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Utilization of Additive Manufacturing for Rapid Repair in Military Applications

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Abstract:

This study explores the application of Additive Manufacturing (AM) to improve the efficiency and responsiveness of spare part production in military maintenance, with a focus on Expedient Repair (ER) within the framework of Battle Damage Repair (BDR). The paper evaluates the limitations and key implementation considerations of various AM technologies in field-based repair scenarios, including classification of spare parts by criticality, material selection, design constraints, and manufacturing feasibility. A real-world case study is presented, encompassing all critical phases of the process: (1) iterative design and prototyping; and (2) reverse engineering and remanufacturing of a brake fluid reservoir for a selected ground platform-a light tactical multirole vehicle. The results validate the utility of AM in producing functional, field-ready components under operational constraints, facilitating accelerated repairs, minimizing logistical demands, and enhancing platform readiness during high-intensity military engagements.

Keywords:

additive manufacturing, battle damage repair, rapid repair, system analysis, system designs, logistic chain

1 Introduction

The effectiveness of machine component design depends on the implementation characteristics of the specific Additive Manufacturing (AM) technologies used in their

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production. Each type of AM technology possesses distinct characteristics related to the properties of its feedstock materials and the conditions under which the manufacturing process is carried out. These characteristics can significantly influence component design and may also impose constraints on the extent to which design modifications can be implemented. The primary limitations of various AM technologies in the fabrication of designed components arise from the inherent characteristics of the AM process. These limitations are mainly related to the use of auxiliary materials and the occurrence of stepped surface formations [1–4].

In addition to the technical limitations of AM technologies, production-related constraints must also be considered when evaluating the applicability of the method. In general, it can be stated that similar production constraints apply in both military and industrial environments. These constraints include high production costs, significant energy consumption, the difficult and potentially hazardous handling of production materials, and the requirement for complex thermal post-processing. The extent to which these factors influence and must be accounted for in specific manufacturing tasks depends on the operating environment [5–7].

Additive manufacturing comprises a group of manufacturing technologies. According to the ISO/ASTM 52900 standard, these technologies are classified into seven categories. Each category includes multiple techniques that differ in terms of the materials used, energy sources, material feed methods, and other operational characteristics. Due to the specific features of these methods, different processes are suitable for different applications [8]. For example, some manufacturing methods, such as material extrusion and metal laser powder bed fusion, require support structures during manufacturing. This partly limits their applicability and necessitates extensive post-processing after production. Other methods, such as cold spray, enable the deposition of very thin layers, but the dimensional accuracy of the produced parts is relatively low. Therefore, additive manufacturing technologies should also be considered from a technology-oriented perspective as part of maintenance.

In the aforementioned AM technologies, support structures are required to provide temporary structural stability for overhanging or protruding geometrical features, such as steep walls or balcony-type overhangs, during the fabrication process. Upon completion of the build, these supports must be removed; however, their removal can be challenging or, in certain cases, impracticable in regions with limited accessibility, particularly where mechanical removal methods are required. To mitigate this limitation, overhanging features should be minimized during the design phase or configured in a manner that ensures complete and reliable removal of the supports. Comparable challenges are encountered in specific AM processes when supports cannot be effectively removed from enclosed or complex open cavities, or from the internal cells of lattice or matrix structures. In such cases, appropriate design modifications to the component geometry are necessary to ensure manufacturability and post-processing feasibility.

Another common issue in AM is the formation of stepped surfaces on inclined features of the manufactured components. This phenomenon, inherent to the layer-by-layer construction process, is typical of nearly all AM technologies. The presence of such surface artefacts is considered highly undesirable, especially when high surface quality is required. To mitigate the formation of stepped surfaces, components should be designed such that inclined features form angles as close as possible to 90° with respect to the horizontal build platform, ideally achieving a perpendicular (90°) orientation where feasible. Additionally, reducing layer thickness and selecting the optimal build orientation can further minimize surface artefacts.

Other limitations of various AM technologies that impact component design include:

- Maximum component dimensions are constrained by the build volume of the specific AM equipment (e.g., 3D printers).
- Dimensional accuracy is determined by the minimum achievable layer thickness. Generally, thinner layers result in higher resolution and accuracy. Each AM system has a specific minimum layer thickness, dependent on the properties of the construction materials and the system's layer deposition mechanism.
- Material compatibility is required, as each AM system is engineered to work with specific types of construction materials.

Fig. 1 illustrates the primary scenario involving several allied nations participating in a mission either in another allied country or overseas. During the mission, a critical component of one of the vehicles becomes damaged and requires replacement. The component is essential for continuing the mission, and transporting the vehicle back to the home base maintenance depot is considered too risky and time-consuming [9–14].

