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Supporting military maintenance and repair with additive manufacturing

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Abstract: The purpose of the study is to explore whether Additive Manufacturing (AM) can support the military maintenance and repair of combat troops at isolated tactical level maintenance sites. The study also sought an explanation as to how AM could be organised in military logistics. The subject was approached from a systemic perspective. A system dynamics modelling was used as an impact assessment method. When selecting the parameters used in the model, the 3D printing data of the spare parts printed on the MTLB armoured personnel carrier (APC) were utilised. With simulation, we identified several key nodes for replacing or enhancing conventional military logistics with an AM added supply chain. As a result of the study, it was identified that by adding metal AM to the mechanised battalion organic maintenance and repair at the field level, it can produce spare parts whose use will improve APC recovery in the event of failure. We found that the relatively slow production speed of AM is the most influential factor in the use of the method. This study introduces a new perspective on reviewing the potential of AM in military logistics.

Keywords: maintenance and repair, military logistic, additive manufacturing, system analysis, system designs

1 Introduction

Additive Manufacturing (AM) is defined as a 'process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies' (ISO/ASTM 2016).

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AM has become a potential manufacturing method alongside traditional manufacturing methods (Lu et al. 2015). The advantage of the method is its ability to produce parts based on numerical (3D) information (ISO/ASTM 2016), almost without the design and manufacturing limitations (Gebusa and Lemu 2017). AM can produce parts of different materials (Wright 2018). This allows a review of military logistics from a new perspective (Department of Defence 2021).

The most important task of military logistics is to enable the fighting force to maintain its combat capability (NATO 2012; Zeimpekis et al. 2015; Minculete and Tutuianu 2017). Combat capability in different readiness states requires different performances from logistics (NATO 2012). Supporting the combat capability of a modern, technologically complex army needs the most efficient logistics possible close to the troops (Puolustusvoimat - Finnish Defence Forces 2003). From a military point of view, maintenance and repair of the troops are key factors in their operation. In particular, the mobility of mechanised troops and thus their combat capability is strongly formed around the usability of the vehicles they use (NATO 2012). The development of maintenance and repair capabilities of modern armed forces requires the utilisation of new and development of the existing technologies further. Through the advancement of military maintenance functions, the usability of the military force can be enhanced (NATO 2012).

The maturity level of the software process and the complexity, benefits and limitations of AM, as well as the use of different printing methods in different applications, have not been fully understood and therefore has resulted in a slow down of its adaptation (den Boer et al. 2020). The military use of AM is being studied in several different countries but still, there is a lack of information on practical applications of AM in the field repair operations. A few countries, such as the United States (Judson 2019), Norway (AM Chronicle 2018), the Netherlands (Additive Center 2020), and Australia (SPEE3D 2020), have experimented with 3D printing of simple parts under field conditions. It is not known that any country has implemented AM as part of tactical-level logistics.

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Spare parts form a critical resource for a military maintenance process (Zeimpekis et al. 2015). If the logistical chain is not able to provide spare parts for replenishment purposes, the military operations can be significantly hampered (GAO 1999). AM can be used to remove the delays of spare part logistics by integrating it as a part of maintenance and repair resources (Khajavi et al. 2013). This requires an understanding of the possibilities and limitations of the AM in the military maintenance system (Gibson et al. 2015; den Boer et al. 2020). About field maintenance, it is difficult to experimentally examine the use of the impact of AM. By modelling the AM spare parts production in the system and taking into account the most important factors, information can be obtained (Law 2007). Existing models cannot directly look at the use of AM as part of maintenance logistics at the tactical level. These models need to be supplemented so that the effect of AM can be considered (Busachi et al. 2018).

The purpose of this research is to identify the factors that affect the military logistics, specifically in the maintenance and repair function in the tactical level military operation, when adding AM to its capability. The research question of this study is: 'How can AM support maintenance and repair at the field level maintenance site?' The approach of the study is based on general system theory (von Bertanlaffy 1968). Military logistics system (Prebilič 2006), as well as the whole military organisation and its performance, can be seen through a system of systems-view. The case study method (Yin 2003) was used to review the AM usability of the mechanised battalion.

The remainder of this paper is organised as follows. Section two presents a literature review. Section three explains the research methodology that includes system dynamics modelling with basic model creation. The main system dynamic model is defined and simulation is conducted at the end of this section. The results of the simulation are presented in section four. Based on the developed model and simulation the AM effect on maintenance is illustrated and the developed model forms the basis to describe maintenance logistics. This paper concludes with a summary and final statements as well as a discussion and short outlook into future work.

2 Literature review

In this literature review, we aim to introduce the reader to the military logistics and AM concepts that have been utilised in this research. In military logistics, we focus on Maintenance, Repair, and Overhaul (MRO), and in AM the usage in the military context. The literature review constructs a theoretical foundation based on prior published literature.

2.1 Military maintenance and repair

Military logistics is a complex system whose complexity is emphasized by an exceptional operating environment (Rogers et al. 2018). NATO divides logistics into different categories. The main categories are production logistics, in-service logistics and consumer logistics. This study focuses on consumer logistics which includes reception, storage, transport, maintenance and disposal of material (NATO 2012). The military logistics system at the operational level is based on a hierarchical military command organisation where logistics are divided into functional areas. The NATO logistics has 12 functions: Supply, Materiel, 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 this study, logistics is examined according to the NATO classification. NATO classification is a common military logistics classification even in non-NATO Armed Forces and therefore offers a good and structured way to look at maintenance and repair in a military environment.

Consumer logistics is a part of military logistics where troops are supported with services where they are (NATO 2012). This sets operational requirements for the logistics supply chain. The nature of military activity varies from troop to troop. Some of the troops may be very static, while others move quickly over long distances. Regardless of the nature of the military activity, the logistics must be able to support the troops promptly, with a sufficient quantity of material, while maintaining a host of combat capabilities (GAO 2005).

The efficiency of operational effectiveness of the armed forces is based on the usability of the material. Equipment maintenance and repair is a logistics function whose main purpose is to keep the material in a specific condition or, if it fails, to return it to the serviceable condition as soon as possible. The usability basis is created under normal conditions where material MRO can be operated as planned. Planned MRO operations are possible because the use of material used in training can be predicted effectively. (NATO 2012; US ARMY 2013a, 2013b).

