

INTEGRATING ADDITIVE MANUFACTURING TO MILITARY MAINTENANCE

INTEGRAÇÃO DO FABRICO ADITIVO NA FUNÇÃO LOGÍSTICA MANUTENÇÃO

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Abstract

The aim of this study is to investigate what kind of conceptual model should form the core for simulation model studying Additive Manufacturing (AM) in the military logistics supply chain. The focus of the study is on the Armoured Personnel Carrier (APC) vehicles spare parts in the mechanized battalion. In the study, the conceptual model of the key functions of a mechanized battalion's two-level maintenance system with AM support was modeled. Polymeric printing was employed for field- and depot-level maintenance, and metal printing was utilized for depot-level maintenance. We found that the conceptual model is an important phase in the simulation when designing a system where the number of 3D printers at two maintenance levels supports military logistics. We found that system dynamics depend on the intensity of battles (spare part demand), maintenance concept, and the size of the parts to be 3D-printed. It is also clear that the original material of spare parts affects the ability of AM to support the maintenance system, which may change the inventory planning.

Keywords: Additive Manufacturing; Military Logistics; Maintenance; 3D printing; AM integration

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Resumo

O objetivo deste estudo é investigar que tipo de conceito deve servir de base para um modelo de simulação que integra o Fabrico Aditivo (FA) na cadeia logística militar. O foco do estudo são os sobressalentes de Viaturas Blindadas de Transporte de Pessoal de um Batalhão Mecanizado. Neste estudo, foi desenvolvido um modelo conceptual das principais funções dos órgãos de manutenção para apoio a um Batalhão Mecanizado com recurso ao fabrico aditivo. A impressão plástica foi utilizada para a manutenção Intermédia (em operações) e de Depósito, enquanto a impressão em metal, foi utilizada para a manutenção de Depósito. O modelo conceptual é uma etapa importante na simulação, para projetar a quantidade de impressoras 3D necessárias nos dois níveis de manutenção, para apoio da sustentação logística. Verificou-se ainda que a dinâmica do sistema depende do nível de intensidade das operações (necessidade de sobressalentes), do conceito de manutenção e do tamanho das peças a serem fabricadas através de fabrico aditivo. Por fim, verificou-se que as propriedades das peças a fabricar, nomeadamente as características dos materiais, podem afetar a capacidade de o fabrico aditivo apoiar os órgãos de manutenção, podendo influenciar a definição das listas de sobressalentes.

Palavras-chave: *Fabrico Aditivo; Logística Militar; Manutenção; Impressão 3D; Integração do fabrico aditivo*

1. Introduction

Military logistics plays a crucial role in the execution of military operations (NATO, 2012; Zeimpekis et al., 2015; Minculete & Tutuianu, 2017). Through logistical functions, the combat capability of forces can be maintained and developed in accordance with the requirements of the operational environment (Black, 2021). Logistics has been described as the "bridge between military operations and the national economy" (Eccles, 1959). Logistics can be said to involve continuous support to the forces in various ways. With the advent of new technology, supporting the forces can be achieved in ways that were not previously possible. One such technology is additive manufacturing (AM), also known as 3D-printing.

In the Ukrainian war, there is a constant need for spare parts. The shortage of spare parts can lead to a diminished operational capability of the affected forces (Brewster, 2023). The use of additive manufacturing can enable the acquisition of spare parts when they are otherwise unavailable (Stevenson, 2023). As a result, several 3D printing devices have been donated to the Ukrainian conflict, aiming to address the challenge of spare parts availability and thus enhance the performance of the forces in battle (Harper, 2023).

In regards of the Ukrainian war and other sizeable military logistics operations it is crucial to acquire more information on the impact of the AM-technology. To this end the research question of this study is – what kind of conceptual model should form the core for simulation model studying additive manufacturing in the military logistics supply chain?

In Europe, several armed forces are adopting or planning to adopt AM (Department of Defence (DOD), 2021; Kremenetsky, 2022; Wood, 2020; Bundeswehr, 2022). The European

Defence Agency is conducting research to support the implementation of AM in member countries (European Defence Agency (EDA), 2024). NATO is finalizing a study that explores the method's use in NATO operations (NATO, 2024). The method can support the development of new military innovations, such as drone production (Goh et al., 2017), body armour (Peck, 2019), sensor production (Bird & Ravindra, 2021), and robotics (South, 2018). Another significant application is leveraging the method's features to enhance logistics in areas such as spare parts production (Knofius et al., 2021; Mustoe, 2023; Salmi & Pei, 2023), medical components (Gimbel, 2020), and the manufacturing of specialized components and tools (Blakey-Milner et al., 2021).

In recent years, the ability of additive manufacturing to support military logistics operations has been of interest to various armed forces (Rautio & Valtonen, 2022; González & Álvarez, 2018; Bundeswehr, 2022). One focus has been on producing spare parts for maintenance purposes. This approach aims to improve material availability by quickly restoring faulty or damaged systems back into service for deployed forces. Previous research has identified that additive manufacturing is suitable for decentralized, on-demand single-unit production, allowing the direct production of spare parts according to the needs of the armed forces (Khajavi et al., 2014). There are varying results regarding the production speed of the method (Zijlstra et al., 2022; Rautio & Valtonen, 2022), largely dependent on the operational environment in which the 3D-printing is conducted. Therefore, the impact of the quantity of produced items on performance and the overall system's availability has received less attention in the research.

The capability of logistics can be examined by recognizing that its performance depends on the resources used for its execution and the planning, management, handling, and utilization of these resources (Kress, 2000). Based on this definition, logistics can be viewed as a system, and its components can be considered subsystems that can be modeled. With a focus on maintenance capability, the impact of additive manufacturing on the availability of systems can be assessed.