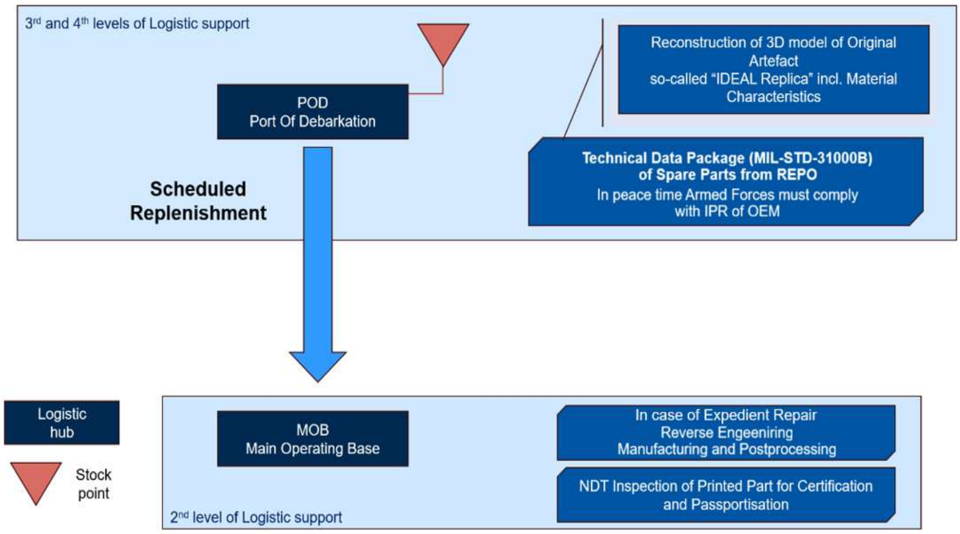

Fig. 1 Methodology of implementation of AdvM (Advanced ED Manufacturing) on different levels in modern logistic operations during overseas operations

The required replacement parts are not available off-the-shelf in any of the nations involved in the mission. Additionally, there is a need to modify the design of the parts to better meet current operational requirements and to prevent future failures. One of the participating nations has brought a mobile additive manufacturing (AM) production facility, equipped with both metal and polymer 3D printers, along with access to a set of qualified materials for producing high-quality components [15, 16].

A nearby local mechanical workshop has offered support using its expertise in traditional manufacturing methods and can assist with post-processing of the printed parts. Moreover, the Structures and Materials Institute at the local university is prepared to conduct mechanical testing and material characterization to ensure the printed parts meet the necessary performance requirements. [12, 17, 18].

From a historical perspective, interoperability within KFOR missions must be considered in the context of technological limitations at the time of deployment, when additive manufacturing technologies were not yet operationally viable. In contrast, subsequent missions – particularly those conducted in Mali – demonstrated a significantly higher degree of standardization and interoperability of ground military equipment across NATO forces. A representative example is provided by the Serval-Barkhane operations, which illustrated effective multinational cooperation. Out of approximately 3 000 components across eight standardized armored vehicle platforms jointly operated by the Royal Netherlands Army, France, and the Federal Republic of Germany, more than 400 components were identified as suitable candidates for localized additive manufacturing. This potential was already indicated by mathematical models developed for planning of future operations in remote locations [11].

According to Geert-Jan van Houtum [19], who evaluated the effectiveness of additive manufacturing (AM) deployment in expeditionary environments, the on-site production of spare parts enables rapid responsiveness to operational demands. Empirical observations from European force participation in Operation Serval – Operation Barkhane indicate that both the logistical and operational advantages of AM deployment are quantifiable. In comparison with conventional supply-chain delivery of selected components, full deployment of additive manufacturing capabilities within the operational theater yielded total cost savings of up to 47 %, with part-specific savings ranging from 20 % to 61 %. Even in scenarios where in-theater AM production was not feasible, optimization of expeditionary logistics alone resulted in cost reductions of approximately 9 % [19]. The evaluation of spare parts based on their potential benefits constitutes a multi-criteria decision-making process. Building on the model proposed by Westerweel et al. (2020) [19], a framework adapted from Knofius et al. (2016) is applied [20]. This framework employs the Analytic Hierarchy Process (AHP) [21] to rank spare parts according to relative component weights and transfer functions that map attribute values onto a composite score. These capabilities contribute to increased system reliability and reduced repair cycle times, thereby enhancing overall unit readiness. Such benefits are particularly significant when accounting for the indirect costs associated with equipment downtime, defined as periods during which critical assets remain non-operational.

Before implementing the new parts on the vehicle, several issues must be addressed. The Mission Logistics Commanders, together with technicians and operators from the mobile production unit and local support resources, gather to evaluate the situation.

The damaged parts appear complex at first glance. An assessment is required to determine whether production should proceed using AM technologies or rely on the local mechanical workshop, which is equipped with advanced CNC (Computer Numerical Control) machinery. A part selection procedure for AM is available to guide the decision-making process. Additive manufacturing is ultimately selected due to the need for minor design adjustments and the advantage of producing lightweight components with optimized internal geometries.