At the normal conditions, maintenance resources are allocated based on annual planning, which is calculated from basic maintenance needs according to a forecast model (Epler et al. 2017; Minculete and Tutuianu

2017). Due to efficient forecasting and economical use of resources (Goetschalckx 2011, pp. 61–62), in the normal level of readiness, the maintenance supply chain is based on a push model (Prebilič 2006; Ekström et al. 2020). Implemented on a push basis, maintenance material is reserved according to expected consumption without the need for troops to order it separately.

The forecast model for normal conditions may not work in a crisis. It is difficult to predict failure in conditions where, in addition to normal wear, kinetic influencing can cause extensive and sudden need of spare parts. The need for maintenance may vary depending on the readiness states (Puolustusvoimat - Finnish Defence Forces 2003). For this reason, the battle damage repair (BDR) model is used in operations.

The main objectives of BDR's activities are: 'limiting the damage, determining the cause of the damage, establishing a plan for the repair of damage, and minimising the risk to the equipment and operators' (NATO 2012). BDR could restore the material to working order during the operation as quickly as possible, regardless of the cause of the failure. The field maintenance in operations close to the forces relies on the replacement of complete equipment. Yet BDR requires all types of material and maintenance to be implemented from the lowest level.

More accurate and sophisticated maintenance of the material is typically carried out after the operation (NATO 2012). Post-mission maintenance with final spare parts is an important part of MRO logistics. The logistics structure for MRO is implemented at different levels (US ARMY 2014).

Requirements for spare parts logistics are different at different levels of logistics (Espíndola et al. 2012). Mainly usability and reliability of military material are affecting principles in MRO. At the lowest level, maintenance is typically simple, and available, which means speed and location of spare parts, in particular, is essential. In military operations, especially in mechanised troops, the number and range of spare parts are high (Finnish Defence Forces 2013). For combat troops, this means carrying replacement devices with the troop or the ability to produce temporary spare parts to replace broken spare parts (US ARMY 2013a, p. 6).

In the deep operations, which includes fighting in isolation, all the necessary replenishment, reserves, and replacements need to be accessible or to be produced/acquired within the force in question. The Finnish Defence Forces have introduced this kind of decentralised way of fighting in the Army (Parkatti 2012). Concerning the deep operations, this usually includes a certain number of spare parts based on the mean time between failure (MTBF) or some other statistical/computational indicator, some spare parts for the most critical systems in anticipation of asymmetric damage and readiness to apply 'jury-rigging'-operations by, for example, cannibalising other equipment (Folkeson and Brauner 2005).

ATA SPEC2000 is a standard which is used for material managing of military equipment and systems. In addition to these, the USA Department of Defense recommends using the MIL STD-1388 1A and MIL STD-1388 2B for managing the life-cycle requirements, including material aspects, of new military and equipment systems to keep the logistics support data records in the discipline. These standards include what data elements are needed for calculating initial provisioning in detail but do not include an initial provisioning algorithm. (Department of Defence 1983, 1991).

Handbooks (NATO 2012; US ARMY 2013a, 2013b), guides, and instructions published on defence logistics served as the main material for analysing the research problem and analysing the maintenance system. Strategies (Prebilič 2006; Finnish MoD 2011), guidance documents (Finnish MoD 2012), laws and regulations related to the material component of military performance, published by different countries, were key elements in building the research vision. Researchers' activities and observations in logistics tasks and military exercises were the building blocks for understanding the subject area.

2.2 Additive manufacturing (AM)

When comparing AM to traditional manufacturing or subtractive manufacturing, the key difference is the fabrication of parts based on digital specification without intermediate processes. AM machines can manufacture at the same time different parts from selected raw material and the result is a usable product (Gibson et al. 2015). Compared to other rapid prototyping technologies, AM can produce complex parts in a cost-effective way (Thomas and Gilbert 2014, Berman 2012).

The main materials for AM are plastics, metals, ceramics and composites (Gibson et al. 2015). The materials can be manufactured either in a single-stage or a multi-stage process. In a one-step process, the shape and material properties of a part are formed in the same process. The shape and characteristics of the product need not be processed. In a multi-stage process, the product is manufactured so that its essential shape is formed in the first step and, in subsequent steps, the material properties of the part are formed by a different method. In the case of both process methods, the production of a part requires post-processing (ISO/ASTM 2016).

AM can use the CAD models which are required by the manufacturing method from a centralised model library (Khajavi et al. 2013). In this case, the management of the spare parts can be implemented based on a prediction model or directly on the need. Original spare parts can be converted to a digital format well in advance of the need and 3D printed as needed. The number of possible spare parts suitable for the digital spare parts library is 5–10% of the total number of spare parts (VTT and AALTO 2018).

AM has been used in a military context for different applications (DeVisser 2017). For example, the replacement of military spare parts is one of its key application areas (González and Álvarez 2018). The development of new products and materials is one of the uses of the method. AM-enabled rapid visualisation of plans and concepts using physical parts or prototypes has enabled the development of military equipment and materials. Developing or personalszing the properties of existing material is one of the uses of AM. Military equipment is procured en masse, even though users are individuals. Problems with the availability of previously acquired military material have caused the repair of material due to wear and tear to be a very typical use of military 3D imaging. (González and Álvarez 2018; Additive Center 2020; Headquarters United States Marine Corps 2020).

Due to the ability of AM to be done 'on-site', it is a potential addition to the sources of spare parts in the field repair operations (Headquarters the United States Marine Corps 2020). Although it requires an organisation, infrastructure and personnel or at least added training and AM facilities of its own, the added surplus could emerge from BDR operations (Department of Defence 2021). This means that AM can reduce logistic delay time and support to keep operation tempo, efficiency and resilience (Busachi et al. 2016; den Boer et al. 2020).

In a study commissioned by the European Defence Agency (EDA), the use of AM to support field operations was divided into four different parts: customised equipment, field assistance, monitoring of information and adapted food. In addition, isolated operations had been identified as one of the key uses for manufacturing, where the manufacture of spare parts had been identified as an essential use. (González and Álvarez 2018).

3D Printers can be placed on different levels in a military organization. Printing centres have been set up in different countries to meet the centralised needs of the armed forces. In addition to production, the centres mainly act as research centres and serve several needs and requirements. These centres are located at the top level of logistics and are not intended to support troops in the isolation battle (Department of Defence 2021). The printers tested on the battlefield have been placed in a container. The advantage of using a container is that the conditions of the printers can be built in the container according to the requirements of the printers. It is easier to transport and use printers in a container than separately (Additive Center 2020; Fieldmade AS 2020). Printers are somewhat housed in forces operating in permanently isolated conditions, such as aircraft carriers (Iftikhar 2019).