In a previous study (Rautio & Valtonen, 2022) we explored through simulation how metal material additive manufacturing can support the field-level maintenance of a mechanized battalion in the two-level maintenance system. In this previous research, it was observed that the primary factor influencing the utility of using metal 3D-printing in maintenance is the slowness. The study found that, relative to the number of troops available to potentially use 3D-printers, it is not possible to operate enough printers at once in the field level maintenance to meet the needs of the troops. Drawing on the findings of previous research, we sought to determine whether greater advantages in maintenance could be realized by positioning metal 3D-printers at the depot level of two-level maintenance and polymer 3D-printers at the field level. This expansion two-level maintenance was the key motivation for this study.

The operational tempo of the operations and the nature of the battles create demands on maintenance. It creates demands also on the capabilities of 3D-printing, when the challenges of spare parts availability are addressed by printing parts directly to meet the needs. (Rautio & Valtonen, 2022)

Based on previous research, we have identified that the use of additive manufacturing at both levels of two-level maintenance is a more complex entity than the previously studied

support of the field-level maintenance level with metal 3D-printing. Therefore, we have decided to use conceptual modeling as the method in this study. In this way, the most essential factors that affect the simulation of the system can be determined. Conceptual modeling is an important stage in modeling and based on it, the final computational model can be coded with which the simulations can be carried out.

The key result of this study was that when modeling additive manufacturing as part of the maintenance and repair in the conceptual modeling phase of a mechanized battalion the following should be created: a failure model, model for maintenance process, model for inventory and its replenishment by Additive Manufacturing. These models allow us to identify the impact of the severity of the battles in relation to how the battalion obtains spare parts for its failing systems and how additive manufacturing can support this spare parts acquisition at two levels. The result of the study is a model and its parameters that can be used to code the model for mathematical simulation.

There has been disagreement among those involved in military additive manufacturing, from capability building, operational planning to those implementing operations, about where additive manufacturing equipment should be located in the logistical chain. 3D-printer manufacturers, original equipment manufacturers (OEM) of military systems, and 3D-printing service providers have their own views on what kind of equipment and where 3D-printers in military use should be located. In this study presented model can be used to make better informed and more rigorous assessment on additive manufacturing in military logistics.

The article is structured as follows. The next chapter discusses military maintenance. In the third chapter, additive manufacturing and its fundamentals are addressed. Chapter four presents the method used to create conceptual model of additive manufacturing and model created in the research. In the following chapter, chapter five provide a discussion and conclusions drawn from the results.

2. Theoretical and conceptual framework

2.1. Military Logistics

Historically, military logistics has been in existence for hundreds of years. The term "logistics" is context-dependent in its usage. It was first coined in 1846, deriving from the French word *logistique*. The military significance of the term was established by Antoine-Henri Jomini, an officer and writer in Napoleon's army, who defined it for the first time in his book: *Précis de l'Art de la Guerre*, in its 1830 edition. Jomini adapted the word from its French language origin, *logis*, meaning "lodging" or "quarters." Originally, its definition encompassed "the skill of organizing the army's operations, coordinating the order of troops in columns, their departure times, travel routes, and communication means necessary to ensure their arrival at a designated location." (Jomini, 1841).

Even in the early times preceding Jomini, fundamental aspects of logistics can be identified, primarily in the form of material transportation and storage. It is evident that the storage of food, in addition to military logistics, influenced the development of humanity (Black, 2021).

In its early stages, the term logistics was associated with only two distinct functionalities: transportation and storage (Topolšek et al., 2018).

The North Atlantic Treaty Organization (NATO) definition for military logistics is: "the science of planning and carrying out the movement and maintenance of forces – logistics covers the following areas (NATO, 2020):

- design and development, acquisition, storage, transport, distribution, maintenance, evacuation and disposal of materiel;
- transport of personnel;
- acquisition, construction, maintenance, operation and disposition of facilities;
- acquisition of provision of services;
- medical and health service support"

Logistics can be categorized in various ways. The services presented above are divided by NATO based on the operational environment into "production logistics, in-service logistics, and consumer logistics" (NATO, 2012). To facilitate the execution and organization of military logistics, it is common to categorize logistics into functions. This assists operators in understanding the responsibilities associated with each part of logistics. (Pääsesikunta, 2014) NATO's functionalities are divided into twelve different parts: Supply, "Materiel, Services, Logistic Information Management, Equipment, Maintenance and Repair, Movement and Transportation (M&T), Reception, Staging and Onward Movement (RSOM), Infrastructure Engineering for Logistics (IEL), Medical Support, Contractor Support, and Host Nation Support (HNS)" (NATO, 2012). In the context of additive manufacturing, it has been recognized that it can be utilized for the production of spare parts (Salmi & Pei, 2023). While the method may have other functions, this study specifically focuses on its role in the maintenance and repair function within military logistics. A closer examination of maintenance and repair allows for the assessment of the use of additive manufacturing in its functions.

2.2. Maintenance

Maintenance techniques is classified according to the European standard (SFS-EN 13306:2017, 2017) into corrective maintenance and preventive maintenance. The goal of preventive maintenance is to keep equipment in working order for as long as possible before it fails or breaks down. The goal of corrective maintenance is to repair failed systems and thus return them to use as soon as possible. Predictive maintenance can be seen as a separate maintenance technique in which the need for maintenance is predicted and the measures are related to the prediction (Mustafa, 2021).