The next consideration involves determining whether the parts are obsolete or simply unavailable. If the parts are not obsolete, clarification is needed whether existing agreements with the Original Equipment Manufacturer (OEM) allow for their reproduction. National restrictions regarding the use and redesign of these components must also be taken into account. Further questions arise concerning which nations have access to the CAD files or basic design drawings, and whether secure transfer of these files between allied nations is permitted [21, 22].

A third allied nation is identified as having experience with the same parts and is capable of sharing the required CAD files. Given the critical nature of the components and the sensitivity of the data, measures must be taken to ensure secure file transfer and prevent unauthorized access. Consideration is given to how files may be securely transmitted between nations to enable redesign and then forwarded to the nation responsible for converting the CAD data into 3D printer code. The potential for interconnecting national databases to enable access to a shared digital repository is also explored. Additionally, provisions are needed for returning the final, redesigned CAD files to the originating country's engineers for quality checks and further simulation, if required.

New questions arise regarding the ownership of the redesigned CAD file. Clarification is sought on whether ownership resides with the nation requiring the part or with the nation responsible for the redesign. Consideration is also given to the possibility of uploading the file to a shared repository accessible to all allied nations to prevent redundancy. Ensuring that OEM rights and intellectual property regulations are upheld is a key priority, prompting contact with legal departments for further guidance.

Once the legal and design issues are resolved, the spare parts are manufactured and tested. All components must pass a quality assurance program. Following successful validation, the parts are installed on the vehicle, allowing the mission to proceed without delay.

In the case study presented in this article, a specific ground platform was selected for demonstration. In a broader context involving a fleet of vehicles, closing the control loop is essential. This includes integrating the digital twin of each platform and component with its physical counterpart. Such integration supports decision-making for maintenance within a system engineered for high levels of automation, adaptability, and evolutionary capability, including updates to more advanced designs. This enables continuous system improvement over the entire operational lifecycle [23, 24]. The scenario and procedural framework described here are broadly applicable across various domains and operational contexts [2, 25, 26].

Fig. 1 illustrates the use of Advanced Manufacturing (AM) technologies within the framework of Battle Damage Repair (BDR), specifically as part of Expedient Repair (ER) at the 2nd Level of Logistics Support. The current application of AM in such contexts remains limited, highlighting the need to address several essential operational considerations for effective in-field additive manufacturing [27–29]. Environmental control is critical. Humidity and temperature must be regulated during printing operations, as in conventional AM facilities. This is especially important for powder-based printing technologies, where uncontrolled humidity can compromise material integrity and print quality. Post-processing equipment is also necessary and can be incorporated into a containerized solution, such as a standard BDR unit, or positioned in a nearby mechanical workshop. Typical post-processing steps include polymer support removal (e.g., through washing stations), sandblasting, grinding, CNC machining, heat treatment, and surface finishing such as painting or coating [30].

Expeditionary environments impose greater mechanical and logistical stress on equipment than home-station installations. Factors such as frequent relocation, challenging ambient conditions, and varying levels of operator expertise contribute to accelerated wear. To ensure continuous operation, deployed AM systems must be provided with sufficient consumables and spare parts. Shortages in these resources can lead to increased transportation needs and delays – particularly detrimental in remote or contested areas – thus reducing the operational value of field-deployed AM capabilities.

To support maintenance and repair in these conditions, clearly structured repair documentation is essential. Guides must be easy to follow, and each system should include a comprehensive manual listing the bill of materials (BOM), complete with part numbers. This is particularly important in environments where users may have limited familiarity with AM systems and their maintenance procedures.

To ensure the most efficient and effective design of machine components, the AM technology and equipment selected should impose the fewest design constraints while remaining compatible with the required materials and dimensional specifications.

Owing to their unique ability to rapidly and efficiently produce components with complex geometries, AM technologies can significantly enhance the operational efficiency of repair facilities, particularly in the provision of spare parts. Traditionally, spare parts are manufactured and distributed in batches of varying sizes, often resulting in prolonged storage periods. This practice ties up considerable financial resources, and demand forecasting, both in terms of quantity and timing, is inherently challenging. In some cases, certain spare parts may never be used at all.

2 Case Study: AM Application in Spare Part Redesign

Doctrine for Land Operations, several aspects of Battle Damage Repair (BDR) are further detailed in STANAG 2418 – Procedures for Rapid Repair, including Battle Damage Repair. These NATO standards highlight the potential for integrating Re-engineering and Additive Manufacturing (AM) technologies into Rapid Repair practices, particularly at intermediate levels of support. Specifically, Type 2 repair procedures, as defined in STANAG 2418, describe:

"An improvised, non-conventional repair that is considered only temporary, allowing the equipment to complete the immediate mission or task, before being replaced by a conventional repair. This repair should meet agreed legal and safety requirements" [31].

