Peer-reviewed

Integrating Emerging Technologies in Military Maintenance and Repairs: An Overview of Current Status, Opportunities and Challenges

Integrace nových technologií do vojenské údržby a oprav: Přehled současného stavu, možností a výzev

Milan Vábek, Ondřej Novosad, Miroslav Pecina, Jan Kotisa

Abstract: Maintenance and repair (M&R) of military equipment are crucial for operational readiness. The article highlights challenges faced by military forces, particularly in the US, with significant equipment non-operable due to inefficient M&R. It emphasizes modernizing M&R through Predictive Maintenance (PM) and 3D Printing (AM). PM employs AI and data analytics for real-time monitoring and foreseeing malfunctions, signifying a strategic shift in M&R. AM significantly curtails downtime by enabling on-demand spare parts production, presenting a solution to traditional military M&R challenges. The article also underscores the economic advantages and potential for operational efficiency improvements through these technologies.

Abstrakt: Údržba a opravy vojenské techniky mají zásadní význam pro operační připravenost. Článek poukazuje na problémy, kterým čelí ozbrojenné síly, zejména v USA, kde je značná část vybavení nefunkční z důvodu neefektivní údržby a oprav. Zdůrazňuje modernizaci údržby a oprav prostřednictvím prediktivní údržby a 3D tisku. Technologie prediktivní údržby využívá umělou inteligenci a analýzu dat pro monitorování a předvídání poruch v reálném čase. Technologie 3D tisku významně zkracuje prostoje tím, že umožňuje výrobu náhradních dílů na vyžádání, a představuje tak řešení tradičních problémů vojenské údržby a oprav. Článek rovněž zdůrazňuje ekonomické výhody a potenciál pro zlepšení operační efektivity díky těmto technologiím.

Keywords: Maintenance; Predictive Maintenance; Repairs; 3D print.

Klíčová slova: údržba; prediktivní údržba; opravy; 3D tisk.

INTRODUCTION

Maintenance and repair of military equipment are some of the key factors that ensure the combat capability of the armed forces. These activities are crucial for all levels of command and control of the armed forces. The condition in which equipment must be maintained is precisely defined for each type of equipment. To ensure the operability of equipment, maintenance and servicing dates are precisely defined.

The maintenance and repair of the equipment are directly related to its operability. For example, the U.S. Navy's backlog of maintenance orders has grown to $1.8 billion, and the Air Force has problems with spare parts availability. Between 2019 and 2021, the U.S. Air Force examined the time that F-35A, F-35B, and F-35C aircraft are capable of partial or full mission deployment. In neither case were the aircraft able to achieve the minimum specified operational capability targets (U.S. Government Accountability Office 2023).

New trends in the repair and maintenance of equipment include artificial intelligence, predictive maintenance, 3D printing, and the use of 5G networks. For example, the use of a 5G network is possible in the Air Force, where Lockheed Martin has introduced a system that is compatible with the US Department of Defense's 5G network for the Air Force. The system is capable of sending flight diagnostic data to a predetermined device immediately after the aircraft lands, including AI-generated aircraft maintenance predictions. New technologies are having a significant impact on the repair and maintenance of military equipment (Lockheed Martin 2023).

Additive manufacturing, commonly known as 3D printing, is progressively becoming a pivotal solution in overcoming the challenges faced by military maintenance and repair operations. Developments in 3D printing technology have revealed new opportunities for producing spare parts on demand, significantly reducing downtime for critical military equipment awaiting maintenance or repair. The application of 3D printing in military maintenance and repair operations is an exemplification of how modern technology can be harnessed to solve traditional challenges, thereby enhancing the efficiency and readiness of the armed forces.

Predictive Maintenance represents a significant shift in the strategy of maintaining and repairing military equipment, which is crucial for ensuring the combat readiness of armed forces. This modern approach leverages technologies such as Artificial Intelligence (AI), Machine Learning (ML), and data analytics to monitor and analyse the condition of equipment in real-time, allowing for the prediction of potential failures or malfunctions before they happen. In conjunction with other modern technologies like 3D printing, Predictive Maintenance can provide valuable insights into when and where spare parts are needed, ensuring more efficient maintenance processes.