Table 1 – Maintenance techniques

	Corrective Maintenance	Preventive Maintenance	Predictive Maintenance
Status of equipment	Malfunction	Malfunction	Working of malfunction
Reason of Maintenance	Fault	Planned inspection	Planned control
Maintenance Tasks	Replace of components	Downtime to maintenance, inspect and replace	Service
Purpose	Return to work	Working for period	Predict and detect faults

Source: Adapted from Mustafa (2021)

The definition of maintenance in NATO includes repair. Therefore, NATO's term encompasses both maintenance and repair, and in NATO operations, these are integrated. The NATO Logistics Handbook (2012) defines that these activities involve: "all actions, including repair, to keep or restore material to a specified condition. The operational effectiveness of land, sea, and air forces largely depends on the high level of preventive maintenance of equipment and related supplies during peacetime. Repair includes all actions taken to restore material to a usable condition as quickly as possible" (NATO, 2012).

Maintenance refers to keeping the material in operational condition and, if it malfunctions, restoring it to operational status as quickly as possible (Headquarters, Department of the Army, 2020). Maintenance functions encompass actions directed towards the material by various operators (Wilson, 2018). The effectiveness of forces in modern warfare is highly dependent on functional equipment (Antai et al., 2024). Therefore, efficient maintenance enables the operational readiness of forces in battles.

In accordance with the above definitions, this study examines corrective maintenance. In military maintenance, it refers to expedient repair activities, in which military systems are brought to a state where they can perform the military function specified for them. This includes the repair of battle damage, or Battle Damage Repair (BDR) (NATO, 2009).

The importance of maintenance is understood very similarly in different military organizations. On the one hand, the reason may be the similarity of functions, on the other hand, the standards in which maintenance is defined. In the common European standard, maintenance is a comprehensive function and is defined as: "Maintenance is the set of all technical, administrative and management-related measures, the purpose of which is to maintain the object in a state or return it to a state where it can perform the required function during its entire life cycle" (SFS-EN 13306:2017, 2017).

Military maintenance is divided into different levels. In a two-level maintenance system, the levels are classified as field and depot maintenance, shown in Figure 1 (Wilson, 2018). The purpose of field maintenance is to quickly repair malfunctioned systems back to troops. Field maintenance involves typically smaller maintenance actions, organizational and system-specific maintenance and repairs required for daily operations. At this maintenance level, intermediate repairs to weapon systems and components, as well as external repairs, can be performed. Field level maintenance is typically "less complex than depot level maintenance, serving as a link between strategic readiness and tactical requirements" (CJCS, 2019).

DEPOT – LEVEL MAINTENANCE		FIELD – LEVEL MAINTENANCE	
Industrial	Workshop	Intermediate	Organizational

Figure 1 – Maintenance system and levels

Source: Adapted from Pääesikunta (2014)

Depot level maintenance is tasked with providing maintenance for material requiring significant refurbishment or complete replacement “of parts, assemblies, subassemblies, and end items”. At this maintenance level, there may be a need to manufacture spare parts, make modifications, test, and if necessary, dispose of them, as well as serve as a distribution point for exchange items to field maintenance (CJCS, 2019). Depot level maintenance supports field level maintenance “by providing technical assistance or performing maintenance tasks” within its responsibility. Depot level maintenance collaborates with both industry and military operations. It also includes manufacturing and modification of new components. The demands of military operations require increasingly rapid logistical support. (NATO, 2012; US ARMY, 2014; US ARMY, 2013a)

The Ukrainian war has shown that military logistics has a significant impact on the execution and, above all, the success of operations. Skoglund et al. (2022) have examined the logistics of the Ukrainian war, analyzing both Russian logistical operations and Ukrainian countermeasures. Their conclusion was that the Ukrainian armed “forces understood the importance of Russian supply lines” and were able to act against them by combining traditional technology with innovative tactics. This significantly hindered the execution of Russia’s “special operation” (Skoglund et al., 2022). This implies that supply lines “will play an increasingly” significant “role in future” military logistics.

In maintenance, especially at the field level, the primary principle is either replacing the entire damaged subsystem or parts with damaged material. In the traditional maintenance model, the performance of maintenance depends on the openness of supply lines. To keep supply lines open, they must be protected. This requires the integration of operational logistics into the operational planning process. Operational planning must consider the constraints of operation execution, the operating environment, and time factors. Grau and Bartles (2016) argue that this factor has been crucial for the success of logistical operations (Grau & Bartles, 2016). Skoglund et al. (2022) identify that the flexibility of logistics is crucial in supporting operations through military logistical measures. This is also supported by the findings that the polycentric defence model can support operations in different areas of warfare, including logistics. In the polycentric defence model, flexibility and adaptability enable the planning and implementation of operations where the need arises. In addition to direct military capabilities, commercial local actors and volunteers can be utilized for this (Alshamy et al., 2024). Without spare parts or the ability to repair damaged components, maintenance relies on the cannibalization of damaged equipment (Ormon & Cassady, 2004).

The use of spare parts can be based on spare parts inventories, on-hand maintenance reserves, or manufactured for special need (NATO, 2012). Typically, spare parts inventories are made during the material acquisition phase. Post-material acquisition, spare parts are often produced through outsourcing. Original Equipment Manufacturer (OEM) may not necessarily guarantee the availability of spare parts. This is often related to different versions of systems and associated obsolescence issues (Department of Defense, 2006). This characteristic differs from civilian material acquisition, where spare parts production typically relies on outsourced spare parts manufacturing and the absence of intermediate storage, resulting in the user having minimal spare parts inventories (GAO, 2005).

Previous studies have shown that additive manufacturing can produce spare parts for military systems (Khajavi et al., 2014; Rautio & Valtonen, 2022). These examples are anecdotal and do not directly demonstrate that additive manufacturing can widely produce spare parts for systems. In previous research, we have identified that the need for spare parts in a typical mechanized battalion battle can be so significant that additive manufacturing may struggle to meet that demand (Rautio & Valtonen, 2022).

