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Resilient Military Logistics with Additive Manufacturing

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Abstract

In this study we explore how novel and relevant technologies can change the overall design of systems, and which factors influence the design of resilient systems in particular. After evaluating the effects of these factors, we describe the potential role of AM-supported maintenance operations in military logistics and draw broader conclusions regarding designing for resilience.

We build a simulation model of the AM-supported maintenance capability of a mechanised battalion to analyse factors affecting its resilience. AM production capacity specifically refers to metal printing, and was verified by data generated from 3D printing of the actual APC parts.

The current AM speed is not able to increase resilience at the depot level, so at present, increasing the spare parts inventory is a better way to improve resilience. However, with future improvements in speed the AM may become feasible in battlefield maintenance.

AM holds great promise in increasing resilience of especially the spare part logistics. At present technology, it is not yet fully realised in our case.
We suggest a concrete system performance measure, where reaching a concrete limit, system resilience is lost. We present arguments for a definition of resilience where pre-disruption activities are not part of resilience. We maintain that simulation, with its ability to include detail, is well-suited in design-for-resilience because supply chains are context dependent and disruptions unexpected.

Keywords: Resilience, Additive Manufacturing, Military Logistics

Introduction

The theoretical framework for this study draws upon current theories of demand-driven supply chains (Mendes, 2011) as well as the digital transformation of the supply chain (Paksoy et al., 2021). The supply chain is observed in the context of systems maintenance operations (International Standardization Office, 2015) and military logistics (NATO, 2012). The key competencies affecting operations strategy are identified as time, quality, flexibility, and cost (van Miehem, 2008). In maintenance operations one time and costs related aspect is logistic delay which can be due to for example “pending arrival of spare parts” (Finnish Standardization Office (SFS), 2010).

Flexibility is closely related to resilience, although the latter emphasises system recovery in the event of adverse surprises or uncertainty (Marchau, et al., 2019). According to Linnenluecke (2017), who conducted an extensive review of resilience in management research, an underexplored topic in this area is the design characteristics that make a supply chain resilient.

Additive Manufacturing as production method is one of the first methods considered to be fitted to become mobile (Headquarters United States Marine Corps, 2020). Other key aspect is the reduction of the difference in base materials. Traditional production methods require different beams, rods, pipes etc. from different materials to act as a base material. In the metal AM base material is the metal powder. Flexibility in production machinery's mobility and in base material are crucial elements when assessing the possibility of adding an organic production element of spare parts into a military force.

The purpose of this study is to analyse the possibilities of a relatively new technology, additive manufacturing (AM) as a part of two-level maintenance system and its spare part supply chain. In this study we explore how novel and relevant technologies can change the overall design of Systems-of-interest, their supporting systems like maintenance, including the design of resilient systems in particular. After evaluating the effects of these factors, we describe the potential role of AM-supported maintenance operations in military logistics and draw broader conclusions regarding designing for resilience.

Military Logistics

The definition of modern logistics is, at its simplest, the satisfaction of customers' needs through the management of services, money, information or materials (Christopher, 2016). This can be accomplished by means of a variety of functions. The American Council for Supply Chain Management Professionals (CSCMP) divides these functions into two categories: (1) supply chain management and (2) logistics management. The supply chain encompasses the operations required to manufacture products, from the raw materials stage to the final product. This definition includes all the activities from the procurement of raw materials to the manufacturing of the product and the placing of the product on the market. Logistics is defined as the storage and transportation of materials and related operations (Zijm, et al., 2019); this definition is typical of non-military organisations.

The principle of military logistics is as described – namely, a holistic approach to meet the needs of the customers – but yet its details differ substantially from commercial logistics. In military logistics, providing all forms of support needed by troops is by definition part of logistics. More specifically, NATO defines logistics as 'the science of planning and carrying out the movement and maintenance of forces'. In a more detailed definition of the term, NATO lists a part of logistics as the 'acquisition or construction, maintenance, operation and disposition of facilities' (NATO, 2020). The U.S. Armed Forces defines military logistics as 'planning and executing the movement and support of forces' (CJCS, 2019). Based on this definition, it can be said that military logistics systems include supply-chain management and therefore encompass all of its functions.

In terms of military operations, logistics is divided into a number of functions that include all logistics-constituting operations in which logistics capabilities exist. NATO classifies logistics functions into twelve categories: supply, materials, logistic information management, 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). The U.S. Joint Logistics Division groups logistics functions in altogether seven categories: deployment and distribution, supply, maintenance, logistics services, operational contract support, engineering, and joint health services (CJCS, 2019).

For military operations, maintenance remains a critical element for ensuring a high level of availability of systems-of-interest. Whereas the other components of military logistics create the conditions for supporting the troops, maintenance produces the conditions under which troops have materiel to operate. An efficient maintenance system requires adequate ability to maintain, repair and, if necessary, rebuild the systems, their subsystems and the necessary components. Systems availability is a function of reliability and maintainability which is stated numerically through the elapsed time of the maintenance operations (Figure 1).

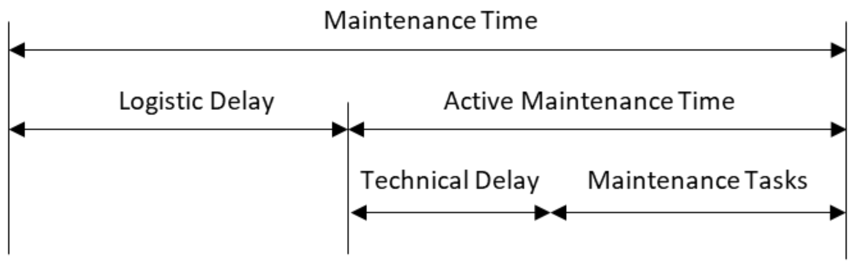


Figure 1. Overall maintenance time

In Western military organisations, maintenance related capabilities are divided into two maintenance levels: depot-level maintenance and field-level maintenance. (US ARMY, 2013) The purpose of the two-level maintenance concept was to optimize the maintenance resources without any reduction in force readiness. (United States General Accounting Office, 1996, Wilson, 2018). Also, the goal was to set key performance indicators for maintenance. These were selected as Turn Around Time (TaT) and Cost Savings (United States General Accounting Office, 1996).