1 MILITARY MAINTENANCE

Ensuring optimal maintenance and repair of military equipment is crucial for the operational preparedness of armed forces globally. The functional reliability of such equipment, paramount to the performance of defence tasks, hinges on myriad factors. These include, but are not limited to, the age and complexity of the equipment, availability of spare parts, and the financial resources allocated.

Currently, while there is significant potential to enhance the maintenance and repair methodologies of military assets, defence forces face a multifaceted set of challenges. A primary determinant of a military's combat efficiency is its capability to adeptly manage and refurbish its assets. Hence, there is an overarching emphasis on integrating novel technologies and best practices to augment the maintenance regimes.

Under the purview of the Regionally Aligned Readiness and Modernization Model, the U.S. Army has delineated an objective of attaining a 66% combat readiness rate for its Regionally Aligned (RA) and Brigade Combat Teams (BCTs) by the year 2023 (Congressional Research Service 2022). Conversely, only 58% of Brigade Combat Teams currently satisfy the combat-ready criteria (The Heritage Foundation 2021).

The global military maintenance, repair, and overhaul (MRO) sector exhibits robust growth trajectories, corroborated by the escalating demand for advanced armaments and defense technologies. To quantify, the military aircraft MRO market was valued at $40.17 billion in 2022, with an anticipated CAGR of 4.39% from 2023 to 2033 (Visiongain Reports Ltd 2023).

The Global Firepower Index 2023 provides a comprehensive evaluation of national military capabilities by scrutinizing over 60 distinct parameters, ranging from financial and health to logistical infrastructure. Such rigorous assessments accentuate the indelible role of adept equipment maintenance in gauging a nation's defense prowess (GlobalFirePower 2023).

Although the principles of maintenance and repair are universally acknowledged across defence forces, individual nations confront distinct challenges. These challenges span budgetary allocations, evolving technological paradigms, and the inherent obsolescence associated with aging equipment.

Recent empirical studies offer intriguing insights. In a bid to optimize its operational efficacy, the U.S. Army is recalibrating its maintenance protocols to more accurately resonate with real-time equipment utilization. Pioneering research endeavours have facilitated a substantial reduction in the maintenance requisites for an estimated million Army vehicular assets and firearms. This strategic realignment prioritizes maintenance based on equipment operational frequency over traditional calendar-based intervals. The change is expected to save approximately 230,000 soldier workdays annually. This equates to around 632 man-years of effort (Winkie 2023).

2 PREDICTIVE MAINTENANCE

Predictive maintenance is gaining traction in the military sector, playing a pivotal role in enhancing operational readiness and cost-effectiveness. Predictive maintenance utilizes real-time asset data gathered through sensors, historical performance data, and advanced analytics to forecast asset failure, enabling timely interventions to prevent costly breakdowns. The biggest problems with predictive maintenance are high initial costs, lack of data, and trained personnel (NexTech Solutions 2023; Salerno-Garthwaite 2022).

Predictive maintenance is mostly used in the civilian sector. Various industries such as manufacturing, healthcare, and transportation have adopted predictive maintenance for efficient operations. In the automotive industry, predictive maintenance helps ensure functional safety over the product life cycle while controlling maintenance costs (Astuteanalytica 2023; Theissler et al. 2021, 1-17).

The implementation of predictive maintenance in the civilian sector, particularly in the automotive and aerospace industries, has demonstrated significant financial and operational benefits. For example, Lufthansa Technik provides predictive maintenance via its Aviatar platform, reducing up to 30 % of unscheduled removals. United Airlines collaborated with LHT to develop predictive maintenance systems for its Boeing 737 aircraft fleet, aiming to enhance operational efficiency and reduce unscheduled maintenance (Derber 2022; Stanton et al. 2023; Verhagen and De Boer 2018).

Another example of using predictive maintenance is Ford. Their model could predict 22 % of failures an average of 10 days in advance with a low false positive rate of 2.5 %. This led to an estimated savings of around $7 million by reducing 122 000 hours of downtime. The reduced downtime from 24 hours to 3 hours per incidence represented significant savings and operational efficiency for their customers (Kortical 2023).

