,255	272,416	1,766	17	275,454	405	4.55

Table L.4: Performance measures of scenario 8, under varying base-stock levels

S_3, S_2, S_1	**Vehicle readiness** (%)	$H_{total}[0,T]$ (€)	$F[0,T]$ (€)	$B[0,T]$ (€)	$C[0,T]$ (€)	**Total operating costs** (€)	**Costs/ order** (€)	**Mean number of AM parts**
6, 6, 9	99.97	978	271,676	14,300	34	286,988	423	4.25
6, 7, 9	99.98	975	272,786	7,506	27	281,276	413	3.32
6, 8, 9	99.99	975	270,072	3,924	18	274,989	408	2.19
6, 9, 9	99.99	980	270,004	3,814	15	274,812	407	1.86
6, 9, 10	99.99	1,073	271,084	3,103	12	275,272	406	1.54
6, 9, 11	99.99	1,169	271,244	2,757	13	275,183	406	1.60
6, 9, 12	99.99	1,264	272,096	2,378	11	275,749	406	1.37

Table L.5: Performance measures of scenario 9, under varying base-stock levels

S_3, S_2, S_1	**Vehicle readiness** (%)	$H_{total}[0,T]$ (€)	$F[0,T]$ (€)	$B[0,T]$ (€)	$C[0,T]$ (€)	**Total operating costs** (€)	**Costs/ order** (€)	**Mean number of AM parts**
2, 8, 11	99.95	1,113	271,328	21,401	1,001	294,844	438	124.71
3, 8, 11	99.97	1,123	272,780	14,224	381	288,508	424	47.41
4, 8, 11	99.98	1,132	274,488	7,741	169	283,530	414	21.01
5, 8, 11	99.99	1,143	270,812	2,820	75	274,850	406	9.40
6, 8, 11	100	1,153	271,352	1,451	36	273,992	404	4.49
6, 9, 11	100	1,159	272,212	1,013	28	274,413	403	3.49
6, 9, 12	100	1,255	271,688	586	24	273,552	403	2.99