The brake fluid tank shown in Fig. 2 represents a suitable candidate for the application of Additive Manufacturing (AM) within the framework of Rapid Repair. Originally constructed from polymer material and featuring a brass insert, the tank has been re-engineered so that the insert can also be manufactured from a polymer using AM technologies. This demonstrates the feasibility of replacing metal components with polymer-based alternatives in field conditions. Such an approach offers clear advantages in operational environments where conventional spare parts are unavailable, storage is limited, or rapid restoration of equipment is required. At the 2nd Level of Logistic Support, the ability to produce these components on-demand aligns with the goals of non-conventional, mission-oriented repairs as outlined in NATO maintenance doctrine.

The selection of the spare part was based on its suitability for rapid prototyping and in-situ manufacturing, as well as its critical function within the vehicle and potential for design optimization. Selection criteria followed a certified methodology used by the Armed Forces of the Czech Republic to identify critical spare parts – specifically, components that directly affect safety, health, environmental protection, or system functionality (e.g., steering, braking, or powertrain systems). These criteria align with Section A.3.2.1 of AQAP-2070 NATO Mutual Government Quality Assurance (GQA), which defines major non-conformities as those likely to negatively impact the environment, safety, interchangeability, maintainability, reliability, service life, appearance, cost to the customer, or delivery schedule [32].

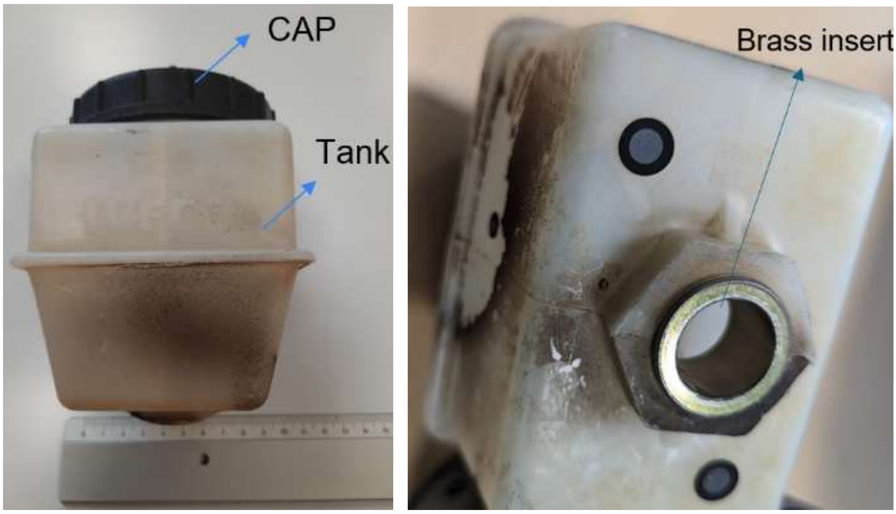

Fig. 2 Brake fluid tank with re-engineered polymer insert produced using AM for ER

All other deviations from the established technical requirements that do not fall into the main category are considered insignificant.

The risk assessment process utilizes a risk matrix based on the (STANAG 7160 Ed. 4 *"AVIATION SAFETY"* and AFSP Ed. B) with two axes: probability of Occurrence and Severity Level (Tab. 1).

For component classification by criticality, we adopted a system ranging from A1 to A4, based on criteria aligned with AQAP-2070 – NATO Mutual Government Quality Assurance:

A.1 – Non-Critical Components (CC1):
Failure does not result in damage to the system or other components, poses no risk of injury, and does not affect order fulfillment. These components are not considered safety-critical under AQAP-2070.

A.2 – Low-Critical Components (CC2.A):
Failure is unlikely to cause system or component damage or injury. It may reduce comfort or impose minor functional limitations, but it does not compromise mission fulfillment. Classified as low safety critical per AQAP-2070.

A.3 – Medium-Critical Components (CC2.B):
Failure poses a minor risk of system damage or injury, with a low likelihood of affecting order fulfillment. While mission success is not compromised, performance may be degraded. These are considered medium safety-critical components.

A.4 – Critical Components (CC3):
Failure may result in loss of life, serious injury, or mission failure. These are classified as high safety critical under AQAP-2070 and are formally designated as Critical Safety Items (CSI) [32].

Tab. 1 Risk Matrix based on the STANAG 7160 Ed. 4 "AVIATION SAFETY" and AFSP Ed. B ver. 1 [33]

Risk Level		Severity Level				
		A CATASTROPHIC	B HAZARDOUS	C MAJOR	D MINOR	E NEGLIGIBLE
Probability of Occurrence	1 FREQUENT	A1 Extremely High	B1 Extremely High	C1 Medium	D1 Low	E1 Acceptable
	2 PROBABLY	A2 Extremely High	B2 High	C2 Low	D2 Acceptable	E2 Acceptable
	3 REMOTE	A3 High	B3 Medium	C3 Low	D3 Acceptable	E3 Acceptable
	4 EXTREMELY REMOTE	A4 Medium	B4 Acceptable	C4 Acceptable	D4 Acceptable	E4 Acceptable
	5 EXTREMELY IMPROBABLE	A5 Acceptable	B5 Acceptable	C5 Acceptable	D5 Acceptable	E5 Acceptable

Another key factor in the selection of the part was manufacturing complexity, which relates more to the technological feasibility of in-situ production than to the criticality of the component itself. Components were categorized into four levels based on the complexity of post-processing and resource requirements following additive manufacturing:

Simplest Components

These components require no post-processing after printing, such as heat treatment, coloring, or surface finishing. They also do not need additional machining (e.g., milling, turning, or threading). Only minimal tasks related to the printing process are needed, requiring no special tools or machines to produce a functional part.