These data show the tangible benefits and substantial savings that predictive maintenance can bring to different industries, hinting at its potential utility in military applications for maintaining and repairing military technology. By adopting predictive maintenance, organizations can significantly enhance operational efficiency, reduce downtime, and achieve substantial cost savings.

Predictive maintenance in military is mostly done by US Army. They are using predictive maintenance technology on helicopters AH-64 Apache, UH-60 Black Hawk, and also on CH-47 Chinook. In six-year period, the Army has reduced the cost of spare parts for these helicopters by more than 12 percent. US Army is also using this technology for approximately 2 500 wheeled vehicles. In a six-year period, it resulted in a cost avoidance of $24 million and helped identify maintenance trends (U.S. Government Accountability Office 2022).

However, the implementation of predictive maintenance faces challenges. Personnel, parts, technology and organization culture are main issues. Maintenance staff are overwhelmed and occasionally hesitant about predictive maintenance. In the area of spare parts, proper planning is necessary as delivery can take days or years. Technological barriers, including data transfer limitations, digitization of maintenance manuals, problems with outdated information systems, and a lack of portable laptops, make the implementation of predictive maintenance difficult (U.S. Government Accountability Office 2022).

3 ADDITIVE MANUFACTURING

The application of 3D printing, also known as additive manufacturing, has been expanding across various sectors, displaying a transition from primarily prototyping to manufacturing at scale (Scott 2022).

The global 3D printing market is experiencing robust growth, with a projected market size of USD 22.40 billion in 2023, escalating to USD 105.99 billion by 2030 at a CAGR of 24.9% (FortuneBussinessInsight 2023). In 2023 alone, analysts predict a 17% increase in market growth compared to 2022, translating to an additional USD 19.9 billion in income generated via 3D printing (Protolabs 2023).

The technology addresses global logistical challenges exacerbated by the pandemic by dispersing manufacturing and reducing transportation needs, thereby improving manufacturers‘ resilience. By localizing production and reducing the need for transportation, 3D printing is also contributing to lowering the carbon footprint associated with manufacturing processes (Scott 2022).

An important part of 3D printing is also the replication of spare parts in cases where the original manufacturer no longer exists or production documentation is unavailable, or where the production of spare parts is unprofitable in terms of small series. This gives older machines a chance for a “second life”.

For quick operational readiness, effective management of digital designs and data is crucial: storing digital models, designs, and data in the cloud. This allows easy sharing of information and real-time collaboration among teams or even with external partners.

Important for quality control and measurement of created parts is 3D scanning and measurement technology. This technology allows comparing actual results with the digital model, ensuring manufacturing accuracy. Universal application of ultra-precise handheld scanners for geometric inspection, as well as digitization of both small and large parts in the field.

Ongoing innovation in hardware, software, and automation within the 3D printing realm is driving major advancements poised to continue in the upcoming years (Protolabs 2023). New innovative materials extend the range of industries, applications, and use cases for 3D printing, marking a significant stride in material innovation (Henkel 2023).

However, new materials and technologies need corresponding software, which is becoming the core driver of innovation. This software facilitates the organization and integration of 3D printers within production workflows and aids in the automation of pre- and post-processing steps. Software advancements, especially those employing modern AI techniques like deep learning, are expected to significantly contribute to automation, traceability, and verticalization (Molitch-Hou 2023) .

The increasing role of artificial intelligence (AI) is influencing and enhancing 3D printing processes, such as optimizing design or manufacturing based on data analytics.

Additive manufacturing has lower fixed costs compared to traditional manufacturing processes like injection molding and vacuum forming. Due to its highly automated nature, 3D printing doesn‘t require expensive tooling, making it economically advantageous for producing smaller volumes of parts (AMFG 2021).

It also facilitates a shift towards digital inventory, allowing companies to store parts in a virtual catalogue, thereby reducing physical inventory costs. When a part is needed, it can be produced on-demand directly from a digital design file, significantly reducing lead times compared to traditional methods (AMFG 2021).