Depot-level maintenance involves maintaining and repairing the most severely damaged items; this form of maintenance connects the logistics of a military organisation to an industrial maintenance component. Field-level maintenance and repair activities are supported by depot-level maintenance. The goal of field-level maintenance is to return systems back to the user as soon as possible. This means sustaining the systems' maximum high availability (HA). Correctly allocating and maintaining resources is a prerequisite for implementing field-level maintenance measures. (NATO, 2012; US ARMY, 2013; CJCS, 2019)

Additive Manufacturing

Additive manufacturing (AM) is a manufacturing method by means of which parts can be made by joining material together, typically layer by layer (ISO/ASTM, 2016). This method has the following prerequisites:

- the digital specifications of the part to be manufactured, or the CAD model;
- the manufacturing equipment suitable for the part to be manufactured; and
- material that is suitable to produce the part.

The characteristics of the part are determined by the model, the operation of the manufacturing equipment, and the properties of the selected material (Gibson, et al., 2015).

The development of various aspects of AM as well as its use cases have advanced sharply since the main patents expired in the 2010s. These advancements are supported by developments in computing power and information technology, as well as by and the relative ease of making CAD models, facilitated by software development and 3D scanning (Wohlers & Gornet, 2016; Gibson, et al., 2015).

The main advantages of this manufacturing method include the ability to manufacture in a non-industrial environment and produce individual parts; flexibility in production of parts; and the ability to simultaneously produce different parts with the same equipment (Berman, 2012; Holmström, et al., 2010).

However, the use of AM requires specialised expertise and may be limited by the technical requirements of industrial-grade printing equipment. The use and management of the raw material, the need to separately determine the manufacturing parameters for each printable item, and the management of digital production information, combined with the requirements of the operating environment required by the systems, create uncertainty about the use of this technology in special conditions. Due to its complexity, it is not clear how and where this method can be best utilised (Abdulhameed, et al., 2019; Lemu, 2019).

AM equipment is optimised to produce single pieces or small series of pieces. For this reason, the production costs are higher than those of traditional manufacturing, especially as the number of parts produced increases. Traditional manufacturing methods typically entail higher start-up costs for manufacturing and lower production costs. For AM, the opposite is usually the case (Baumers, et al., 2016) so AM has smaller scale economies. AM costs consist of machine costs, which includes all costs related to the purchase and use of the machine; personnel costs; and material costs. The material costs are direct and depend on the pieces that need to be printed. The indirect costs are almost independent of the number of parts printed, but they represent a significant amount of the total cost of printing (Costabilea, et al., 2017).

The development of AM materials has been fast. The first printed materials were polymers, but later composites, ceramics, glass and metals have been developed for the use of different printing methods. Metal printing can create complex structures, combine several metal parts into one, reduce production costs and shorten the total processing time of products. (Liu, et al., 2021) In most mechanical constructions for military purposes, a significant majority of the parts are made of metal. If metal-spare-parts logistics can be improved, either directly on the field or at the depot level, it can enhance the usability of the material. For this reason, many armed forces are especially interested in metal printing technologies relating to maintenance. (Spee3D, 2021; Fieldmade AS, 2022; Joint Defense Manufacturing Council, 2021) Metal printing technologies are more complex and they require more time than polymer printing. Also, due to the AM process limitations, it cannot produce finished parts without some post-processing steps. (Gibson, et al., 2015)

Recently, militaries have attempted to use AM in several countries (Additive Center, 2020; Headquarters United States Marine Corps, 2020; González & Álvarez, 2018). The most typical uses cases have involved replacing spare parts or to manufacturing individual products directly for their intended use. Entirely new types of concepts and new features for existing systems have also been developed using AM manufacturing capabilities (Department of Defence, 2021).

The benefits of using AM can be assessed by using four key metrics: delivery time, price, quality, and delivery reliability. Obviously, price is a significant part of AM usage for almost any system; however, when printing under exceptional conditions, the other factors often become more significant (Headquarters United States Marine Corps, 2020).

The ability of AM to produce spare parts based on a wide range of specifications, one by one enables meeting the users' exact requirements for spare parts under different conditions. In military operations, due to varying circumstances, the peace time supply chain is typically unavailable, and therefore high priority is given to material availability.

This factor is the main reason for examining the use cases and expanding the use of AM in military logistics. The effect of quality factors has also been studied, but there is still uncertainty in the research results as to which structures have sufficient AM quality and how the quality of usable parts can be verified. Based on these factors, it can be said that the use of AM as part of maintenance can be beneficial, and its various factors should be considered in greater detail (González & Álvarez, 2018).

In the near future, advances in AM may ease the conditions for its use. The development of materials, computing power and, above all, new AM technologies can enhance the usefulness of this manufacturing method. One example of a new development in this area is a cold spray technology, whereby a part is grown formed by spraying metal powder particles. This can improve both the size of the printed parts and AM production speeds. It is predicted that in the long run, by employing this method, end-users will be able to print up to 100–1,000 times faster than at present with the current AM technology (Korpela, et al., 2020).