Simple Components

These parts require basic finishing operations (e.g., manual filing, threading) that can be performed using simple tools and without specialized equipment or extensive training beyond the 3D printing system itself.

Moderately Complex Components

These components necessitate additional finishing or post-processing using auxiliary equipment and may require more advanced skills or training. However, they can generally be completed within the capabilities of a standard field or maintenance workshop.

Complex Components

These parts require advanced post-processing using specialized machinery and skilled personnel. The capabilities of a typical workshop are insufficient for their production. Additionally, such components may demand extensive functional testing before deployment.

3 Quality Assurance (QA) Abroad (for Critical Components)

In response to the increasing security challenges in Europe, the Ministry of Defence of the Czech Republic (MO ČR) has, over the past two years, signed numerous contracts with foreign suppliers as part of an expanded global supply chain. For newly acquired equipment, it is anticipated that certain spare parts, particularly for critical components, may be manufactured at the third level of logistical support (stationary capacities) using AM technologies, especially in the event of supply chain disruptions.

When spare parts are produced outside the Czech Republic in support of multinational operations, appropriate QA and servicing must be ensured through formal quality agreements and quality management contracts, in line with both supplier-specific regulations and applicable international legislation.

While the core contractual principles remain the same as those used for domestic production, individual supplier agreements (e.g., with BAE Systems, Rheinmetall, etc.) must account for specific quality protocols, validation requirements, and liability terms. Within NATO, quality assurance activities are governed by STANAG 4107 [33], implemented nationally via ČOS regulations, with Government Quality Assurance (GQA) requirements aligned with AQAP 2070.

In cases where the country of the Original Equipment Manufacturer (OEM) is not a NATO member but participates in NATO's Partnership for Peace (PfP) and complies with the relevant STANAGs, GQA should be implemented through a bilateral agreement, based on a Memorandum of Understanding (MoU) or Implementation Arrangement (IA).

Because Additive Manufacturing introduces unique quality assurance challenges, such as material variability, process repeatability, and certification of non-traditional geometries, it is essential to establish clear acceptance criteria, inspection procedures, and traceability documentation within QA frameworks. Coordinating these standards across national and organizational boundaries in multinational operations requires robust planning, harmonized standards, and flexible contractual structures to ensure compliance without compromising operational readiness.

The term "prototype" originates from ancient Greek and translates to "primitive form". In the context of spare part design, a prototype typically refers to the initial manifestation of a component in the form of a model, mock-up, or experimental sample.

Model:

A 3D object that replicates or simulates specific characteristics of the intended component. It is primarily used to evaluate performance principles and to determine functional or physical characteristics.

Mock-up:

A scaled or simplified 3D representation of the designed component. Mock-ups are commonly used to verify design decisions, particularly those related to form, ergonomics, and appearance, and to validate the conceptual integrity of the design.

4 Experimental Sample

A full-scale, functionally complete 3D component that incorporates the principal features of the final design. It is developed for structural testing, performance validation, and refinement of specific design elements.

Prototypes are employed throughout various phases of the design process to refine the geometry, evaluate ergonomic and visual aspects, verify assembly feasibility, and confirm the accuracy of the proposed configuration. The use of rapid prototyping, particularly via AM enables faster iteration cycles, early detection of design flaws, and reduced development time, which is particularly valuable in time-sensitive military and field applications.

Prototypes are essential for verifying the functionality of designed parts, ranging from individual components to entire machines. Traditional prototyping methods are often labor-intensive, costly, and time-consuming, particularly when iterative design modifications are required following repeated tests. Each design change typically demands the creation of a new prototype, and in many cases, the development of specialized tooling, which must also be modified as the design evolves.

Rapid prototyping, a key application area of AM technologies, addresses these challenges by enabling the fast and flexible production of models, mock-ups, and experimental samples. This significantly improves the efficiency of the design and development process, especially for machine components and mechanical assemblies. Rapid prototyping serves multiple roles in product design, including:

- visualization of the product for presentation or customer approval,
- verification of manufacturability and production feasibility,
- assessment of functional, ergonomic, technical, and aesthetic properties,
- evaluation of assembly quality and ease of integration,
- concept modeling to validate core design principles.