An example illustrates that a small aluminium bracket can be produced within a few days using 3D printing (DMLS technology), compared to the 12 weeks required by traditional methods like extrusion and metal bending processes (AMFG 2021).

Direct 3D printing of metal is not yet economically viable. Therefore, hybrid production can be used, when a one-time mold is printed into which the final product is cast. The disposable mold is printed from a mixture of sand or powdered plexiglas, which is then covered with a ceramic material. This is how combine modern additive manufacturing with classic conventional manufacturing. The costs, especially for the lower series of products, are noticeably lower, because there is no large input cost for an expensive mold.

The capability of 3D printing to produce complex geometries also enables the creation of customized or specialized spare parts, particularly beneficial in the automotive and aerospace sectors for producing parts that might be otherwise difficult or expensive with traditional methods (Formlabs 2023).

While 3D printing enables the creation of complex geometries, some parts may require final adjustments.

3D printing can also optimize the design of complex devices that are assembled from multiple, intricate, small parts. 3D printing in these cases allows multiple parts to be printed as a whole, eliminating complex and expensive product assembly.

The increasing significance lies in cloud-based 3D printing, with emerging trends in networked 3D printing, where printers are interconnected, collaborating on the production of more complex products. An example includes cutting-edge 3D manufacturing technologies such as HP MJF 3D Printing (Plastic) or HP Metaljet (metal), which already leverage cloud solutions. Manufacturing data is pre-prepared and does not include specific, sensitive geometric part data. This allows for the rapid production of innovative parts (updates) and their global sharing within NATO.

Examples of successful applications include companies like British Airways, which explored using 3D printing to create up to 10 aircraft spare parts, suggesting a proactive approach to leveraging additive manufacturing for maintenance and repair purposes (Bellamy 2020).

Airbus has integrated 3D printed parts into various aircraft models(Wang et al., 2019, 4059-4069). A proof of concept by Autodesk showcased that a 3D printed aircraft seat was, on average, 56% lighter than its conventional counterpart. This weight reduction indirectly leads to fuel savings, making aircraft more cost-effective and environmentally friendly (Vertas 2023).

Electrolux is exploring 3D printing for spare parts production to increase savings without additional investments, highlighting the potential cost-saving aspect of additive manufacturing in spare parts production (Song and Zhang 2019, 3860–3878). This move responds to the fact that over 85% of spare parts suppliers will integrate disruptive 3D printing technology into their businesses within the next five years to reduce lead time and costs (Saunders 2017).

The potential of 3D printing lies in reducing maintenance costs, improving operational efficiency, and promoting sustainable practices through weight reduction and material savings. Similar to predictive maintenance, 3D printing for spare parts production could significantly benefit the maintenance and repair of military technology by ensuring timely availability of crucial parts, reducing logistic burdens, and promoting cost savings.

Information on military use is challenging to obtain. However, an overview of the current situation can be sourced from U.S. Department of Defence projects. 3D printing is being used in the conflict in Ukraine for both defensive and civilian purposes. The ability to 3D print a digital file of a broken or damaged part and obtain a finished product in less than 48 hours facilitates a rapid response to equipment repair needs, crucial for mission-critical operations (Ross 2022).

The U.S. military has increasingly harnessed 3D printing to tackle supply chain challenges exacerbated by the pandemic. Issues like pandemic-induced backlogs, raw material blockages at ports, and halted production lines due to chip shortages prompted innovative solutions. In one notable effort, the U.S. Navy strategized to match suppliers struggling with submarine parts‘ demand to 3D printing companies capable of continuous metal part production, thereby enhancing supply (Schwaar 2022).

3D printing isn‘t just about meeting demand – it‘s revolutionizing logistics and production. This technology cuts down both costs and time typically spent shipping replacement parts from distant machine tooling centres. In a bid to move manufacturing closer to operational zones, the Department of Defence (DoD) partnered with ExOne to create a mobile 40-ft long additive manufacturing unit suitable for deployment on both land and sea (Schwaar 2022).