There are still few globally reported experiences with the military field use of AM. In many countries, the use is limited by the regulations governing the use of parts and the printing methods and materials used. In large military exercises with a 3D printing container in use, most of the prints produced have been prototypes or simple plastic parts that have failed due to normal wear and tear. In the exercises, the researchers have been responsible for carrying out all the different stages of the printing process.

2.3 An identified gap in the literature

There are studies investigating the military use of AM. Den Boer et al. (2020) studied the advantages and disadvantages of the spare parts supply chain and identified key factors in the use of printing as part of military logistics. In particular, Den Boer et al examined supply chain change, change in responsiveness, sustainability and conditions for the use of AM in military and humanitarian missions. In the EDA study, the use of the method was divided into several different categories. The focus of research has been on determining the factors in the use of the method in the supply chain. Previous research has therefore focused on the functionality of the whole system. Previous studies have not examined the role of AM in the availability of combat troops at the tactical level. There is also no idea how 3D printers should be placed in an organization. In this study, this gap is filled by examining tactical level maintenance by adding AM as a maintenance resource.

3 Material and methods

Systems research can be divided into two different ways, experiment with the actual system or experiment with a model of the system. Examining the real system is useful whenever possible. When the actual system cannot be studied, the system can be studied using a model. The model can be either a physical or a mathematical model.

The mathematical model allows the analytical solution or simulation of the system. (Law 2007, p. 4).

A simulation through the generation of a mathematical model was chosen as the research method. In this study, experimenting with mechanised battalion maintenance would have required the battalion to fight and instal a 3D printer at its maintenance site (Fieldmade AS 2020). This system would not have been possible to study the real world.

The mathematical model was created on the principle of developing a system dynamic model (Rumbaugh et al. 1991; Katok and Hasselblatt 1995, Li and Yang 2017). This method is suitable for studying a complex system (Nieminen and Hyytinen 2015). System dynamics models can be used to analyse the structure and behaviour of the system (Merten 1991; Morecroft 2017). Simulation can be used to look at changes in the system (Rumbaugh et al. 1991). By looking at the changes, it is possible to estimate the impact that the change would have and thus predict the consequences. System dynamics modelling can be used to explore the spread of new products and services (Bass 1969; Meier 1998; Milling 2002).

The development of the model is based on theoretical material of military maintenance and repair and AM techniques (Gibson et al. 2015; Busachi et al. 2016; Gebusa and Lemu 2017). Military maintenance and repair main factors have been determined based on the literature. The authors' own experiences over the years have made it possible to evaluate the factors. AM factors and processes have been evaluated theoretically and empirically. The empirical data supplement theoretical knowledge and allows the definition of the conditions to be set for the simulation.

The military maintenance was examined by modelling in the mechanised battalion. The system dynamic and mathematical model in one workshop was developed step by step (Pejić-Bach and Čerić 2007). In the development of the model, the focus was on the key change factors (Table 1) that are specific to military maintenance in the workshops (US ARMY 2013a). The model described the impact of AM on spare parts logistics in a military maintenance workshop. Mechanised battalion uses armoured personnel carriers' (APC) for transporting combat troops to the battlefield and back. The usability of Armoured Personnel Carriers is one of the key elements of capability.

The model was developed in four stages.

(1) Development of the basic model.
(2) Conducting the basic evaluation tests.
(3) Expansion of the model with two feedbacks and AM.
(4) Re-conducting aforementioned evaluation tests for the new version of the model.

3.1 Development of the basics model

The goal of the field maintenance operations is to return the broken equipment back into service as quickly as possible while preventing any queues from forming. In this respect, time, personnel, and facilities are important variables (US ARMY 2013a). In reality, this is a very rough generalisation, and maintenance is affected by many different factors and their relations. However, from the spare parts logistics point of view, it is the logistical delay that is focused on in this simulation.

To estimate the impact of the AM technologies in maintenance, we identified the basic elements in military spare parts logistics as a part of field maintenance operations and formed a basic model with these elements (Pejić-Bach and Čerić 2007). The basic model simulates spare parts' demand and availability in the tactical level maintenance workshop. The fighting force has the resources for a predetermined mission and its planned timeframe. However, some resources, like spare parts and their need are hard to predict. This is mainly due to the level and severity of sustained battle damages being asymmetric in nature.

In the first stage of the model, the supply and demand of spare parts were simplified through the perspective of the operational ability of the mechanised battalion and the applied maintenance concept see Figure 1. It was found that the maintenance process is a basic queuing model. With this information, we identified the primary and secondary variables linked into the process (Law 2007, pp. 12–17). Primary variables are relevant on the workshop level and secondary variables, while meaningful, can be ignored in this simulation.

Tab. 1: Primary and secondary variables

Variables	Primary	Secondary
	Personnel	Doctrine
	Time	Price
	Demand	Organization
	Supply	Logistics
		Supplier
		Data
		Facilities

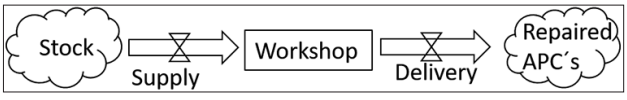


Fig. 1: Basic model. APC, armored personnel carrier. Modified from (Pejić-Bach and Čerić 2007).

3.2 Conducting the basic evaluation tests

System modelling is a way to simulate the real world (Campuzano and Mula 2011). All models have some inaccuracies. Thus, we can say that there are no fully valid models. All models are in some parts less than the system they model (Shreckengost 1985). It is possible to enhance the reliability of models. Typically, system dynamics models need to be evaluated by a test. There are two different groups of tests: structure and behaviour (Forrester 1969).

Schreckengost (1985) has recognised nine different tests: Model Parameter Test, Boundary Adequacy Test, Extreme Conditions Test, Behaviour Replication Test, Anomalous Behaviour Test, Behaviour Sensitivity Test, Behaviour Prediction Test, Family Member Test, and Behavioural Boundary Test (Shreckengost 1985).

In this case, we conducted three basic tests that would point out errors and mistakes in the model. The tests helped to understand the model behaviour. The basic model was evaluated with these separate tests:

- Dimensional consistency test.
- Extreme conditions test.
- Behaviour sensibility test.

The dimensional consistency test includes the measurement of variables. In the dimensional test, the variables need to be equal on both sides of the equation. In the extreme conditions test the model is tested for its capability to behave in extreme conditions in the same way as a real system would behave. The behaviour sensibility test focuses on detecting the parameters whose small changes cause a significant change in the model behaviour. (Pejić-Bach and Čerić 2007).