In mechanical design, rapid prototyping is particularly valuable for producing testable prototypes using AM. These are often subjected to a range of tests (e.g., mechanical, aero-hydrodynamic, or thermal) and subsequently optimized. Testing under real-world operating conditions helps to identify potential design flaws early in the development cycle.

AM technologies allow the production of functional prototypes (experimental samples) without requiring traditional, high-cost tooling. For example, a combustion engine cylinder block, typically manufactured via casting, can first be prototyped using AM without any foundry equipment. Full-scale production tooling is only developed once the prototype and associated manufacturing processes have been validated. Although metal components can also be prototyped using AM, plastics are more commonly used due to their lower cost and the fact that their strength is often sufficient for preliminary functional testing. In most cases, affordable 3D printers are sufficient for producing prototypes during early-stage design.

5 Step-by-Step Process

Figs 3–5 show the progressive development of a re-engineered brake fluid tank, a component of the Light tactical multirole vehicle fuel supply system, intended for engine bench testing. The prototype was produced using several Additive Manufacturing (AM) technologies (see Fig. 5) with a high-strength, heat-resistant polymer, offering a faster and more cost-effective alternative to traditional methods.

This example demonstrates how rapid prototyping supports faster design iterations and functional improvements. It enables visualization of a product’s geometry, testing for fitness and assembly, and assessment of compatibility with host systems. Prototypes are also useful for evaluating material filling and removal, particularly when working with hazardous or abrasive substances, and for identifying areas prone to wear during operation. Functional testing of prototypes made from transparent polymers from producers on request, can even reveal internal flow behavior and material interaction (see Fig. 6c).

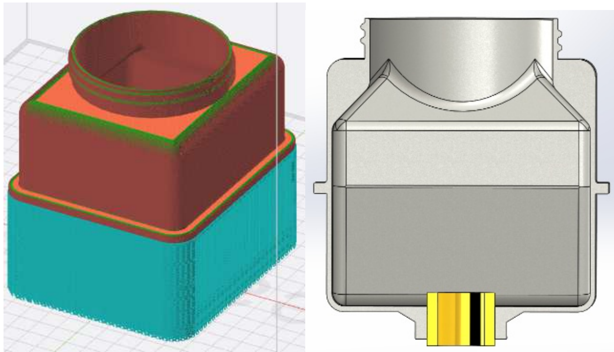

Fig. 3 Basic digital model of the re-engineered part, 22 hours *of print*

The use of AM technologies in prototyping helps reduce cost, avoid early-stage design errors, and increase the reliability and efficiency of the final product. It supports quick modifications to geometry, ergonomics, and aesthetics, while also enabling feedback collection through presentations, exhibitions, and user evaluations.

Importantly, this design evolution reflects not just re-engineering but also a transition to next-generation components that can be produced and implemented without removing the vehicle from operational deployment. The updated Technical Data Package can be accessed directly from a digital repository, allowing field-based upgrades without transporting the platform to a repair facility.

The role of rapid prototyping is discussed below with the example of the design and manufacture of new product modifications.

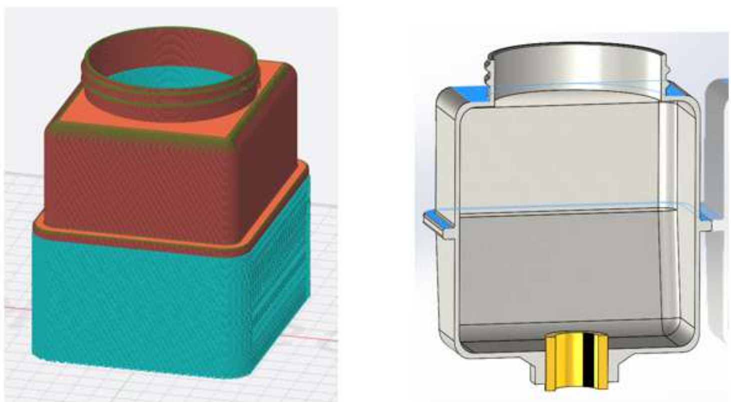

Fig. 4 Optimized version of the re-engineered brake fluid tank with reduced support structures, lowering print time to 18 h

Rapid prototyping affords:

- visualization of a product's appearance; confirmation of the compatibility of the product's kinematic parameters with the basic machine,
- the ability to assess the filling of the product with a material and its subsequent removal, which is important to take into consideration when working with highly toxic materials,

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- identification of areas of the product that are subject to the highest abrasive wear during operation,
- working up the individual elements of the traditional technological procedure for manufacturing the product.

The roles of rapid prototyping can differ significantly thanks to the use of materials with various properties for manufacturing prototypes. For instance, a prototype made using transparent polymer from PRUSA Research allows us to study not only the interaction between the product surfaces and a material when filled, but also the processes taking place within the material during contact with various product materials (Fig. 5c).