Resilience in Logistics and Supply Chains

In 2021, a 100-day report commissioned by President Biden defined a resilient supply chain as 'one that recovers quickly from an unexpected event' (White House, 2021). There are several academic definitions of resilience (see e.g. Ponomarov and Holcomb, 2009; Christopher and Peck, 2004; United Nations, 2009), some of which specify that a resilient system should continue to perform at an acceptable level during a disruption, or an unexpected event. In addition to definitions that focus on response and recovery after disruption, there are a few that include pre-disruption activities such as preparedness and resilience-capability building (Al Naimi et al. 2021, Hohenstein et al. 2015). An example of the latter is the definition of supply-chain resilience as "the capability to prevent disruptions and to reduce the impact of disruptions through developing required level of readiness, quick response and recovery ability (Chowdhury & Quaddus, 2016 p.4)."Overall, quite a few systematic literature reviews focus on the concept of resilience (e.g. Bhamra & Burnard, 2011; Hohenstein et al. 2015; Ribeiro & Barbosa-Povoa, 2018 and describe and categorise existing definitions of resilience. Many authors end up pointing out the lack of a commonly accepted definition of supply-chain resilience.

Resilience features can be classified for time and effectiveness. The time classification is divided into: preparation, mitigation, response, and recovery (Carlson et al. 2012). These categories transcend all dimensions of external and internal resilience. Internal resilience can be seen as an organizational resilience, a technical resilience and economic resilience. The external resilience can be divided into technical, organizational, economic, and social resilience. (Bologna et al., 2011) Technical resilience refers to the ability of an organization's physical system to function after a crisis (Bologna et al., 2011). The classification according to the characteristics of effectiveness is composed of: robustness, resourcefulness, and rapid recovery (NIAC, 2009).

Table 1. Concepts related to resilience

Author	Concept	Definition
Das (2001)	Flexibility	*The ability of a manufacturing system to change states across an increasing range of volume and/or variety*
Gunasekaran, (2001)	Agility	*Being able to react quickly to unpredictable changes*
Fisher (1997)	Market-responsiveness	*The ability to react quickly to unpredictable demand changes*

Chowdhury & Quaddus (2016)	Readiness	*Upfront capability to reduce the likelihood and impact of disruptions*
Durach et al. (2014)	Robustness	*The ability of a supply chain to resist or avoid change*
Modarres et al. (1999)	Reliability	*The ability of a system and its components to perform required functions under stated conditions for a specified period of time*

A number of concepts are closely related to and also partly overlapping the concept of resilience, as shown in table 1. One such concept is flexibility, which is one of the four competitive priorities in operations strategy. Although risk does not fully or strictly equal resilience, Bhamra & Burnard (2011) view risk to be contained within the scope of resilience, and Ribeiro & Barbosa-Povoa (2018) point out "a natural relationship" between risk and resilience. The field of reliability engineering studies the reliability of components and systems by using, for example, the MTBF and MTTR concepts. The difference between resilience and reliability on the one hand, and resilience and robustness on the other, is that in the former, the component is either functioning or malfunctioning, while in the latter, the system is able to maintain its nominal performance. Uday and Marais (2015) offer a list of system-level attributes that are closely related to resilience, which, in addition to flexibility, agility, robustness and reliability, also includes survivability, pliability, and safety. They note that resilience, as a system-level attribute, has no meaningful interpretation at lower levels. Figure 2 shows a notational depiction of the performance of a system after disruption. It indicates how following a disruption, the system performance level first becomes reduced. In Figure 2 the performance drop occurs at one instant, but the disruption could also last and result in continuing degradation of performance. Figure 2 also shows the recovery phase and the return to the nominal performance level afterwards by the resilient system.

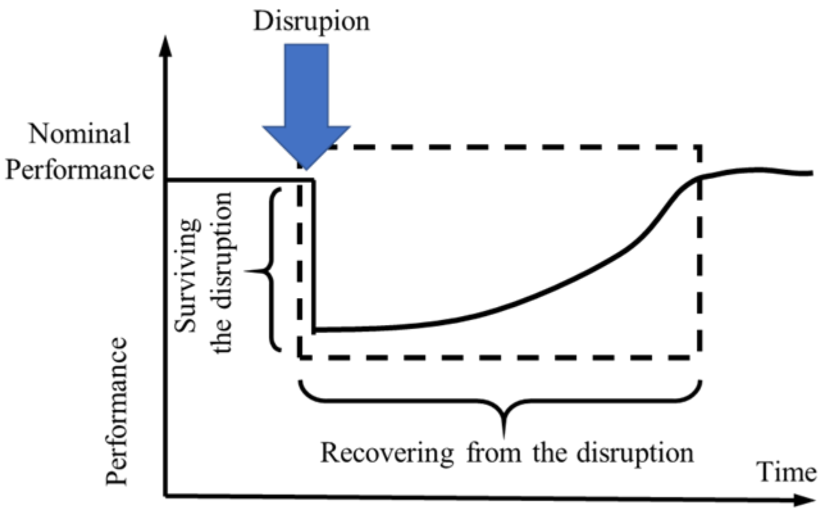


Figure 2 – Notational depiction of resilience following a disruption (Uday and Marais, 2015).

Resilience can be approached from a supply chain perspective (e.g. Christopher et al., 2011) or from a national perspective, as is the case President Biden's 100-day report. Al Naimi et al. (2021) add organisational and industry perspectives to the notion of resilience. Resilience is highly context dependent (Uday and Marais, 2015), meaning that little can be said of resilience in the absence of a particular system and a specific disturbance. Assessing the disturbance, in turn, may also be found in risk assessment. Risk assessment and management approaches typically pose four questions: ‘What can go wrong?’, ‘What is the likelihood or probability of something going wrong?’, ‘What are the consequences?’ and ‘What can be done to mitigate the risk?’ (Steele at al. 2022, p. 34; ISO/IEC 2010). If such questions are not raised, then it is difficult to say much about the resilience of a given supply chain, as supply chains tend to be open systems, constantly evolving and less easily definable than engineering systems in which control theory and its tools such as Bode plots or step change apply.