3.3 Expansion of the model with AM

Maintenance requires spare parts following the operating model shown in Figure 2. The availability of spare parts is typically based on a predetermined logistical chain where spare parts are delivered to the maintenance site under the preliminary estimation of the consumption (Romeijnders et al. 2012; Minculete and Tutuianu 2017). Spare parts can also be delivered to the workshop on an order basis, whereby the order is created by a diagnostics process. Delivery from an outside source is not possible when troops fight in isolation.

The expanded model see Figure 3 was constructed using the *primary variables*. The mechanised battalion is a restricted force with restricted resources so all outside influences and secondary variables can be, to analyse the effectiveness of AM, ignored. This is further supported by the fact that the isolation and a restricted operational period and area of the force is a presumption.

In the Expanded Model, the Repair Station consists of two parallel and identical workshops. These both have an equal supply of spare parts and access to Personnel e.g. Mechanics. This means that two vehicles can be simultaneously repaired. The repair facilities are considered to be adequate for field maintenance activities. Explicit estimation of a person's capabilities is hard and that is why no deviation of these was modelled.

The capability of the workshop is dependent on spare parts supply and availability of Mechanics at the precise time. The first feedback is the number of malfunctioned or damaged technical constructions (e.g. vehicles). This marks the Demand variable. The second feedback is Supply. The need for spare parts is normally evaluated based on the MTBF value of the vehicle. However, as combat damages are asymmetric and not predictable in nature the estimation of needed spare parts is not simple. Still, the fact remains, that if the damaged vehicle requires spare parts that are not available in the maintenance element of the force, the vehicle cannot be restored to service.

3.4 Re-conducting evaluation tests

The new version of the model was evaluated by the aforementioned tests. If both, the availability and the need for

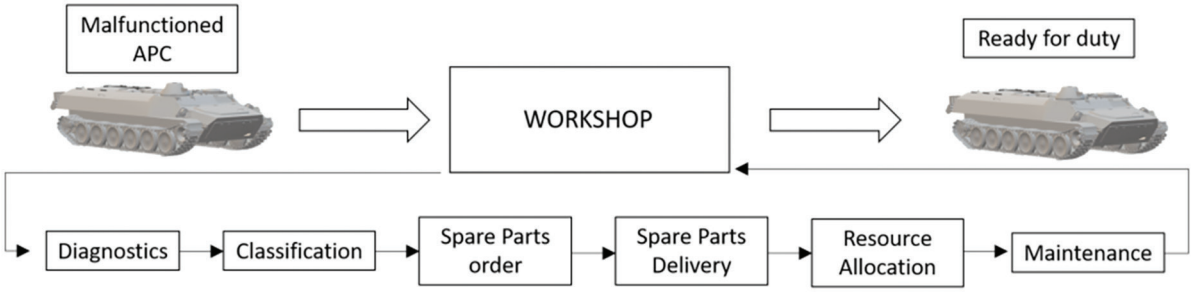


Fig. 2: Maintenance process from spare parts view. APC, armored personnel carrier.

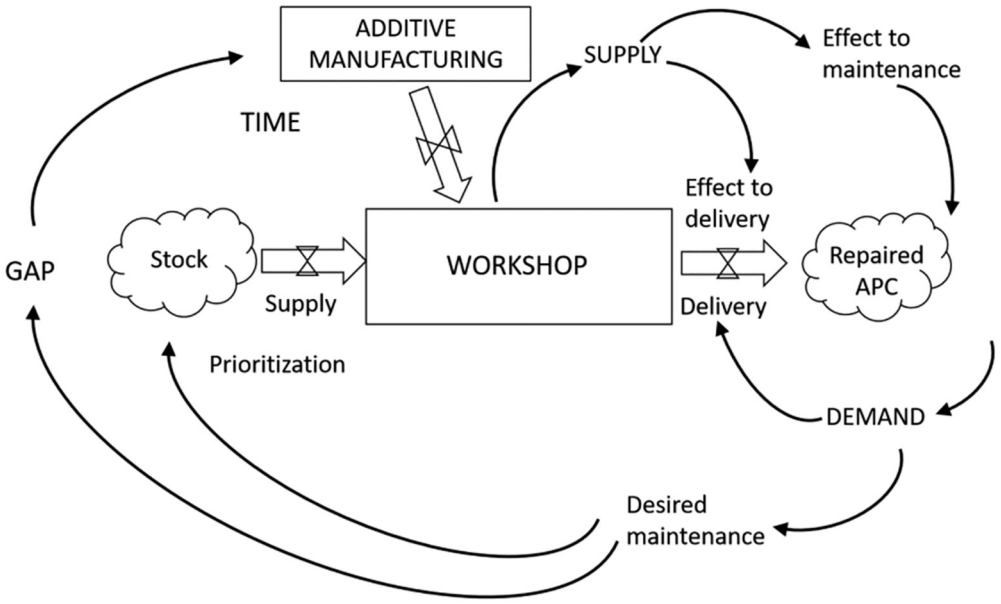


Fig. 3: AM in maintenance model. AM, additive manufacturing; APC, armored personnel carrier. Modified from (Pejić-Bach and Čerić 2007).

spare parts to maintain APCs match, the logistic network is correctly optimised.

When the number of spare parts used in the maintenance increases, in the initial situation, the spare parts at the workshop can meet the maintenance requirement. In the simulation, we simply demonstrated the implication of baseline spare part storage with and without the ability to restock.

The spare parts that are supplied for the maintenance workshop from stock and the spare parts used for maintenance constitute the material flows to be examined. Therefore the dimensional consistency test (Shreckengost 1985) was done by looking at the variables in the model. The time and inventory of spare parts in the maintenance object are the variables to be considered. When looking at the variables time and inventory in the system we can see that these variables are equal on both sides of the equation. In the extreme conditions test, this model was tested by material flows. Two extreme conditions were recognised: (1) when the maintenance workshop does not receive spare parts and (2) when an APC does not need spare parts.