The need for and use of spare parts is environment-dependent (NATO, 2012). The requirements imposed by the military operational environment necessitate exceptional flexibility in supply lines. In a military operational environment, the use profiles of systems can significantly differ from normal use cases. This may result in the need for battle damage repair (BDR) to be performed on systems. In these repairs, systems are aimed to be restored to combat capability by any means necessary. The military operational environment poses challenges in predicting system wear and the severity of damage caused by kinetic effects. Therefore, forecasting consumption complicates production planning (Pan & Nagi, 2010).

2.3. Additive Manufacturing

Matt Audette from US Marine Corps (2023) says:

In a nutshell, additive manufacturing is a game-changer for the Marine Corps. It allows us to repair equipment and innovate solutions right on the frontline. With its smaller footprint and easy-to-use technology, we can construct essential components right on the battlefield, making us nimbler and more responsive in any combat scenario.

Manufacturing can be divided into the traditional manufacturing and advanced manufacturing (Pereira et al., 2019). Traditional manufacturing can be described as: "the act of converting raw materials into finished products by using manual or mechanized transformational techniques" (Thareja, 2012). Different sources classify traditional manufacturing methods in different ways. Schuhmann (2022) classify methods by forming, separation, joining, and coating. These could be subclassified into a way where forming includes e.g. casting, deep drawing and stamping, separation includes all subtractive processes and coating includes spraying (Schuhmann et al., 2022).

Swift & Booker (2013) groups processes into categories such as casting, cutting, forming, and fabrication. Kalpakjian & Schmid (2020) organizes processes into categories like

casting, machining and finishing, joining, sheet metal work, polymer processing, and bulk deformation methods. One way to classify traditional manufacturing is: forming, welding and joining, machining by powder metallurgy and additive manufacturing (Narayanan & Gunasakera, 2023). A commonly used advanced manufacturing definition by President's Council of Advisors on Science and Technology (PCAST) (2011) is:

[...] a family of activities that (a) depend on the use and coordination of information, automation, computation, software, sensing, and networking, and/or (b) make use of cutting-edge materials and emerging capabilities enabled by the physical and biological sciences, for example, nanotechnology, chemistry, and biology. This involves both new ways to manufacture existing products, and especially the manufacture of new products emerging from new advanced technologies”.

Like Traditional Manufacturing, Advanced Manufacturing Processes and Technologies are defined different ways in different sources depending on the purpose. Zhong et al. (2017) categorize advanced manufacturing as following: “intelligent manufacturing, IoT-enabled manufacturing, and cloud manufacturing”. Chen (2017) divide Advanced Manufacturing to ten major technologies: 3D Printing, “Robotic Automation, Advanced Materials, Virtual reality, Industrial Internet, Cyber-Physical Systems”, “Big Data analytics, Cloud Computing, Applications and Mobile Devices”. Purpose for all Advanced Manufacturing technologies is to offer flexibility to lean manufacturing production. Advanced Manufacturing try to simplify supply chain and offer possibilities to single unit and very low-volume production with cost effective way (Pereira et al., 2019).

Additive Manufacturing (AM), commonly known as 3D printing, as a one of Advanced Manufacturing method, can open new possibilities for military logistics. AM is not just a single Advanced Manufacturing method, but a set of manufacturing methods that follow the same basic principle (Gibson et al., 2015). Like in other Advanced Manufacturing technologies, Additive Manufacturing is based on digital definition. Its distinctive feature, as per the definition, is to manufacture components by adding material, typically layer by layer, opposite to subtractive methods (ISO/ASTM 52900:2017, 2017).

The technologies of Additive Manufacturing are classified into seven main categories. These categories include “binder jetting, direct energy deposition, extrusion, material jetting, powder bed fusion, sheet lamination, and vat photopolymerization”. All emerging technologies and their combinations in Additive Manufacturing are classified into these categories (ISO/ASTM 52900:2017, 2017).

In Additive Manufacturing, the materials used greatly influence the applications for which components manufactured by the method can be used. Materials for Additive Manufacturing have advanced rapidly in recent years (Kanishka & Acherjee, 2023). Materials are typically classified into three categories: polymers and their composites, metals and their composites, and ceramics and ceramic composites. The most common printing materials are typically polymers and composites, as well as metals (Wohlers et al., 2021).

All 3D printers within the Additive Manufacturing seven main categories can print all the main material classes mentioned above. However, that does not mean that all systems can

print all materials. Typically, one type of material requires a manufacturing device specifically developed for it (Gibson et al., 2015).

3D printing devices can be classified into industrial-grade printers and non-industrial-grade printers. The division can be made based on various criteria such as the printer's build volume, production speed, manufacturing materials, or the printer's price (3DGENCE, 2023). Additive manufacturing can thus be either industrial production or the in-house production of an individual operator depending on different factors. Typically, non-industrial printers for individual or consumer operators are small, relatively inexpensive devices ranging from a few hundred to a few thousand dollars. These printers are typically operating with the extrusion method, which prints plastic materials from filaments. Other possible easily portable printers include machines using the vat photopolymerization method, although they require more tools for post-processing (Gibson et al., 2015). Military operators such as the United States Marine Corps (Michael, 2023), the German Bundeswehr (Bundeswehr, 2023), and the Dutch Armed Forces (Chemtron Pte Ltd, 2019) also utilize these tools. In the war in Ukraine, parts for various military needs have been produced using such printers (Feldman, 2022).