Christopher et al. (2011) divided the company view of resilience into five distinct risk categories: process risk, control risk, demand risk, supply risk and environmental risk. The first two risks are internal to the given company. Demand and supply risks are upstream and downstream distributions in the supply chain, and environmental risk is external to supply chain.

Measuring resilience is a key component in designing resilient systems, but it remains challenging to develop generalisable measurements to be applied broadly across a wide range of different systems (Uday and Marais, 2015). Yu Han et al. (2020) conclude that only a few articles discuss supply chain resilience measurement and have reached no common agreement on a measurement model. As there is no common agreement on the concept of supply chain resilience, it is perhaps not surprising that this also applies to measuring the concept. Figure 2, however, suggests four system resilience performance measures. Three first in the list below are mentioned in the literature (see e.g. Macdonald et al., 2018; Hosseini et al., 2019):

- maximum loss of nominal performance;
- total performance loss in that area between true and nominal performances;
- time needed to recover to nominal performance; and.
- time until system breakdown, or non-resilience, if ever reached.

Christopher et al. (2011) proposed four generic strategies for managing a global sourcing risk: network re-engineering, collaboration, agility and a risk management culture. The traditional ways to prepare in advance shortages and disruptions include stockpiling, reserve capacity, alternative supply sources, and contingency plans. Linnenluecke (2017) found that studies on resilient supply chains have called for slack resources (diversity, redundancy) and that the supply chain resilience design principles most commonly mentioned were flexibility and redundancy. Uday and Marais (2015) presented a 10-point list of concrete resiliency-design principles that can be summarised as follows: redundancy, repairability, localised capacity to prevent cascading failures, better control and communication, and layered defence.

As Cristopher and Peck (2004) remind, it seems that resilience should be integrated as part of design. However, as the relationship between logistics capabilities and supply chain resilience remains largely unknown (Ponomarov & Holcomb, 2009), resilience will continue to be highly context-dependent, as Uday and Marais pointed out.

Case Study – Simulation Model Description

A simulation model provides a convenient lab environment for testing the effects of different factors. Banks et al. (1996) view simulation as the imitation of the operation of a real-world process or system over time. The use of models frequently requires large amounts of quantitative data (Shapiro, 1996). The reliability of the results is highly dependent on the reliability of the input data. However, using approximate data is often more effective than abandoning the effort to make an analysis at all (Shapiro, 1996). Unlike optimisation models that provide a normative, best answer, simulation models are descriptive models that describe how all or parts of the system will operate over time as a function of parameters and policies (Shapiro, 2001). Simulation is practical for studying how a production system will behave without having to experiment with the system itself (Banks et al., 1996).

In a previous study, we investigated the effectiveness of using AM in military field maintenance by modelling its ability at a mechanised battalion-level field maintenance station. We found that due to slowness of current metal AM technology, the method fails to be cost-efficient at present. The current study models the supply-chain factors affecting the maintenance capability of a mechanised battalion and simulates a set of maintenance events (Busachi, et al., 2018), both in the field and at the depot level, as is common in NATO logistics (NATO, 2012).

Of the mechanised battalion equipment utilised in this case, armoured personnel carriers (APCs) were examined. A discrete-event simulation model was developed using MATLAB Simulink, based on a literature review of factors affecting military supply chains, AM production capacity and the logistics of mechanised battalion operations.

Depending on the intensity of the battles, the rate of damaged APCs per day is 10%, 20% or 30% of the available APCs (Defence Command Finland, 2003). This was implemented in the model as continuous failure model according to the battle intensity with Poisson distribution. Of the damaged APCs, 10% are destroyed, while 20% suffer major damage and are assessed to require depot-level repair. Additionally, 70% receive minor damage and can be repaired at the field level. The estimation of distribution of the extent of damage caused to APCs in battle is based on previous studies of battle damages suffered by armoured troops (Peltz, et al., 2004). Damage to individual parts was modelled in the following way. For APCs that suffer minor damage and are maintained at the field level, there were five spare-part types that each had a 50% chance of being damaged. This means that APCs that suffer minor damage had an average of 2,5 damaged parts. For damage at the depot level, there were 20 spare-part types that had a 50% chance of being damaged bringing the average number of damaged spare-parts to 10 in total. However, deep uncertainty remains regarding both the likelihood of battle damage and the extent of APC repair needs during an actual conflict. This is because in-situ battle conditions and ensuing damages may vary depending on, for instance, the tactics implemented, weather conditions prevailing, enemy weaponry engaged, terrain contours such as forest, plains etc.

Altogether three repair lots operated at the field maintenance station level and ten lots were functional at the depot level, which featured two separate stations, with five repair lots to each. The APC repair times were constant 4 hours at the field-level and 20 hours at the depot-level, independent of how many parts were actually damaged. Maintenance personnel were excluded from the modelling for, due to liability for military service, personnel availability is not considered to be a constraint. There was no transport time at the field level, whereas the transport time to the depot level was constant 20 hours, and similarly 20 hours returning back to battle. This is based on the depth and width of the operational area of the mechanised battalion and on the approximate distance from the frontline to the rear.