Highlighting the versatility of 3D printing, the U.S. Army Aviation and Missile Command (AMCOM) pinpointed 77 components as prime 3D printing candidates. In a groundbreaking project, Wichita State University teamed up with the U.S. Army to dismantle a Black Hawk helicopter. Every component was 3D scanned, resulting in digital models ready for immediate 3D printing whenever spare parts are required (Sertoglu 2020).

In New Jersey, the U.S. Army‘s Armament Research, Development and Engineering Center (ARDEC) procured a Rize One 3D printer, aiming for swift production of spare parts and tools (Scott Hay 2019). Demonstrating the Army‘s earnest investment in this technology, the Additive Manufacturing Center of Excellence at Rock Island Arsenal boasts 21 3D printers. These machines can craft products from materials like titanium, steel, and aluminium (NatinoalDEFENSE 2020).

Furthermore, the Picatinny Arsenal in New Jersey introduced an innovative grenade launcher named the Rapid Additively Manufactured Ballistics Ordnance (RAMBO). This device, a refined version of the M203 launcher, showcases the practical application of 3D printing in weapon production (Defensemedianetwork 2023).

Highlighting the strategic importance of this technology, the US DoD has been integrating 3D printing into the Defence Logistics Agency’s system, specifically the Joint Additive Manufacturing Model Exchange (JAMMEX). This move underscores the military's escalating dependence on additive manufacturing to bolster its logistical backbone (SIGNAL 2023).

The use of additive manufacturing offers an economically and time-relevant solution for specific situations. However, there are many problems and challenges to overcome. 3D printing, while revolutionary, is susceptible to the proliferation of counterfeit or unauthorized products. These not only present safety concerns but also potential cybersecurity threats. When manufacturers enable third parties to 3D print parts, they expose their design files, creating a gateway for malicious entities to produce subpar, unauthorized items (Cooley 2021).

Navigating this territory requires addressing numerous legal hurdles. Issues related to warranties, particularly in regions like China where purchases from non-OEM suppliers are common, need clarification (Strategyand 2017). As of now, there's a lack of specific legislation in the EU, UK, or US tailored to oversee 3D printing. Typically, responsibilities fall on manufacturers, importers, and distributors to ensure product safety. Consequently, any third party selling 3D printed parts must adhere to the same compliance and safety norms as other consumer products (Cooley 2021).

Existing product liability regulations stipulate that 3D printed part producers are held accountable for any defects leading to damage. However, pinpointing the root cause of such defects is complex. It's challenging to determine whether the fault lies in the design file, the raw materials, the manufacturing process, storage conditions, installation methods, or even in the design or functionality of the 3D printer itselfc (Cooley 2021).

It is also important to remember that while 3D printing improves military maintenance logistics by enabling on-demand production of spare parts, the supply chain of 3D printing materials must not be forgotten. Efficient supply and distribution of these materials are crucial for maintaining system efficiency and avoiding delays in equipment repairs, which requires a coordinated effort between production and logistics.

CONCLUSION

The evolving landscape of military maintenance and repair is at a critical juncture where the integration of modern technologies like Predictive Maintenance and Additive Manufacturing can significantly enhance operational readiness and cost-efficiency. The insights provided in this article underline the paramount importance of transitioning from traditional M&R practices to a more technologically driven approach, in alignment with the current digital transformation era. The economic advantages and operational efficiency improvements are compelling arguments for advancing the integration of these technologies.

However, several hurdles need to be navigated for successful implementation. The high initial costs, the necessity for trained personnel, and the critical issue of counterfeit production in AM pose significant challenges. Addressing these challenges necessitates a holistic approach that encompasses not only technological advancements but also robust policies, training programs, and international collaborations to establish standardized protocols and ensure security. Furthermore, a structured framework for evaluating the effectiveness and ROI of PM and AM technologies in military M&R will be instrumental in guiding future investments and research in this domain.

The potential of PM and AM in revolutionizing military M&R is vast, yet it requires a concerted effort from military organizations, technology developers, policymakers, and the global defence community to realize this potential fully. The discourse presented in this article aims to foster a deeper understanding and stimulate further research and discussions on optimizing military M&R strategies through technological advancements. Through collaborative efforts and a forward-thinking approach, the military sector can significantly benefit from PM and AM, ensuring a higher level of operational readiness, cost savings, and a strategic edge in the modern battlefield.