Industrial grade 3D-printers are typically larger, and their processes can involve a wider range of different materials (Gibson et al., 2015). These may include various metal alloys, more durable polymers, and bio-organic substances (Wohlers et al., 2021). In addition to the most commonly used metal materials such as titanium, aluminium, and stainless steel, other metals and their alloys have also become more prevalent as printing materials (Shi et al., 2021; Korpela et al., 2020). In addition to metals, industrial-grade devices can print a wide variety of polymers such as "Polyether Ether Ketone (PEEK), polyetherimide (ULTEM), acrylonitrile butadiene styrene (ABS), nylon, and polycarbonates (PC)" (Balaji, 2024). Industrial printers have been used by the Australian Defence Force to support their land and naval forces (Sertoglu, 2021; Burnett et al., 2018). Western countries have donated industrial-grade 3D printers to Ukraine to aid in warfare (Harper, 2023).

Additive manufacturing has evolved rapidly (Korpela et al., 2020). When examining the manufacturing industry, the method is quite new, making it difficult to predict its future development. The expiration of key patents in the 2010s and the significant increase in computing power have facilitated the method's use and the discovery of application possibilities (Gibson et al., 2015). The development of additive manufacturing as part of the manufacturing industry's evolution is illustrated in Figure 1.

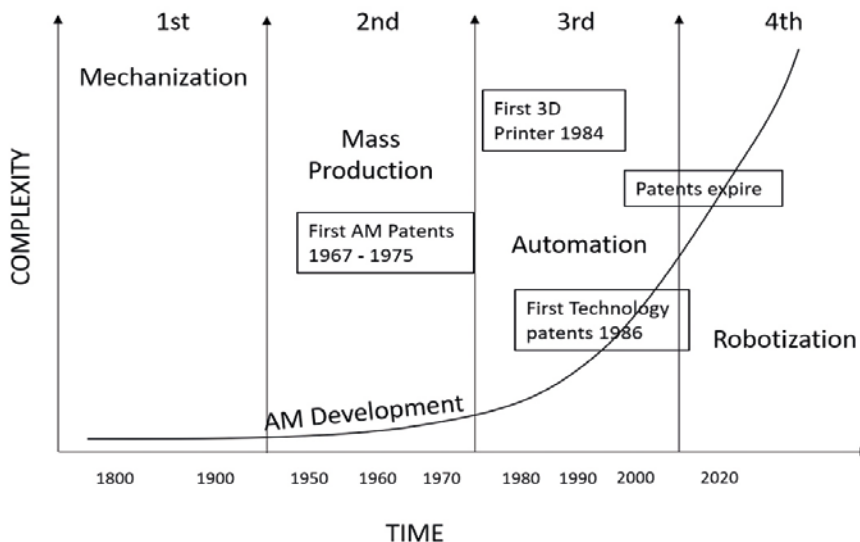


Figure 2 – Additive Manufacturing Development through industrial revolutions

Source: Adapted from Wohlers & Gornet (2016); Gibson et al., (2015)

The use of additive manufacturing for military purposes has not yet been fully established. The United States military has developed a roadmap and strategy for its use (Department of Defence, 2021). Most militaries are still in the experimental and testing phase. Some countries have made decisions regarding the method's usage and the integration of equipment into normal operations (Bundeswehr, 2022; Kremenetsky, 2022). Typically, AM is used in spare parts manufacturing and damage repair. The range of spare parts in military operations is extensive, leading to a variety of materials being used. Although metal additive manufacturing has been identified as crucial for military use, there is an increasing need to also consider the use of plastic materials in military settings (Rautio, 2023).

Earlier studies have shown that both metal and plastic additive manufacturing techniques can be employed to produce spare parts for armored personnel carriers (Rautio & Valtonen, 2022). Example parts are depicted in Figure 3. Previous research has also investigated the factors influencing the placement of metal 3D printers in a two-level maintenance system. The study identified that metal 3D printing has limited capabilities to support maintenance of a mechanized battalion-sized unit in combat missions at the current maturity level of the technology. The primary reason is that the speed of metal printing devices is insufficient to produce parts in the quantity required to have a meaningful impact on maintenance (Valtonen et al., 2022). The ratio of metal to plastic spare parts in the investigated MT-LB armored personnel carrier was approximately 1:20, with metal being the predominant material (МТЛБРУС, ООО, 2017).



Figure 3 – Additively Manufactured spare parts (polymer and metal) to Mechanized Battalion Armored Personnel Carrier (APC)

3. Methodology and method

Conceptual modelling means building a blueprint for a simulation model for the system under study. It “is probably the most important aspect of a simulation study while also the most difficult and least understood” (Robinson, 2008a). He defines it as: “*a non-software specific description of the computer simulation model (that will be, is or has been developed), describing the objectives, inputs, outputs, content, assumptions and simplifications of the model.*”

Conceptual modeling typically involves simplifying real-world complexities, and in the absence of reference data, it often relies on assumptions and informed guesses. Without such simplifications and assumptions, the model would essentially be a replica of the real system rather than an abstraction. When the problem situation is not well understood or clearly defined, the goal should be less about achieving accuracy in the conceptual model and more about using it as a tool for discussion and fostering a shared understanding of the problem (Robinson, 2008b). Robinson (2008a) suggested that a conceptual model must meet four key criteria: validity, credibility, utility, and feasibility. Naylor and Finger (1967) presented a three-step simulation model validation process including a face validity check by knowledgeable persons, model assumptions validation and comparing model input-output transformation to the real system known as the correlated inspections approach. As the last one is not possible in this case even when the simulation results are at hand, this leaves face validity and assumptions validation as validity criteria.

Understanding its implementation requires an in-depth analysis of its related sub-assemblies, which differ from typical industrial applications of AM. Specifically, the demand

for military system components, combined with the time constraints of military operations, can easily lead to errors in production decisions. The interactions between these sub-assemblies influence how AM should be integrated into a military logistics system. However, testing these sub-assemblies and their interactions in real-world scenarios would be extremely challenging. Beyond AM capability itself, a military system and various operational functions that impact its use would also be required. For this reason, modeling serves as the most viable approach to investigating the factors influencing AM integration in military logistics.