When all the spare parts required for replacing the damaged parts necessary in the APC repair were in stock, the APCs were assigned to station 1. If one or more parts were out of stock, then the missing parts were ordered from the AM factory, and the APCs were assigned to station 2 where that waited for repair start until the missing parts were manufactured.

The printing factory comprised two different production lines. One had only one printer, whereas the other had three printers with the capacity for both individual and simultaneous production. Assigning the jobs to the AM machines was modeled in a very simple way. The spare part requests with printing time less than 10 hours got routed to the production line with one printer. The spare part requests involving longer printing times were routed to the second line. This resulted in the throughput times of the parts becoming more consistent. The simulation model flowchart is shown in Figure 3, and the model parameters are displayed in the Table 2.

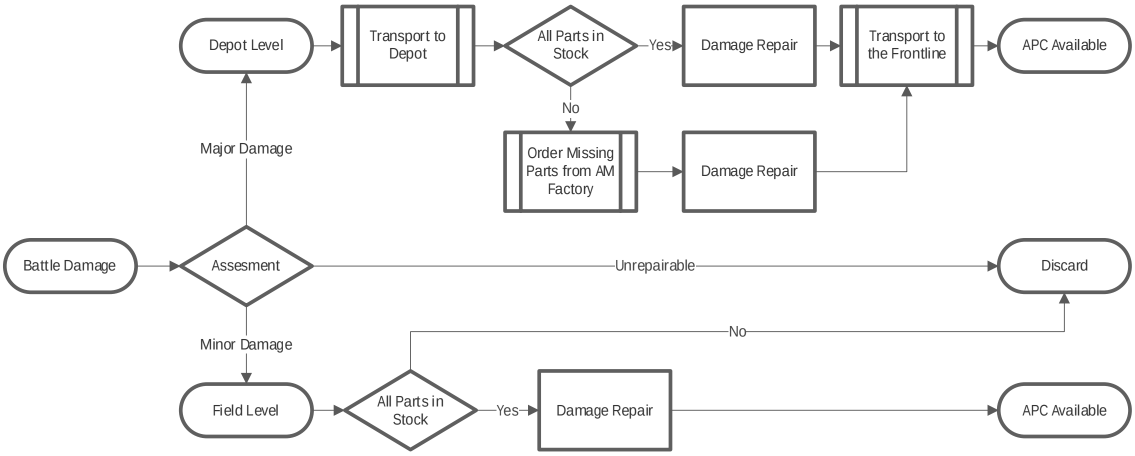


Figure 3 – Replenishment model

Table 2, Simulation Model Parameters

Maintenance level	Field	Depot	Discarded
Battle Damage Severity (of damaged APCs)	70 %	20 %	10 %
Possibility of a Part Failure in each type	50 %	50 %	N#A
Spare Part Item types	5	20	N#A
Number of Repair lots	10	3	nil

In this model, the AM production capacity specifically refers to metal printing, and was verified by data generated from 3D printing conducted by the Finnish Defence Forces for APCs. The AM manufacturing time depended on the size of the part and lasted between 1, 5, and 54 hours. The 3D printing times were based on a particular APC model, the MTLB, as shown in Figure 4.

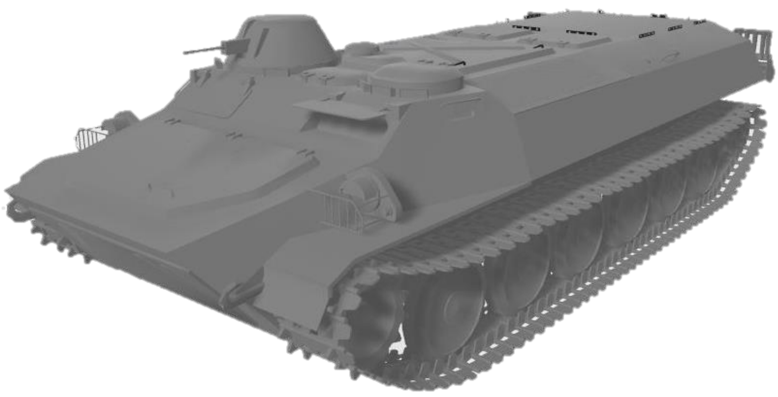


Figure 4 - MTLB APC

The main criteria when selecting the subset of metal spare parts to be printed was the possibility to install the parts to an APC. The base material was either aluminum (AlSi10Mg) or stainless steel (316L). Some of the parts were single prints, whereas and others were printed in small batches. A printing time calculation was made concerning each part. Figure 5 displays examples of printed parts for the Mashina Transportnaya Legkaya Boyevaya (MTLB) APC.