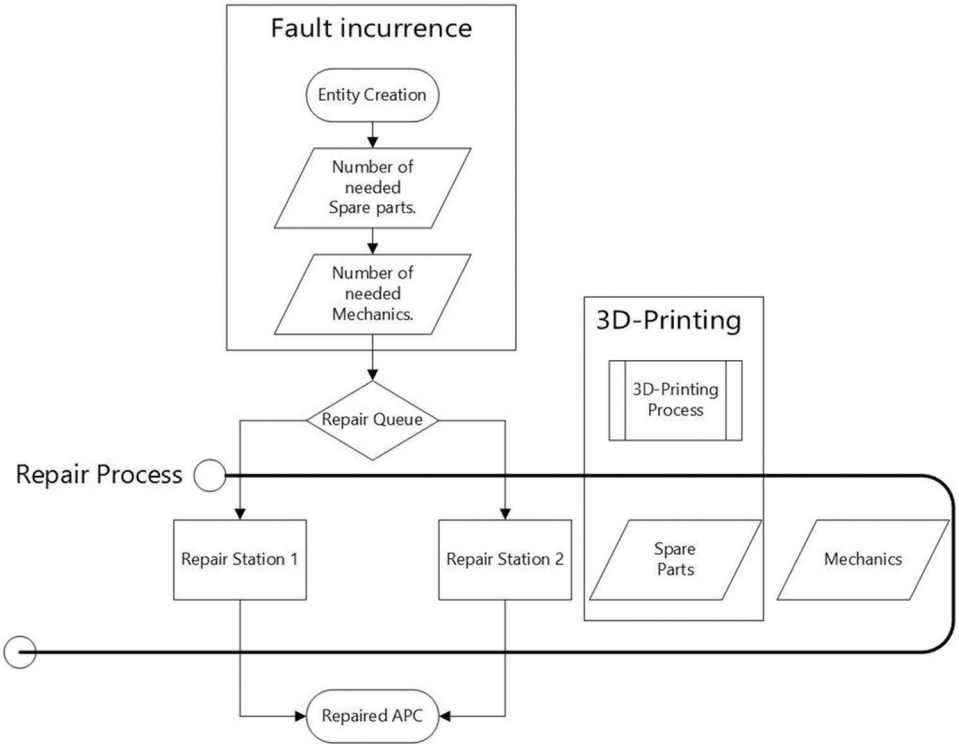
3.5 Simulation

The model was coded to Matlab Simulink software which is based on the Discrete Event Simulation. This makes it possible to build and run the simulation around the timeline and interdependences between primary variables to be evaluated.

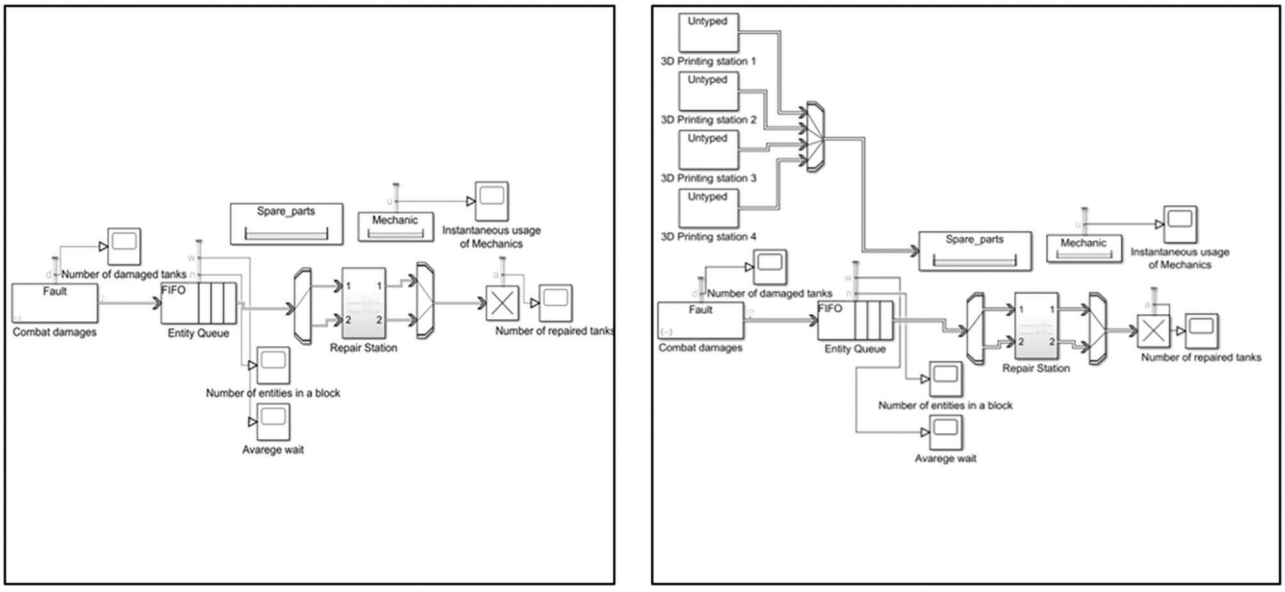
The goal of the Finnish Defense Forces is to develop the troops' ability for a two-week continuous combat mission, of which 3–4 days for a continuous decisive battle (Puolustusvoimat - Finnish Defence Forces 2020). The simulation overall duration is based on the operation time of the mechanised battalion e.g. 15 days. Within this time period, the unit should survive and be able to carry out all the planned activities without outside support. In Simulink, this means that the simulation runs for 360-time units. One time unit can be understood as 1 h and thus the one run lasts 15 days. Simulation process is shown in the Picture 1.

For the field repair process of individual APC applies:

- New faults and Demands incurrence is randomised between 1 h and 24 h. For each entity in Simulink applies:
  - $Sp=(z=\mathbb{Z}_{+}|1\leq z\leq 24)$
  - $dt=randi[(1,24)]$
- The severity of the fault is represented by the need for spare parts. The need of spare parts is randomly set between 1 and 20.
- The more severe the fault the more it requires man-hours. The number of required mechanics is set according to the spare parts need as follows:
  - $$\begin{cases} 1,1 \leq z \leq 4 \\ 2,5 \leq z \leq 8 \\ 3,9 \leq z \leq 12 \\ 4,13 \leq z \leq 16 \\ 5,17 \leq z \leq 20 \end{cases}$$



Pic. 1: Simulation process.



Pic. 2: Model, Left the model where there is no 3D printer in the maintenance site, Right the model where there are four 3D printers.

- The repair time of the fault is determined by the need for spare parts through 1 h for each part. To repair time appilies:
  - $T_s = Sp_x$
- The restock of spare parts and 3D-printing time in the expanded model was set according to the actual printing times of metal parts. To 3D-printing process applies:
  - $R = (z = \mathbb{Z}_+ | 20 \leq z \leq 33)$
  - $dt = randi[(20,33)]$

When the 3D-printing station was added to the model as a re-stock unit for the spare parts, its production speed

was varied between 20- and 35-time units, see Picture 2. The re-stock of the spare parts was scaled from one to four printing stations. This was done to evaluate the impact of the increased printing volume.