Conceptual modeling offers several key benefits, particularly in understanding complex systems. It helps structure information in a way that facilitates the design and development of systems using existing data. Additionally, conceptual modeling serves as an effective communication tool between different stakeholders (Thalheim, 2010). In this study, communication plays a crucial role in developing the model. Conceptual modeling helps convey key factors that military capability developers must consider when making decisions about additive manufacturing. One of its primary benefits is supporting decision-making by providing a clear and structured representation of the modeled phenomenon (Thalheim, 2010).

Different conceptual modeling methods can be used to generate information based on specific needs. Common modeling methods include the “Entity-Relationship Model (ERM), Unified Modeling Language (UML), Workflow Modeling, Event-Driven Process Chains (EPC), Statechart Diagrams, Data Flow Diagrams (DFD), Object Role Modeling (ORM), Structured Charts”, Rapid Application Development (RAD), Structured Analysis (SA), and Petri Nets. These methods can be used individually or in combination, depending on the objectives of the modeling process. (Fettke, 2009) The primary modeling approach used in this study is Event-Driven Process Chains (EPC). This approach enables the creation of a model that considers the effects and relationships between different activities and their corresponding events within the activity chain, presenting them in a logical sequence.

The aim of this model is to serve as a basis for computational discrete event simulation in addition to communication. David W. Embley et.al. (2011) discusses the conceptual model as programming: “A conceptual model is code”. The premise of this argument is that when creating a model, the model compiler ensures that the conceptual specification is sufficiently precise to enable software computation to be performed on it. This means that the model must be sufficiently complete and comprehensive to adequately represent the parts of its environment. The model must describe structure, functions and interactions. In addition, the model must be conceptual but precise (Embley et al., 2011).

Robinson (2008a) defines four key “requirements for a conceptual model: validity, credibility, utility, and feasibility”. He also emphasizes the importance of simplicity in the model (Robinson, 2008a). To evaluate the requirements presented by Robinson in his study, they must be examined more closely. Feasibility can be demonstrated through the creation of the mathematical model – that is, when the model can be coded for simulation with software. Credibility arises from experts agreeing that the model accurately represents what it is intended to describe. The usefulness of the model is proven when the information it produces can be utilized for its intended purpose. Among Robinson’s requirements, validity is the most

difficult to prove. There are many factors related to validity, specifically how accurate the model is. Robinson (2019) identifies three key challenges in creating a conceptual model for a discrete event simulation. These factors significantly impact both the validity of the model and the evaluation of its validity. The first factor is the conceptual model itself. The creator's experience and their understanding of the phenomenon underlying the model often play a critical role. The second factor is the model's framework. Developing a framework helps define the most important elements of the model. The third and final challenge is the presentation of the model. The ability to present the conceptual model in a clear, comprehensive, and communicative manner influences its validity (Robinson, 2019).

In this study, the impact of AM on military maintenance operations is investigated through conceptual modelling. A conceptual model is created to represent the capabilities of military logistics maintenance, additive manufacturing, and the failure of systems within a mechanized battalion in various combat scenarios. Based on the model, the system's operation is simulated, and conclusions are drawn from the simulation about how AM alters maintenance and what factors related to printing capacity should be considered when planning the use of additive manufacturing.

As presented in the previous chapters, military logistics – more specifically, maintenance and repair – is context-dependent; therefore, examining it at a general level is not meaningful. The relevant context provides an opportunity to analyze in more detail the factors that affect the implementation of logistics. For the purpose of dimensioning and comparing capabilities, we have created a model in this conceptual study, following the same principles used in previous studies on the maintenance of a mechanized battalion.

4. Presentation and discussion of the results

The model focuses on the availability of armored personnel carriers (APCs) in a mechanized battalion under war-like battle conditions. We create a conceptual model to examine the supply chain factors influencing the battalion's maintenance capability, incorporating both field and depot-level maintenance, in alignment with standard NATO logistics practices (NATO, 2012).

The model consists of three sub-models: the Model for Battle Damages, the Model for the Maintenance Process, and the Model for Inventory and Its Replenishment by Additive Manufacturing. By integrating these sub-models into a single conceptual model, the most critical functions within the overall system can be identified. The sub-models facilitate simulation and calculation. Adjusting their parameters to reflect different scenarios allows Additive Manufacturing to support case-specific two-level maintenance.

The model excludes supply from higher-level logistics centers, as it assumes a high-intensity battle lasting approximately two weeks (15 days), during which the mechanized battalion must be self-sufficient. Additionally, we focus only on parts that can be manufactured using additive manufacturing (AM) and exclude others when analyzing AM integration into military maintenance.

4.1. Model for battle damages

There are two aspects in battle damages in the conceptual model. The first is the battle intensity (BI) that determines the proportion of damaged APCs i.e. how many APCs are damaged each day. The second is the extent of damages that determines whether it can be repaired and if so, at depot or field level. When modelling the battle intensity, the assumption is that the use of APCs is constant and therefore damaged APCs are proportional to available APCs. The other possibility would be a constant transport need, constant number battle damages and increasing APC utilisation with diminishing availability. Damages can be modelled e.g. by each day, for each available APC randomizing if it is damaged with BI probability and pacing damage occurrence randomly across the day. The battle intensity is seen as a decision variable in the model.

For the damaged APCs, the extent of damages is modelled so that 10% are destroyed; 20% suffer heavy damage and require depot-level repair and finally, 70% receive light damage that is repaired at the field level. The estimation of the damage extent to APCs in battle is derived from previous studies on the battle damage experienced by armored units (Peltz et al., 2004). Lightly damaged APCs are repaired at the nearest field level location. As there are three locations, the individual lightly damaged APCs arrive at field level maintenance location with a randomised chance 1/3 for each. To our knowledge, there is no publicly available data on what and how many parts are damaged especially with MT-BL.