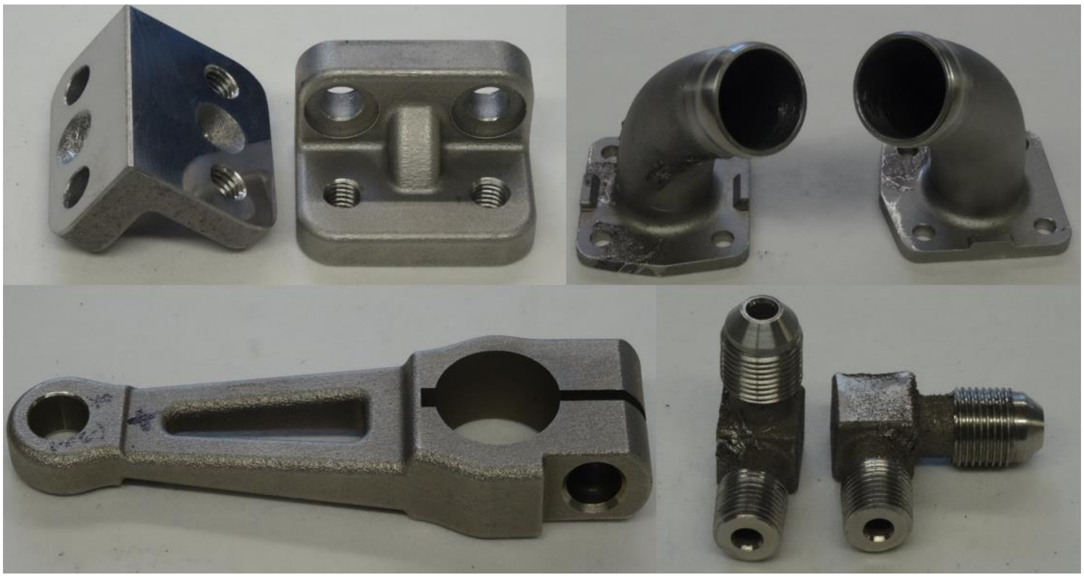


Figure 5 – Examples of AM manufactured parts in case

The time needed to produce each part was evaluated as part of a 3D printing study by the Finnish Defence Forces. The spare parts were printed with metal by means of an AM machine using Laser Powder Bed Fusion (LPBF), and therefore a metal AM was the chosen manufacturing method. We also modeled two future AM technologies in sensitivity analysis scenarios which utilised AM machines that were 5 and 10 times faster, respectively.

The main goal of the military logistics system is to sustain the mechanised battalion in battle as long as possible in its operational condition. This system resilience criterion was operationalized in the simulation model as the length of time the mechanized battalion is able to perform operations with 70% of the APCs in operational condition and ready for engagement. All other possible APC states (in transport, waiting for AM spare parts, being repaired, or discarded) reduce the number of operative APCs. In the wake of than 30 % losses of the original number of 77 APCs, the mechanized battalion can no longer perform. We used the value of 70%, following Peltz (2004) as our resilience cut-off criterion, while also the report results with 50 % cut-off criterion. The simulation experiments tested the effects of the following three design factors (see Table 3 for numerical values).

- Battle intensity: Light, Medium and Hard
- AM manufacturing: no AM, 1x current speed, 5x current speed, 10x current speed.
- Initial stock of spare parts at Field and Depot level: Low, Average, High

Table 3. Experimental Design Factors and their values

Factor	Factor Values			
Battle intensity (damaged APCs per day)	Light (10 %)	Medium (20 %)	Hard (30 %)	#
AM speed (times current speed)	No AM (x0) -	Current (x1) AM1	Current (x5) AM5	Current (x10) AM10
Initial stock (total pcs)	Low (Field 180, Depot 20)	Average (Field 300, Depot 60)	High (Field 500, Depot 100)	#

The experimental design was a baseline scenario design where each factor value was changed one at time. This approach gives a sensitivity analysis for each factor value compared to the baseline scenario. In the baseline scenario, battle intensity was medium, the AM speed was the current speed, and the initial stock of spare parts was at average level. In addition to the baseline scenario, there were seven sensitivity analysis scenarios. The scenarios are referred to in the results figures and tables as follows: battle damage/AM speed/Initial stock, e.g. the baseline scenario is referred to as Med/AM1/Ave. All the results are based on the averages of 10 runs in each scenario. The run length was two weeks, which is based on the expected length of major battles. As a variance reduction technique, the same random number sequences were used in each of the sensitivity analysis scenarios.

Case Study – Simulation Results and Discussion

Table 4 presents the main results: the resilience i.e. days until the 70% threshold is reached in each scenario. Table 4 also shows the days until 50% threshold for comparison. Figure 6 features the chart of APC availability each day, and Figure 7 presents both field-level and depot-level daily inventory levels.

No modelled scenario was able to withstand the goal of two-week-long battles (Table 4). As can be seen both in Table 4 and Figure 6, battle intensity has the most significant effect on resilience with point of non-resilience reached in just 2,3 days in case of hard battles and 12,5 days in case of light battles. Currently, incorporating AM production at the depot-level increases resilience only insignificantly as the effect is not even statistically significant. However, if future AM machines could produce spare parts faster, then this would increase the resilience considerably up to 6,0 and 7,3 days, which is even more than the effect of increasing the initial spare parts inventory. When looking closer at Figures 6 and 7, one can notice that the field level spare parts inventory is depleted in the baseline scenario around day 9. After that, the availability of all AM speed scenarios that have equal initial spare parts and sustain medium battle damage, rapidly decreases as the lightly damaged APCs cannot be repaired anymore at field level maintenance in which 70 % of APCs arrive.

*Table 4. Resilience in battle of each scenario in days, t-test p values * p<0,05, ** p<0,01.*

Availability	Med/-/Ave	Light/-/Low	Hard/-/Ave	Med/-/Ave	Med/AM5/Ave	Med/AM10/Ave	Med/-/Low	Med/-/Hi
70 %	4,5	12,5**	2,3**	4,2	6,0*	7,3**	4,2	5,5**
50 %	8,5	15,0**	5,1**	8	10,2**	10,4**	6,1**	9,7**

The improved resilience (cf. Table 4) of both the future AM scenarios results from their ability to supply spare parts for major damage repair at the depot level. But because of longer delays, mainly transport-related, the effect is not discernible in Figure 6 until after some days. The fastest AM scenario reaches 70% availability in 7,3 days while the large initial inventory scenario reaches the level of 70% more quickly in 5,5 days. The initial spare part inventory lasts for fewer days at the depot level, so a fast AM is able to perform better than a larger initial inventory scenario with a normal AM speed.