In light of the advancements discussed, the future trajectory of military maintenance is likely to be profoundly shaped by the continued evolution and integration of predictive maintenance and additive manufacturing technologies. Predictive maintenance, with its capability for real-time monitoring and forecasting, is expected to significantly enhance operational readiness and cost efficiency. Simultaneously, additive manufacturing promises to revolutionize logistics and supply chains through on-demand production capabilities. Together, these technologies are poised to address current limitations in maintenance efficiency, spare part availability, and logistical flexibility. As they mature and their adoption widens, a paradigm shift in military maintenance strategies towards more resilient, responsive, and technologically advanced frameworks is foreseen, resulting in the improvement of combat readiness and operational capabilities of military forces worldwide.

In conclusion, while the integration of predictive maintenance and 3D printing technologies presents a significant advancement in military maintenance, it also opens avenues for future research. Specifically, logistics, distribution chains, and the costs associated with these technologies are anticipated as key areas.

REFERENCES

AMFG. 2018. “How 3D Printing is Transforming the Spare Parts Industry 2021 Update.” Accessed November 1, 2023.
https://amfg.ai/2018/05/29/3d-printing-transforming-spare-parts-industry/

Astute Analytica. 2023. “Predictive maintenance market – Industry Dynamicsm Market Size, And Opportunity Forecast To 2031.” Astute Analytica. Accessed November 1, 2023.
https://www.astuteanalytica.com/industry-report/predictive-maintenance-market

Bellamy, Woodrow III. 2020. “How the Aerospace Industry is Finding New 3D-Printing Use Cases for Old Aircraft Parts.” Avionics International. Accessed November 1, 2023.
https://www.aviationtoday.com/2020/11/30/aerospace-industry-finding-new-3d-printing-use-cases-old-aircraft-parts/

Congressional Research Service. 2022. “The Army’s Regionally Aligned Readiness and Modernization Model.” Congressional Research Service. Accessed November 1, 2023. https://crsreports.congress.gov/product/pdf/IF/IF11670

Cooley. 2021. “3D printing of spare parts – multi-dimensional implications for consumer product regulation.” Accessed November 1, 2023.
https://products.cooley.com/2021/01/26/3d-printing-of-spare-parts-multi-dimensional-implications-for-consumer-product-regulation/

Defensemedianetwork. 2023. “Additive Manufacturing.” Accessed November 1, 2023.
https://www.defensemedianetwork.com/stories/additive-manufacturing-department-of-defense-3d-printing-military-logistics/

Derber, Alex. 2022. “Airlines Using Predictive Maintenance Reap Big Benefits.” Aviation Week.
https://aviationweek.com/mro/emerging-technologies/airlines-using-predictive-maintenance-reap-big-benefits.

Formlabs. 2023. “How to 3D Print Replacement Parts and Spare Parts”. Accessed November 1, 2023
https://formlabs.com/blog/3d-print-replacement-parts-spare-parts/

FortuneBussinessInsight. 2023. “3D printing market.” Accessed November 1, 2023
https://www.fortunebusinessinsights.com/industry-reports/3d-printing-market-101902

GlobalFirePower. 2023. “2023 Military Strength Ranking.” GlobalFirePower. Accessed November 1, 2023.
https://www.globalfirepower.com/countries-listing.php

Henkel. 2023. “Henkel Loctite 3D Printing launches novel innovative materials for industrial applications at Formnext.” Accessed November 1, 2023
https://www.henkel.com/press-and-media/press-releases-and-kits/2023-10-31-henkel-loctite-3d-printing-launches-novel-innovative-materials-for-industrial-applications-at-formnext-1895510

Kortical. 2023. “Predictive maintenance: Predicting vehicle failures before they happen via connected modem data with Ford.” Accessed November 1, 2023
https://kortical.com/case-studies/ford-predicting-failures-ai-example

Lockheed Martin. 2023. “Lockheed Martin Demonstrates Scalable, Portable Maintenance Capabilities On 5G Network.” Lockheed Martin. Accessed November 1, 2023.
https://news.lockheedmartin.com/2023-04-03-Lockheed-Martin-Demonstrates-Scalable-Portable-Maintenance-Capabilities-on-5G-Network.