4 Results

This section presents the outcomes of our analysis to answer the research question. Tables and graphs have been utilised in order to illustrate our findings. As mentioned above, maintenance and the ability to return the APCs back into service is used as the performance indicator along our defined dimensions. The purpose is to address the role of AM in field logistics and identify the factors that influence AM use.

The following variables were modelled and simulated:

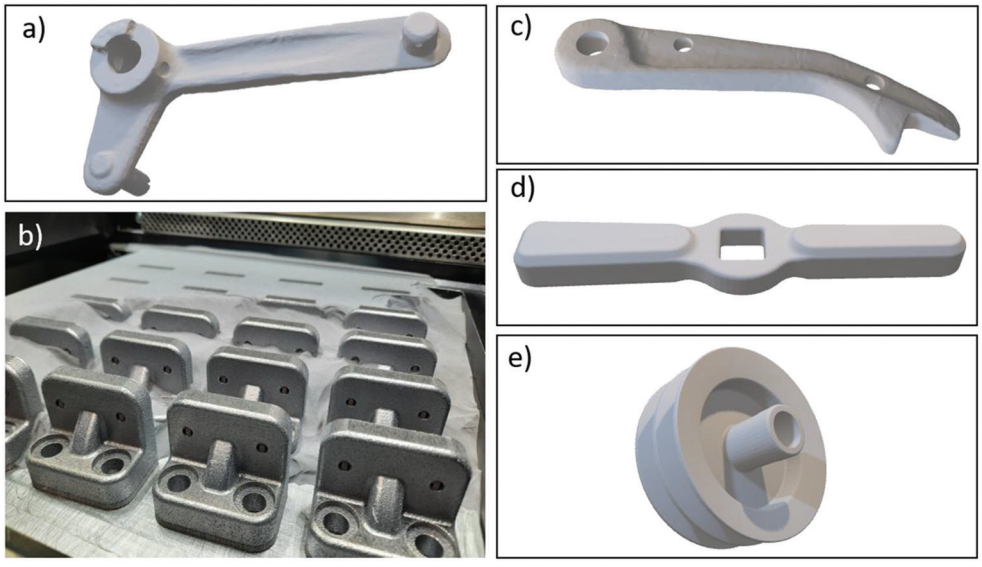
- Personnel
- Time
- Maintenance
- Spare parts

To examine the applicability of AM as part of field repair operations the system dynamics model was used as a framework and a specific Armoured Personnel Carrier was used as a reference system. The spare parts library of the APC was screened to identify the spare parts eligible for 3D-Printing.

Five spare parts were selected from the library and printed from metal with a 3D printer in Finnish Defence Forces (Hokkanen & Rautio, 2018). Parts are shown in the Picture 3. The selection of spare parts was made in four different stages. Before the selection of spare parts, a logistics organisation was interviewed and asked for its views on the structure to be selected. Once APC was selected as the research topic, the basics and operation of spare parts logistics for that structure were clarified. The researchers became acquainted with the need for spare parts and their inventory cycle. In addition to the printing itself, the study aimed to find out the installability and operation of the parts in the real operating environment, which was why the parts had to meet the safety needs of the forces operating the APC. Eligible spare parts were selected in collaboration with an expert panel of mechanics and technical personnel operating APC. Spare parts failure and the resulting operational implications are classified information and were therefore not addressed in this study.

One short batch from one of the parts was also printed. The spare parts were printed with the SLM280 Twin and EOS M290 3D printer. The Printed spare parts for the MTLB Armoured Personnel Carrier were: pulley, air firing hatch retainer, rear door interior handle, fuel valve handle, and fastener. (МТЛБРУС ООО 2017). The used materials were maraging steel (18Ni(300), 1.2709) and stainless steel (361L).

After printing the spare parts, their structure was examined and they were installed to their respected places. The results from the different stages of the 3D printing manufacturing process were used in modelling. In our case, the average size of APC spare parts was 87.77 cm^3. SLM280 Twin 3D printer build envelope (L × W × H) is 280 × 280 × 365 mm (SLM Solutions 2018). EOS M290 3D printer built envelope is 250 mm × 250 mm × 325 mm (EOS 2021).



Pic. 3: (a) Rear door interior handle (b) 20 printed Fasteners (c) Air Firing Hatch Retainer (d) Fuel valve handle (e) Pulley.

The fastener has optimal size and dimensions for AM. It was possible to build 20 parts at the same time. The printing volume of all these spare parts was 20×20.6 cm^3. Typically, the support material volume is approximately as much as the original parts' volume. In this case, it was possible to print these parts without support. The time to prepare the printing process took 2 h, the printing phase was 33 h and post-processing took 2 h. The time factors of printing at the different stages of the production chain are consistent with the actual values of the printed parts. In the actual model, the whole printing process was simplified.

The simulation was based on the Finnish Army Mechanised Battlegroup and its APC strength was used as a reference. In the battlegroup, there are 77 MTLB-V APCs. In one APC there are approx. 7500 spare parts (МТЛБРУС ООО 2017). The baseline in the simulation was that there are no active maintenance processes, and the workshop has initial spare parts for continuous operation during the 15days. All military material consists of repairable and consumable spare parts. Approximately 27% of all spare parts are repairable and 73% consumables (Zeimpekis et al. 2015).

Each variation of the simulation had the same combat damage incurrence rate. The goal was to simulate a steady flow of damaged vehicles. The average intergeneration time was 15-time units. This is a good reference for the load of the Repair Station although the actual real-life load would be more irregular and depended on the intensity of the fighting e.g. low, normal, heavy and the losses sustained per day accordingly (low 5%, normal 10%, heavy 20%).

In the first case, the maintenance workshop can maintain APCs until all initial spare parts have been used. After that, the vehicles must wait for spare parts. The workshop has 100 spare parts. If the outside re-stock option is disabled, then the damaged vehicles start to pile up. The repair station was able to repair 7 vehicles out of the 24 that were damaged, see Figures 4 and 5.

In the second case, the initial supply of spare parts is re-stocked with one 3D-printing station able to produce one spare part every 20 to 35-time units. In this simulation, the number of repaired vehicles was 8 out of 24 that were damaged. The results are represented in Figures 6 and 7.