For APCs with minor damage maintained at the field level, there were five metal spare parts, each with a 50% probability of being damaged, and two plastic parts with a 25% chance of damage. Heavy damages were modelled 20 metal spare-parts that each had a 50% chance of being damaged and two plastic parts with 50% damage probability. The 50% chance means that damage to any part is independent of that to other parts. The numbers of parts were greatly reduced from the actual number of parts while having a rather high value for part damage. This was done with the idea simplifying the model while still gaining knowledge of the effects of decision variables. Finally, it must be noted that deep uncertainty remains regarding extent of damages as well what parts and how are damaged in an actual conflict because of e.g. the tactics, enemy weaponry and terrain.

4.2. Model for maintenance process

The extent of damages determines the maintenance level. Destroyed APCs cannot be repaired while heavy damages are repaired at depot level, and light damage can be fixed at field level maintenance. The model of the process in Figure 4 contains one field-level depot and three geographically separate field level maintenance facilities.

When a damaged APC arrives to maintenance it is checked whether all damaged parts, both metal and plastic, are available in the stock. If any part is missing, the APC will wait until all parts are available and then reduces the inventory for each damaged part. The APC is moved into repair or, if every lot is occupied, queuing until a lot is vacated. We exclude the possibility of using damaged or destroyed APCs as a source of spare parts for other APCs, even though this is sometimes observed in practice.

Each of the three field-level maintenance stations has three repair lots, while the depot level has ten lots. The repair times for the APCs are fixed at 4 hours for field-level maintenance and 20 hours for depot-level maintenance, regardless of the number of parts that are actually damaged. Field-level maintenance should be performed in six hours and if the repair need is more extensive, it is repaired at depot level. Repair times are informed by Kunnessapito-opas (2003). In reality, repair times are variable within limits but are here modelled as averages for simplicity. Maintenance personnel were excluded from the modeling because personnel availability is not considered a constraint.

There is no transport time at the field level, because the material is maintained directly near the point of failure. Heavily damaged APCs need to be towed to the depot-level maintenance, and being located in the rear, there is transport time back and forth. Transport time to the depot level is modeled as a constant 20 hours, with another 20 hours for the return trip to the battlefield. This is based on the operational area's depth and width of the mechanized battalion, as well as the estimated distance from the frontline to the rear.

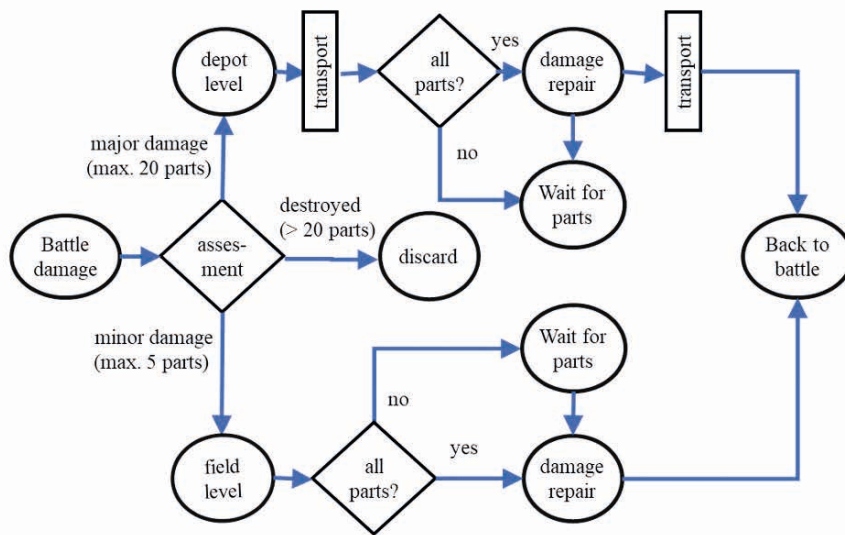


Figure 4 – Maintenance Process Flow

4.3. Model for inventory and its replenishment by additive manufacturing

There is an initial inventory for all parts in both depot level and each of the three field level units. Even though there are defined levels for spares inventories, it is hard to know their status at the beginning of the battle as they may have been depleted prior to the start of the battle i.e. modelling start. Moreover, the AM would not be needed if there were unlimited amount of initial inventory, but this is not the case due to costs.

Initial inventories of metal and plastic parts at field and depot level are modelled through specifying the initial inventory level in expected Days-of-Supply (DoS). Days of Supply (DoS)

levels are translated to amount of initial inventory by calculating the expected daily spare parts requirement with 77 APCs and medium battle intensity, maintenance level and 50% damage likelihood. As the damage likelihood is equal (50%) for each part (except for 25% of field level plastic parts), the initial inventories are set equal for all parts in that instance which is based on more perfect i.e. unbiased estimate of damage between parts. This kind of information is not available in advance of real scenario. The initial inventory is modelled as a decision variable.

The polymeric printing is located both at field level and depot levels as the machines are of low acquisition cost. The metal AM machine capability is only at depot level as they cost more. Metal parts can be ordered to replenish field level depot inventory with a 20-hour transport time of finished parts to field level. Part manufacturing times are based on our previous study (Valtonen et. al., 2022). The AM capacity i.e. number of machines, is a decision variable in the model. Each inventory is replenished from its AM machines with a lot-for-lot control. As the model period is two weeks, it would be optimal to draw down the inventories during the period. However, as this duration may not be known in advance, we order immediate AM replenishment for each part that is consumed. As AM lot size is one, the reorder lot size is also one. For metal parts transports to field level there probably could be some transport lot size but this is omitted.