Testing allows the following:

- saving money on testing a full-scale product; prevention of mistakes when designing and assembling the product,
- reduction of the product's weight,
- increasing the product's efficiency and the resulting reduction of consumption of material for manufacturing the product,
- increasing the product's reliability,
- assessing the product's service life and the degree of wear of its internal surfaces when filled with various types of material. Rapid prototyping plays an important role in conceptual modelling when the image of a product designed for the first time needs to be presented as fully as possible.

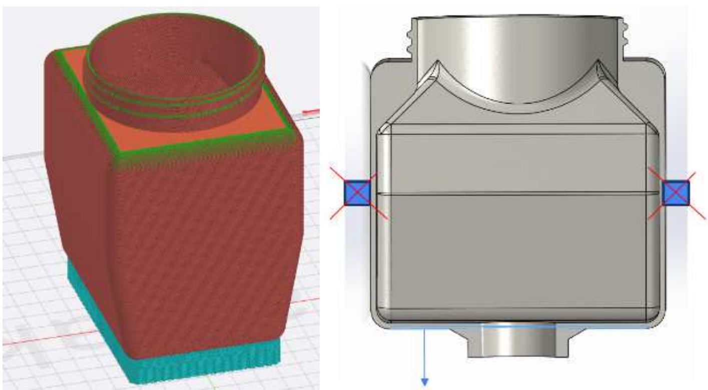

Fig. 5 Final optimized model using Design for Additive Manufacturing (DfAM) principles, achieving an 82 % *reduction in support volume and reducing print time to* 13 h

The presence of the conceptual model allows the resolution of many issues, which helps improve the new product's consumer properties:

- studying the product's geometry, taking into consideration its interaction within the real environment; verifying the ease of use of the product,
- rapid realization of the required modifications to the product's appearance, its shape and size,
- performance of a marketing survey to forecast the potential consumers' future opinions of the product,
- displaying the new product at exhibitions and presentations for more active promotion on the market.

Already in these very early stages of development, we can see that it is not only about the reverse-engineering but about evolution levels that can let you upgrade the combat platform to the next generation, thanks to an updated version of the actual Technical Data Package in the repository during exploitation, eliminating the need to transport the platform to a repair facility for modernization.

In the context of Rapid Repair, it is essential to consider the full value chain – not only for certified, high-performance printed parts but also for lower-quality, temporary 3D-printed components. In many cases, such parts may be sufficient for short-term use where cost-efficiency, speed, and mission continuity take precedence over long-term durability. However, their application must be supported by thorough risk analysis and cost-effectiveness assessments, especially in forward-deployed or resource-constrained environments.

As shown in Fig. 3, the initial digital model of the re-engineered part required 22 hours of print time, using 100 % infill and 5 shells, with approximately 50 % of the volume consisting of support structures. Fig. 4 shows that the first optimized version reduced the support volume and print time to 18 hours. Finally, Fig. 5 presents the fully optimized model, redesigned using Design for Additive Manufacturing (DfAM) principles, achieving an 82 % reduction in support material and completing the print in just 13 hours.

Fig. 6 shows several versions of the 3D-printed brake fluid tank installed in the engine bay of the selected Light tactical multirole vehicle during preliminary driving tests. These prototypes were manufactured using different AM-compatible polymer materials, each selected for specific performance characteristics, availability, or testing scenarios. The blue version shown in Fig. 6a is made from recycled PETG, demonstrating the potential for sustainable material use. The red variant shown in Fig. 6b, was printed with Prusament PTG in an optimized design for improved dimensional stability. Additional variants include Prusament PP11 (a polypropylene-based material) and a high-strength version made from Nylon with 15 % carbon fiber reinforcement (CF15), sourced from Fiberlogy, with a technical data sheet (TDS) attached.

This testing phase aimed to evaluate the behavior of various materials under operational conditions, including exposure to heat, vibration, and fluid interaction. The results will guide subsequent material selection, durability evaluation, and risk analysis for Rapid Repair applications – particularly in scenarios requiring temporary or field-fabricated components to sustain mission readiness.

To validate the functional performance of the re-engineered polymer component, the printed spare part was installed directly onto the engine platform, as shown in Fig. 7. This step marked the final phase of preparation before field testing. The part underwent installation checks for fitness, sealing, and mechanical stability under static conditions. Following successful integration, a controlled driving test was conducted to evaluate the component's behavior under real operational loads. This phase was critical in verifying the component's temporary service viability within the framework of Rapid Repair, demonstrating how AM-fabricated polymer parts can be used effectively in field conditions without immediate access to conventional metal replacements.

	
Fig. 6a Material: PETG-Recycled	*Fig. 6b Material: Red Optimized/PRUSA Research (Prusament PTG)*
	
Fig. 6c Material: Optimized/PRUSA Research (Prusament PP11)	*Fig. 6d Material: Nylon + CF15 from Fiberlogy (TDS attached)*

Fig. 6 Installed 3D-printed brake fluid tank prototypes made from various materials, prepared for evaluation under real operating conditions prior to driving tests

6 Discussion

The productivity of additive manufacturing (AM) processes is a key indicator of their effectiveness in supporting Rapid Repair in military and field environments. Productivity in this context is defined not only by the printing speed but also by the overall ability to produce a required number of functional components within a limited time frame, especially when operational constraints and supply chain disruptions exist [34-36].