Molitch-Hou, Michael. 2023. “3D Printing Predictions: Software and Automation.” 3Dprint.com. Accessed November 1, 2023
https://3dprint.com/296552/2023-3d-printing-predictions-software-and-automation/

National DEFENSE. 2020. „Army Gung-Ho on 3D Printing Spare Parts“ Accessed November 1, 2023.
https://www.nationaldefensemagazine.org/articles/2020/12/11/army-gung-ho-on-3d-printing-spare-parts

NexTech Solutions. 2023. “The Importance of Predictive Maintenance for the Military.” NexTech Solutions. Accessed November 1, 2023.
https://www.nextechsol.com/the-importance-of-predictive-maintenance-for-the-military.

Protolabs. 2023. “Market Insights and Forecasts for 3D Printing Trends in 2023.” Accessed November 1, 2023.
https://www.protolabs.com/resources/guides-and-trend-reports/market-insights-and-forecasts-for-3d-printing-trends-in-2023/

Ross, Laura. 2022. “U.S. Military Turns to 3D Printing for Mission-critical Supplies.” Thomas. Accessed November 1, 2023.
https://www.thomasnet.com/insights/u-s-military-turns-to-3d-printing-for-mission-critical-supplies/

Salerno-Garthwaite, Andrew. 2022. “Predictive maintenance in US military needs action: GAO.” Army Technology. Accessed November 1, 2023.
https://www.army-technology.com/features/predictive-maintenance-in-us-military-needs-action-gao/.

Saunders, Sarah. 2017. “Studying Feasibility: 3D Printing for Spare Parts Production.” 3Dprint.com. Accessed November 1, 2023
https://3dprint.com/191516/spare-parts-3d-feasibility-study/

Schwaar, Carolyn. 2022. ”U.S. Military To 3D Print Its Way Out Of Supply Chain Woes.” Forbes. Accessed November 1, 2023
https://www.forbes.com/sites/carolynschwaar/2022/02/27/us-military-to-3d-print-its-way-out-of-supply-chain-woes/

Scott, Daniel. 2022. “2023Trends: 3D Printing Looks to Take the Next Step” Icr. Accessed November 1, 2023
https://icrinc.com/insights/2023-trends-3d-printing/

Scott Hay, James. 2019. „U.S. Army acquires Rize One 3D printer for spare parts on-demand“ LinkedIn, March, 3, 2019.

https://www.linkedin.com/pulse/
us-army-acquires-rize-one-3d-printer-spare-parts-on-demand-hay

Sertoglu, Kubi. 2020 "U.S. ARMY AND WSU TO 3D PRINT BLACK HAWK HELICOPTER COMPONENTS." 3DPrintingIndustry. Accessed November 1, 2023
https://3dprintingindustry.com/
news/u-s-army-and-wsu-to-3d-print-black-hawk-helicopter-components-171927/

SIGNAL. 2023. "Additive Manufacturing and 3D Printing Keeps the U.S. Army Ready." Accessed November 1, 2023
https://www.afcea.org/signal-media/defense-operations/
additive-manufacturing-and-3d-printing-keeps-us-army-ready

Song, Jing-Sheng and Zhang,Yue. 2020. "Stock or Print? Impact of 3-D Printing on Spare Parts Logistics. Management Science 66,(9). 3860–3878.
https://doi.org/10.1287/mnsc.2019.3409

Stanton, Izaak, Kamran Munir, Ahsan Ikram, and Murad El-Bakry. 2023. "Predictive maintenance analytics and implementation for aircraft: Challenges and opportunities." Systems Engineering 26 (2): 216-237.
https://doi.org/10.1002/sys.21651.

Strategyand. 2017. "The future of spare parts is 3D: A look at the challenges and opportunities of 3D printing." Accessed November 1, 2023.
https://www.strategyand.pwc.com/gx/en/insights/2017/future-spare-parts-3d.html

The Heritage Foundation. 2021. "Heritage Foundation Releases 2022 Index of U.S. Military Strength. Online." The Heritage Foundation. Accessed November 1, 2023.
https://www.heritage.org/press/
heritage-foundation-releases-2022-index-us-military-strength.