4.4. Model decision variable and their values

Decision variables describe those factors whose values can be influenced within certain limits. In our model, the decision variables are the intensity of fighting, the capacity of additive manufacturing, and the level of the initial spare parts inventory:

- The Battle intensity (BI) is modelled with following values of low (10%), medium (20%) and high (30%) proportion of damaged APCs out of those that are in use during that day.
- AM capacities can have the following values: no AM capacity at the field level, baseline capacity (seven metal AM machines and one plastic AM machine), high capacity of five times baseline.
- Initial inventory levels with values of (DoS 2), medium (DoS 4) and high (DoS 8) that should be calculated based on medium BI scenario.

4.5. Performance measures and outputs

The model includes the following performance measures that inform about the relative quality of each scenario or combination of decision variables in each model run:

- The time it takes to reach availability under 50 % i.e. how long mechanised battalion has at last 39 APCs in use and not destroyed, in or waiting for repair or in transportation. This is the main performance measure of the model and is based on assumption that with 50 % losses capability is seriously reduced.
- How many APC days are available can be calculated by simply summing the available APCs for each day.

As outputs that illustrate the model performance and help in verifying the results, the following are used:

- The inventory levels in total as well as by individual part inventories.
- The AM queue levels.

4.6. Discussion

Using the conceptual model, a simulation model may be developed with which various scenarios of how the method can be evaluated at different maintenance levels. Such a simulation model can provide maintenance systems with information on the implications of AM for spare parts logistics for each stakeholder. Through simulations, decisions can be made regarding the adoption of additive manufacturing. These simulations can guide technological choices regarding the types of 3D printers and materials to be used at each level of maintenance.

Although previous research shows that additive manufacturing can produce individual spare parts, our conceptual model suggests that its implementation in maintenance supply chains is influenced by multiple factors. Through conceptual modelling the following key model performance factors and sources of uncertainty were identified:

- Initial spare part inventories that together with the other battle variables determine the need for AM manufactured spare parts.
- APC Battle Damage model and the battle intensity together determine maintenance requirements, there is very high uncertainty regarding both of these variables. For example, initial data for faults other than normal wear are difficult to define, and uncertainty is high.
- Additive Manufacturing capacity is determined by the number and speed of the individual machines as well as features of the parts. While features of the parts can be studied the number and speed of the machines are decision variables but they also contain uncertainty in practical battalion battle conditions.

Regarding the choices made in the model, it has been recognized that they are partially system-dependent and not directly applicable to other countries with different maintenance concept. Therefore, the conceptual model cannot be directly used for examining maintenance of all military systems concerning AM. Its general features can be used to describe common functions, but detailed choices need to be examined considering the specific characteristics of different branches and military system types.

5. Conclusions

Based on the information obtained from the war in Ukraine, it is known that AM is used for military purposes. Military applications of AM include not only spare parts but also new innovations and parts that can replace other components. In wartime situations, in addition to the shortage of spare parts, military forces are likely to have a wide range of needs that additive manufacturing can fulfill. In this study we examined one use case - spare parts – and created a conceptual model for one - militarily relevant - unit.

There is only a little practical experience in using AM to support the maintenance of an operational military unit, as AM is a novel technology. Therefore, it is unclear how the capability of additive manufacturing can enhance military logistics and support units. Of particular interest is determining the types of 3D printers and how many printers should be deployed and where within the overall military logistics system. That is creating AM military supply chain strategy.

In terms of potential, it is essential to understand the shift in manufacturing from Traditional Manufacturing to Advanced Manufacturing methods. It enables digital manufacturing. Regarding digital manufacturing, additive manufacturing and its simplest 3D printers enable printing near the troops. Although printing with such devices may not produce the highest quality parts, they can be essential for the operation of the military unit.

The study identified that in the development of the conceptual model for AM simulation, it is essential to thoroughly understand the operations of military activities, maintenance systems, and AM. In addition to the researchers' own experiences, familiarity with transportation equipment maintenance and additive manufacturing timelines and systems enabled the creation of a conceptual model for simulation. Detailed examination of the systems of one mechanized battalion's personnel carrier – MT-LB – enabled the analysis of 3D-printable spare parts in terms of quantity, material, and size. Based on this, the estimates for AM manufacturing times of the model could be established.

The conceptual model includes the parts that are in Robinson (2008a) definition: objectives, inputs, outputs, content. Even though we did not provide an independent face validity test of the conceptual model, this paper follows the advice of Robinson (2008a) making assumptions and simplifications explicit and declaring these openly.

As a result of the study, factors related to the unique characteristics of AM usage were identified in addition to the model. The benefits of the manufacturing method can be recognized as part of the entire logistics chain. While the armed forces of different countries have varying needs, operational environments, and starting points regarding the use of AM as part of logistics, this study generates information on how production capacity can be planned and allocated. Common principles of maintenance provide a solid foundation for applying the research results not only to the entire logistics system but also in the planning and execution of military operations. This study contributes to the understanding of logistics, particularly the use of additive manufacturing, in special conditions, even beyond military logistics.

The possibility of additive manufacturing to support maintenance could enable a completely new approach because manufacturing can be brought close to the troops. This means that the benefits of using the method can be achieved from the method itself, not necessarily from the logistics chain. In the model, it was recognized that the benefits of additive manufacturing in the spare parts logistics chain and its support may be marginal with current 3D printing capabilities, but significant benefits can be obtained by transforming the user into a manufacturer. If the user becomes a manufacturer, this transformation needs to be considered in all capability factors. The change entails reevaluating the entire system in a new way, not just importing 3D printers as new tools alongside others.

The armed forces of different countries have varying needs, operational environments, and starting points regarding the use of AM as part of logistics. This study contributes to the understanding of logistics, particularly the use of additive manufacturing, in special conditions, even beyond military logistics.

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