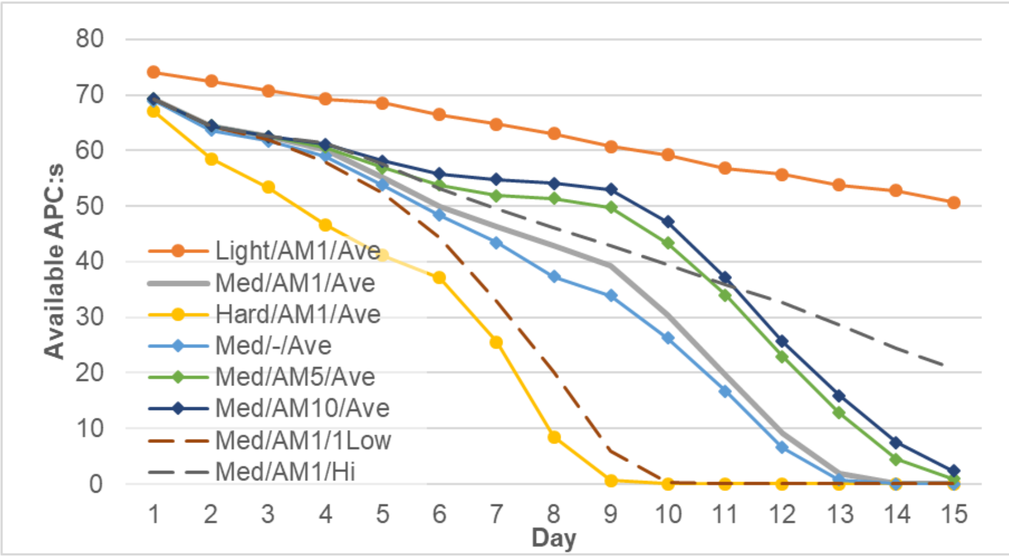
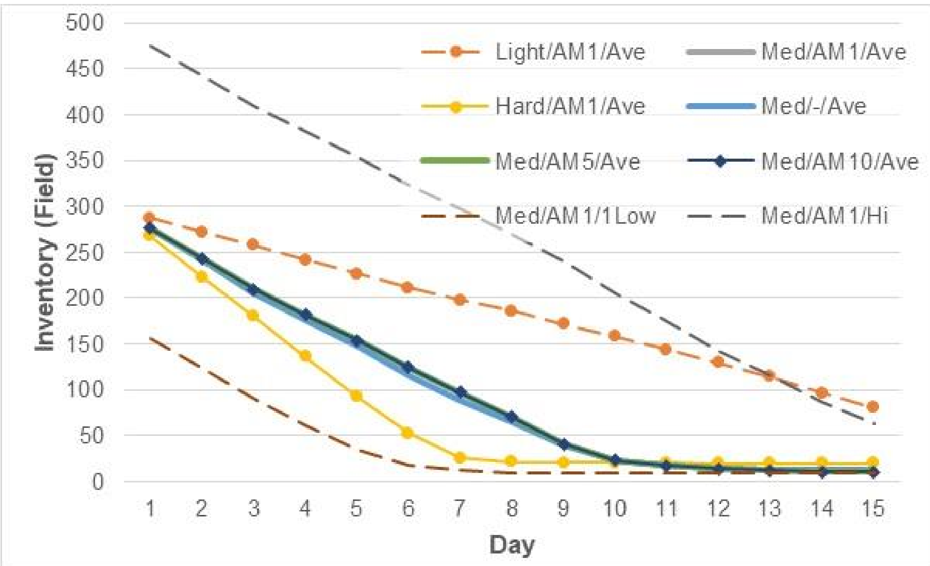


Figure 6 –The average (n = 10) number of APCs in each scenario.



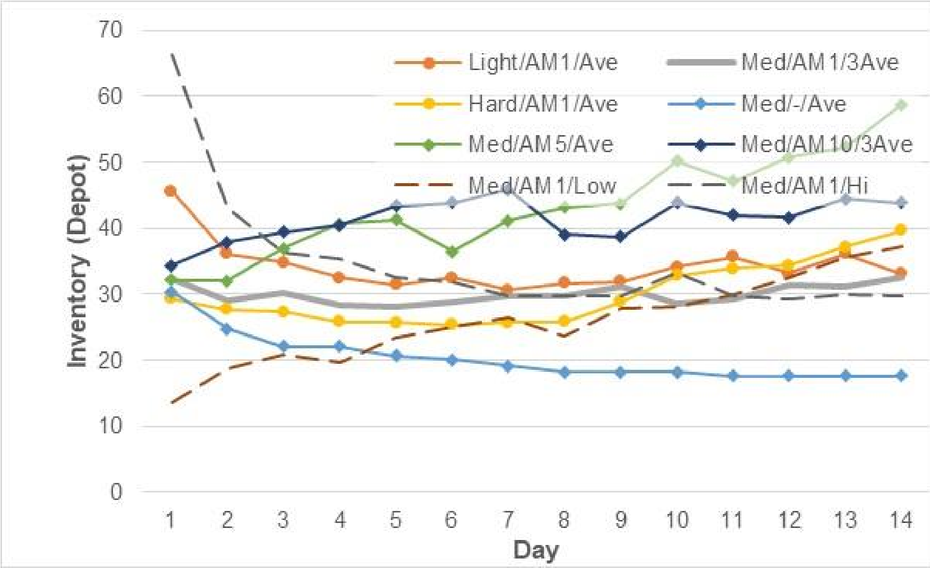


Figure 7 – Field level inventory per spare part (upper) and depot level total inventory (lower) averages in each scenario.