By creating a model for performing military maintenance at a workshop, it was found that, especially in situations where the demand for spare parts is growing rapidly through intensified battles or queued faults, the ability of a maintenance site to support troops becomes hindered as the availability of spare parts decreases. Localised AM capability can produce spare parts when their availability from the logistical system is otherwise obstructed.

The core problem for the military force fighting in isolation is the sufficient quantity of resources. The availability of spare parts directly influences the usability of technical constructions like vehicles. Although the production speed of one 3D printer, in addition to four, makes only a small improvement to the maintenance capability, it is still an improvement. An increase of the 3D printers to four has notably increased the repair capability.

The added value through AM to the field repair capabilities is obvious. However, the problem is the demand

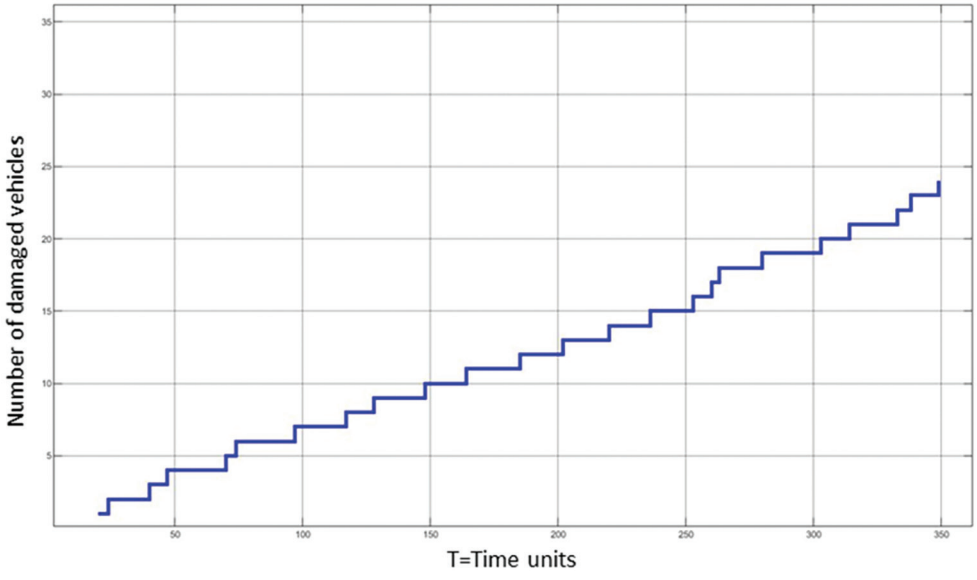


Fig. 4: Number of damaged vehicles.

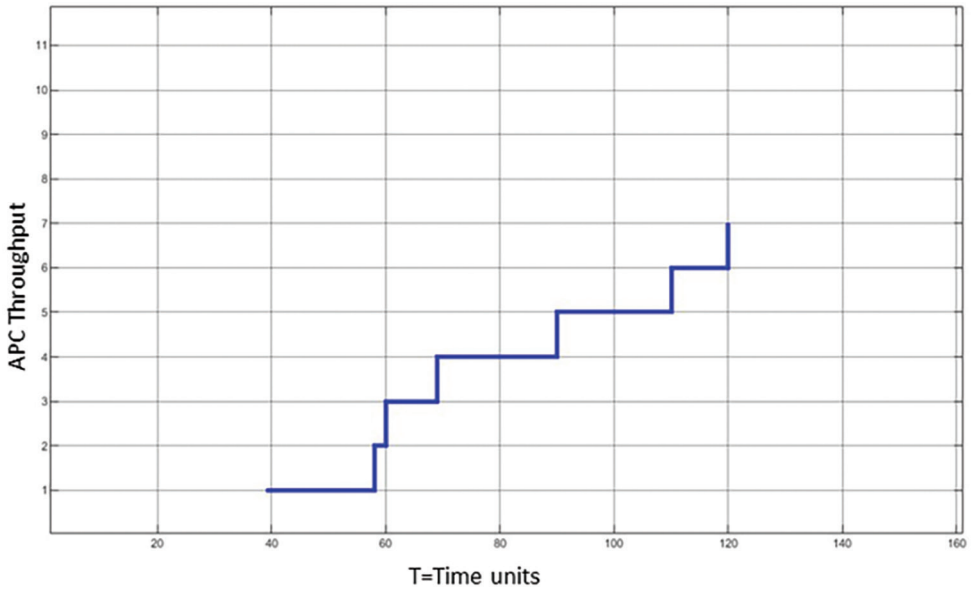


Fig. 5: Spare parts in case 1. APC, armored personnel carrier.

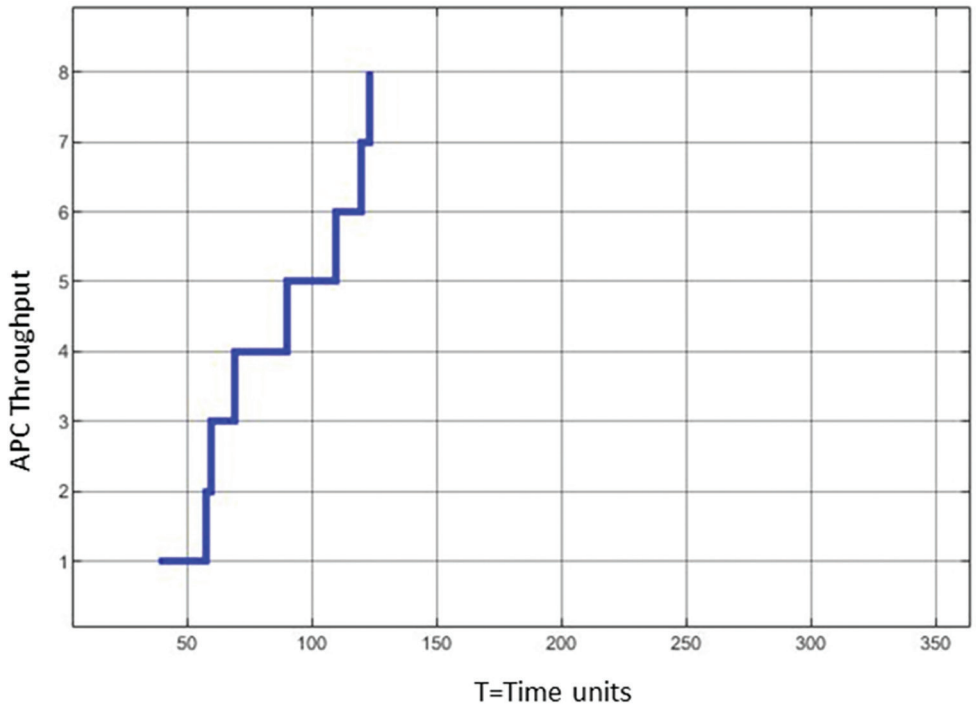


Fig. 6: Repaired vehicles with one 3D-printing station. APC, armored personnel carrier.

for spare parts versus the capability to supply them. The volumes tend to be so big, especially if the amount of battle damages increases substantially, that localised printing ability ultimately makes no difference. Also, the main purpose of the Mechanised Battalion is to produce the military capability element and not to focus on spare part production.