Theissler, Andreas, Judith Pérez-Velázquez, Marcel Kettelgerdes, and Gordon Elger. 2021. "Predictive maintenance enabled by machine learning: Use cases and challenges in the automotive industry." *Reliability Engineering & System Safety* 215.
https://doi.org/10.1016/j.ress.2021.107864.

U.S. Government Accountability Office. 2023. *Military readiness: Actions Needed to Further Implement Predictive Maintenance on Weapon Systems. GAO-23-105556.* Washington, DC. Accessed November 1, 2023.
https://www.gao.gov/assets/gao-23-105556.pdf.

U.S. Government Accountability Office. 2023. *Military readiness: Improvement in Some Areas, but Sustainment and Other Challenges Persist. GAO-23-106673.* Washington, DC. Accessed November 1, 2023.
https://www.gao.gov/assets/gao-23-106673.pdf.

Verhagen, Wim J.C., and Lennaert W.M. De Boer. 2018. "Predictive maintenance for aircraft components using proportional hazard models." Journal of Industrial Information Integration 12: 23-30.
https://doi.org/10.1016/j.jii.2018.04.004.

Vertas. 2023. "3D printed spare parts – a market worth US$400 billion." Accessed November 1, 2023
https://www.vertas.com/news/3d-printed-spare-parts-a-market-worth-us400-billion/

Visiongain Reports Ltd. 2023. "Military Aircraft Maintenance, Repair & Overhaul (MRO) market is projected to grow at a CAGR of 4.39% by 2033: Visiongain Reports Ltd." Yahoo Finance. Accessed 1 November 2023.
ttps://finance.yahoo.com/news/military-aircraft-maintenance-repair-overhaul-151500010.html

Wang, Yu.-Cheng.; Chen, Toly.; Yeh, Yung.-Lan. 2019. "Advanced 3D printing technologies for the aircraft industry: A fuzzy systematic approach for assessing the critical factors." Journal of Advanced Manufacturing Technology 105, 4059–4069.
https://doi.org/10.1007/s00170-018-1927-8

Winkie, Davis. 2023. "Army overhauling vehicle, weapon maintenance in 'common sense' move." Army Times. Accessed 1 November 2023.
https://www.armytimes.com/news/your-army/2023/10/18/army-overhauling-vehicle-weapon-maintenance-in-common-sense-move/

Authors: ***1LT Milan Vábek****, born 1995. Graduate of the Master's degree programme of the University of Defence. He is currently working as an assistant at the Department of Logistics at the University of Defence in Brno and at the same time he is a student of the PhD programme in the Theory of National Defence. He is interested in modelling and simulations and application of new technologies in logistics.*

1LT Ondřej Novosad*, born 1997. Graduate of the University of Defence (2021). From 2021 to 2023 he worked at the battalion headquarters. He is currently studying a PhD in the Theory of National Defence programme at the Faculty of Military Leadership of the University of Defence.*

Assoc. prof. Miroslav Pecina, PhD*, born 1957. He worked his way through basic technical functions at tactical and operational level. He worked, among others, as the head of the Strategy and Operational Logistics Management Group at the Institute of Operational and Tactical Studies and Deputy Head of the Department of Military Logistics. He has contributed to a number*

of scientific papers, technical texts and military publications. Currently, he works at the Department of Logistics at the Faculty of Military Leadership of the University of Defence. He deals with the issue of information support of operational logistics

***LTC Jan Kotisa**, born 1974. Graduate of the Bachelor's degree programme in Military Logistics, specialization in POL at Military academy Vyškov (1995) and Master's degree programme in Economics and Management, study programme in Economics of National Defence, Military academy Vyškov (2003). During his military career he worked 25 years in various logistics functions and completed 2 foreign missions. He is currently working at the University of Defence as the Head of the Logistics Services Group, Department of Logistics, Faculty of Military Leadership. He is also studying a PhD in National Defence Theory at the Faculty of Military Leadership, University of Defence.*