The current AM speed is not able to increase resilience at the depot level with the AM capacity that was modelled, so at present, increasing the spare parts inventory is a better way to improve resilience. Typically, stockpiling spare parts for military equipment is difficult, especially for older military equipment. So, with future improvements in speed the AM may become feasible in battlefield maintenance.

In the light of the results, one enhancement to the maintenance system could be to enable on-demand delivery of metal spare parts to the field level from the AM machines at the depot level. As APCs are already transported from the field to the depot, transport of spare parts would not present a problem. This would improve the resilience when APC repairs ceased due to stockout in the scenarios with available AM capacity at the depot level. The fact that the field-level spare parts ran out around day nine, also implies a more theoretical notion of AM as a way to increase resilience that has relevance especially in maintenance logistics. The great promise of AM is that it enables on-demand, lot-size one production.

Conclusions

The purpose of this study was to observe the effects of a relatively new technology, Additive Manufacturing, to a military maintenance system and its spare part supply chain. In this study we identified how a relatively new and relevant technology can affect the design process of the system-of-interest and its supporting systems. In the system-of-systems design, in this case the military logistics system, all the subsystems contribute towards making the system resilient.

The design methods to increase the resilience of APCs logistics system and thus the availability of the APCs in a mechanised battalion involved increasing inventories and producing spare parts by means of AM. While avoiding intensive battle also kept mechanised battalion operational longer, battle intensity as an environmental condition is not part of the logistics system.

Unlike when increasing initial spare parts inventories, the AM production does not require committing to exact numbers of each spare part in advance. Compared to traditional manufacturing methods, the key promise of AM is the economies of scope that it offers as it is able to manufacture a variety of parts with a single AM machine that enables having manufacturing capacity at the Depot level. This applies to cases involving deep uncertainty, as would be the case of anticipating the type of battle damages that will actually surface. Yet this advantage relating to AM utilisation is not easily quantifiable as it is not known how incorrect our best estimates will be. This is mostly due to the asymmetric nature of the battle damages.

The results apply in a general level to the used printing method as well as to the metal materials from which the speed of AM machines for different spare parts has been modeled. Although AM will probably not be the production method to make all the conventional production methods obsolete, it still is focused in current military studies in European Defence Agency, NATO and USDoD. Combined with other production methods AM can increase the robustness of the supply chain through layered capabilities. Also, as most of the metal parts still needs some level of post-processing, for example machining, it is highly unlikely that spare part production will be solely done in the field maintenance level. At the depot level AM can provide major advances in regards of supplying spare parts that are not currently or at all available. This can be due to, for example, disturbances in national or in the global supply chains. These disturbances are seen already due to the Covid 19 pandemic and the war in Ukraine.

This study provides key information for determining the relative influence of factors when designing resilience for military logistics and improving the availability of APCs. The performance estimation of AM shows clearly, that at the field level it cannot improve the availability of APCs at current level of the techology. So at the moment, it seems that increasing the preparedness is best achieved by increasing spare part inventories. While the contributing factors as such still remain context-specific and entail substantial uncertainties, the broader simulation-based approach of the case offers a viable approach for designing resilient supply chains of spare parts and military maintenance system.

We chose a definition of resilience in which anticipation is not included as part of resilience definition. On a practical level i.e. in our model, in its conclusions and managerial implications, this distinction between definitions of resilience has no relevance as it denotes meaning only at the theoretical and conceptual level. Even though including preparedness in resilience can be viewed as being a more comprehensive definition, we prefer to exclude advance actions because firstly, as for concepts such as reliability and flexibility, they signify system properties, and designing a system that displays such properties is not included as a part of either concept. For example, a production system may be flexible but designing a flexible factory is system engineering and not flexibility. Secondly, the operationalisations (i.e. ways to measure) of resilience as outlined in Figure 2, start only from the disruption event and do measure preparedness only indirectly.

Yet it is often only with hindsight that disasters look like events that should have been prepared for (Bhamra & Burnard, 2011), or that a disruption was "unexpected". In fact, if resilience or lack of it is only revealed ex-post, one can ask whether such an understanding is even scientific as it is not falsifiable. At the minimum such an understanding of resilience is intertwined with the ex-ante unknown disruption event. It seems that when designing for resilience, one should have an idea of plausible risks in order to design for resilience. The risks may be unexpected in the sense that they are small but not unanticipated in the sense of being unknown at the time of system design.

If we are to design more resilient systems, it cannot be done without taking a system engineering viewpoint and specifying system capability requirements i.e. what is acceptable system performance is e.g. in terms of maximum nominal performance level drop. In addition, we need to have an idea of what kind of disruptions are conceivable by defining tangible risk scenarios and system operating environments.

For the successful introduction of new technologies such as AM, the concept of operations itself needs to be reassessed in order to fully reap its potential benefits. This conceptual work allows logistics operational designers and systems developers to plan the use of AM in military operations. In the future, as a part of maintenance AM can support the whole logistics system and thus affect to military operations.

Linnenluecke (2017) points out the difficulties in observing resilience as a quality through empirical research, as the exceptionally demanding circumstances cannot easily be replicated by means of surveys or experiments. Therefore, simulation modelling may be especially well suited for purpose of studying resilience. According to Macdonald et al. (2018), with simulation, researchers are not limited to actual supply chain disruptions and may freely explore alternative combinations of disruptions and resilience-inducing investments. This is highlighted in this study by being able to assess the system-of-interest resilience of different levels of battle intensity together with alternative combinations of AM technology and spare parts. While making experiments in a controlled environment as simulation advantage is common knowledge in OR community (see e.g. Naylor, 1996), using simulation in resilience research may answer both the context-specificity of resilience as simulation models are capable of incorporating context specific features – and the fact that resilience, as a system property, should be designed in advance for the unexpected disruption.

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