AM can develop the materiel readiness of military maintenance especially on the battlefield and as a part of field repairs. The conversion of spare parts to a digital form and the development of the manufacturing capabilities improve the ability of a maintenance site to support troops in carrying out their tasks. It was recognised that conceptually AM can be considered a separate supportive

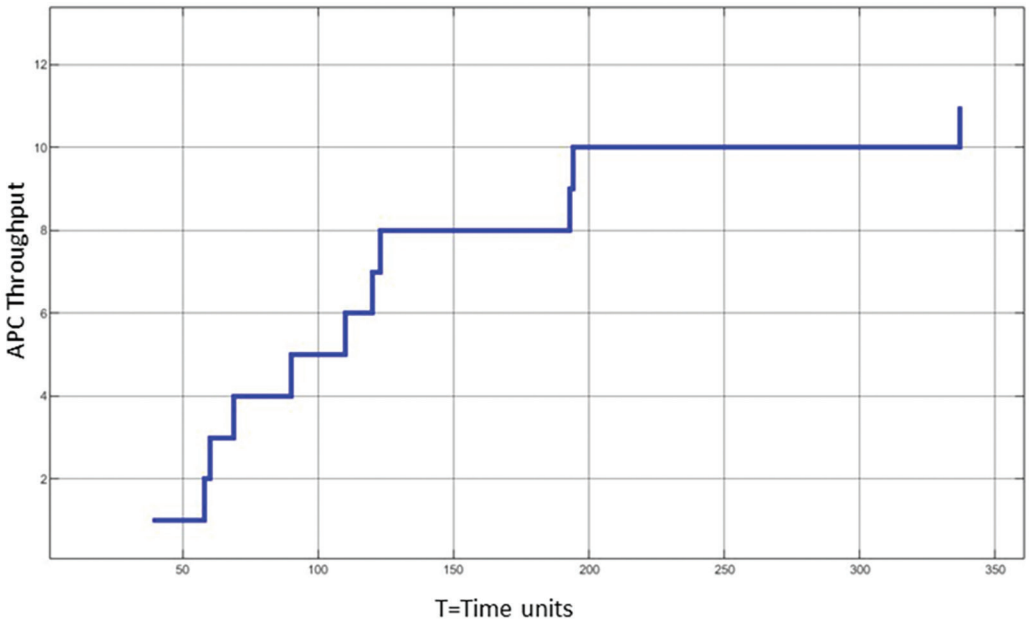


Fig. 7: Repaired vehicles with four 3D-printing stations. APC, armored personnel carrier.

maintenance asset without being otherwise connected to the actual maintenance site.

5 Discussion and conclusions

In this study, we examined how the new technology, AM, can reasonably support military maintenance at the tactical level. We found that the literature on military logistics does not have precise information on how AM affects Military Maintenance at the tactical level and how different factors behave in the system. We created a simulation model to find out the effectiveness and factors of AM related to MRO activities.

Especially maintenance close to the troops, where large storage capacity is impossible to maintain, may suffer from a lack of spare parts in the BDR. The basic assumption of the BDR model is that damage, its cause, and its severity are almost impossible to predict. Therefore, all available methods can be utilised to restore the material to the state of combat readiness. Spare parts for an isolated battle cannot be pushed out of stock on-demand, which is why every part made for need can allow the troops a better ability to operate.

In military logistics, maintenance has previously been based on spare parts warehouses and cannibalisation of damaged systems. This has led to a decline in overall performance. By generating the model and simulating the system we found that AM can improve troops' performance. Results suggest that AM can be used at the maintenance site, eliminating dependence on these elements, and supporting troops when fighting isolated.

The productivity of spare parts produced by a single 3D printer is relatively slow, concerning the number of spare parts required for mechanised troops in battle. Due to the slowness, adding a single 3D printer as part of a maintenance site does not bring significant capability.

We found that adding four printers to the maintenance site could cause significant changes to the maintenance organisation. From a technical point of view, it could be possible to add more 3D printers to the maintenance site, but the conditions for their use must be considered. In addition to the possibility of using several machines, the result of using different AM methods must be reviewed.

When using multiple 3D printers, taking into account all the procedures required for printing, is not possible without personnel dedicated to AM. The solution could be that 3D printers can be operated by a separate unit at the maintenance site. The military maintenance organisation must then consider the requirements of the maintenance site and the conditions for its operation. This is a state-of-the-art technique and requires a more detailed analysis.

It is essential to look at a situation where the demand is increased in the area of the workshop, but at the same time, the workshop in question is favoured by increasing the spare parts supplied to it. On the other hand, for example, the operational reasons demand a formation of a centre of gravity, also the logistic grid and thus the focussing of spare parts might be affected.

Despite the slowness of AM, every part made to need develops the performance of a mechanised battalion. AM can produce spare parts from a digitalised library, which improves the usability of the method. This is also one of the key aspects in which the use of AM differs from other manufacturing methods. Using the traditional manufacturing method, making parts would require significantly heavier tools as well as manual drawings from the entire spare parts library.

Although in normal conditions spare parts consumption can be assessed through standard maintenance programmes and observed wear and tear, the failure modes in fighting conditions are asymmetric. This makes it impossible to consider the need and requirements of a system at the level of individual spare parts. In this context, the model and simulation-based approach provide a sufficient understanding of the system's ability to support maintenance.

Maintenance often has to balance between predictions and risk tolerance. From this perspective, the estimated spare part amount or a capability to manufacture them is, in practice, risk management for the military.

Based on this study, in future research, it is worth considering the use of AM at the next level of maintenance e.g. depot level. In this way, it could be examined whether the use of the method can be better resourced and thus produce more spare parts for the troops. This requires the troop maintenance connections to be open.

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