In AM, print speed can be assessed in two ways: through vertical (linear) speed, assuming consistent cross-sectional area throughout the height, or volumetric speed, which accounts for varying geometry. As demonstrated in Case Study 1, where multiple iterations of a brake fluid tank were produced, significant gains in productivity were achieved through design optimization (Fig. 4). By applying Design for Additive Manufacturing (DfAM), the final version of the component reduced print time by over 40 % while maintaining functional integrity, clearly highlighting how geometric efficiency translates into operational readiness.

Fig. 7 Installed printed spare parts before driving tests

On the one hand, it is necessary to understand additive manufacturing technologies, including their material properties, capabilities, and limitations; on the other hand, non-technical constraints such as intellectual property rights must also be considered. From a technological perspective, a key limiting factor in the application of a given method is often the compatibility between the technology and the material for the intended application. This compatibility ultimately determines whether the required technical properties of the application can be achieved.

From a non-technical perspective, one of the most significant limiting factors is often the lack of clarity regarding the ownership of intellectual property rights or how such rights are defined. In conditions such as wartime, there is a reluctance to risk violating intellectual property rights, and determining these rights is often complex and costly.

Moreover, AM technologies present a clear cost advantage in low-volume, one-off production scenarios, particularly in battle damage repair where traditional supply chains and tooling are not practical. Complex or custom-shaped components that are costly, or even impossible, to fabricate using traditional methods can be rapidly produced with AM. This was particularly evident in the following case study, where a team of experts worked on the same light tactical multirole vehicle, successfully re-engineering an aluminum engine cover and producing it using high-performance polymers.

Despite the part's demanding operational environment (exposure to heat, oil, and vibration), it functioned reliably as a temporary substitute, proving that polymers can serve as viable short-term replacements when properly selected and tested.

A second key benefit of AM lies in the possibility of lightweight construction through topological optimization. By concentrating material only in high-stress zones and eliminating underutilized regions, components can be significantly lightened while retaining their strength. In agricultural and military vehicle applications, this translates to less wear on drivetrains, reduced energy consumption, and improved mechanical efficiency. AM allows these optimizations to be realized in practice without the constraints of traditional subtractive manufacturing.

However, additive manufacturing is not only about cost or weight reduction. When resources and time allow, AM can support the production of "next-generation" spare parts – components that go beyond simply replicating the original by integrating functional enhancements. These improvements may include bionic design features, modular integration of multiple parts into one, or internal geometries tailored for improved performance.

The ability to link multiple traditionally manufactured parts into a single additively manufactured component also simplifies design and reduces assembly complexity. This approach is conceptually validating in several Case Studies running inside the community, where multi-feature components were consolidated, further reducing the need for secondary fastening, sealing, or joining processes. In modern military logistics and equipment design, this simplification can translate into improved maintainability and reduced failure points.

Overall, the three case studies illustrate that AM is a multifunctional enabler – capable of delivering emergency solutions, cost-effective replacements, and even upgraded components within the same framework. Its flexibility across materials, geometries, and use cases makes it a powerful tool for Rapid Repair, especially at the 2nd and 3rd levels of logistic support.

7 Conclusions

This research confirms the effectiveness of Additive Manufacturing (AM) as a practical tool for rapid repair in military maintenance. AM enables accelerated prototyping, cost-efficient low-volume production, and the functional replacement of both polymer and metal components. In the case studies presented, AM facilitated faster design iteration and lightweight part optimization.

Equally important is the support provided by home-based facilities or other operational units, which significantly extends the capabilities of on-site AM deployments. This collaboration enables tasks that are often difficult to carry out in expeditionary environments, such as training in the operation of deployed systems and reach-back support for the design and qualification of parts not yet included in the digital repository.

With remote support, engineers at home stations can provide 3D modelling and finite element (FE) analyses to field personnel. This reach-back capability also supports the expansion of digital libraries, allowing for direct reproduction of conventional parts through one-to-one printing (when CAD data is unavailable), redesign of existing parts for AM adaptation, or the creation of entirely new component designs.

Authorization and certification processes typically require approval from personnel outside the expeditionary environment, particularly for mission-critical components. In such cases, the home base or the designated authority within the national defense materiel agency may be responsible for final approval. Critical components may also be produced and tested at home stations or certified facilities, ensuring consistency in materials and processing parameters with those used in the field.

From strategic levels down to tactical units, AM has demonstrably reduced production lead times and costs, enabled field-level manufacturing, and supported both repair and modernization initiatives. These outcomes highlight the strategic value of AM in strengthening mission readiness and resilience within defense logistics operations.

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