ADDITIVE MANUFACTURING OF SPARE PARTS IN MILITARY MAINTENANCE SYSTEMS: A REVIEW OF TECHNOLOGICAL ADVANCES AND LOGISTICAL IMPLICATIONS

Rumen Angelov

Sofia University "St. Kliment Ohridski"
Sofia, Republic of Bulgaria
E-mail: rumen.angelov@uni-sofia.bg

Received: 17.01.2026. Revised: 14.04.2026. Approved: 18.05.2026.

Review Scientific Article

DOI: https://doi.org/10.65932/military-studies-2026-1-8 **UDC:** 621.7:355.415

Abstract: Military maintenance organizations hold some of the largest and least liquid spare parts inventories in existence, and they operate them under conditions that commercial after-sales networks rarely face: intermittent demand, aging platforms, vanished suppliers, and supply lines that an adversary actively tries to sever. This review examines what additive manufacturing (AM) can realistically contribute to such systems. Drawing on 49 verified sources published between 2019 and 2025, of which 46 are peer-reviewed journal articles, the analysis is organized along three axes: the technological maturity of AM processes relevant to spare parts production and repair; the logistical and economic evidence on when printing outperforms stocking; and the qualification, certification, and digital-security constraints that currently govern adoption. The evidence supports a consistent conclusion. AM already delivers documented value at the margins of military supply chains. Audit data record procurement lead times cut from two years to roughly one week, and unit costs reduced by several orders of magnitude for selected parts. Yet operations research modeling shows that printing complements rather than replaces inventory, with dual-sourcing savings of 8-30% concentrated among low-demand, long-lead-time items. The binding constraints are no longer primarily technical: qualification pathways, fatigue-critical defect populations, and the cybersecurity of the digital thread now set the adoption frontier. The review contributes a three-axis readiness framing that connects engineering, logistics, and assurance literatures which have largely developed in isolation, and identifies the research gaps that matter most for defense maintenance planners.

Keywords: *additive manufacturing, spare parts, military logistics, maintenance, supply chain, qualification and certification, digital thread.*

INTRODUCTION

Few problems in defense management are as persistent, or as expensive, as the supply of spare parts. A 2019 audit established that at least 81 depots, maintenance facilities, and field units across the United States armed services had already introduced additive manufacturing (AM) for parts and tooling, a figure that signals both real momentum and considerable fragmentation, since the same audit criticized the absence of a shared parts database and of standardized reporting across the services (U.S. Department of Defense Office of Inspector General, 2019). The logistical background explains the interest. Military maintenance systems support platforms whose service lives routinely exceed four decades, whose original suppliers may no longer exist, and whose repair parts exhibit demand patterns so intermittent that

Military Studies: Journal for Strategy, Technology and Defence Sciences , Year 2026, Volume: 4, Issue: 1, Serial number: 5, p. 117 – 131.

classical forecasting performs poorly (McDermott et al., 2021; Mecheter et al., 2022). The Defense Logistics Agency manages millions of line items of Class IX repair parts, and its 2022 implementation plan treats additive production as a standing element of supply policy rather than an experiment (Defense Logistics Agency, 2022).

Interest has sharpened for a second reason: contested logistics. Deployed forces operate at the end of long, vulnerable resupply lines, and recent operational experience, including the extensive use of desktop printing for improvised components in the war in Ukraine, has demonstrated that localized production can substitute for disrupted supply in ways that were largely theoretical a decade ago (Marciniak, 2023). The United States Department of Defense issued its first department-wide AM strategy in January 2021, structured around five goals that range from integrating AM into the defense industrial base to securing the additive workflow itself (U.S. Department of Defense, 2021). Case research from European forces points the same direction. Studies of the Dutch army's spare parts chain in expeditionary missions identify shorter lead times, reduced inventories, and lower waste as realistic gains (den Boer et al., 2020), while Finnish work documents a deliberate national effort to embed printing capability inside the military maintenance system through a hybrid arrangement with a commercial partner (Valtonen et al., 2022).

The academic literatures that bear on this development are curiously disconnected. Engineering reviews synthesize process physics, materials behavior, and qualification practice in great depth. A single aerospace-focused review draws on 357 sources (Blakey-Milner et al., 2021). But these works rarely engage inventory theory. Operations research has produced increasingly refined models of the print-versus-stock decision (Knofius et al., 2021; Sgarbossa et al., 2021; Song & Zhang, 2020), yet those models seldom incorporate the qualification and security constraints that dominate defense practice. Defense-specific empirical studies exist, but they remain few and are scattered across journals that engineering and logistics scholars do not usually read together (Rautio & Valtonen, 2022; Valtonen et al., 2023; Westerweel et al., 2021). Systematic reviews of AM in supply chains confirm the imbalance: of 60 studies analyzed in one such review, most concerned civilian aviation, with military applications forming a small minority (Mecheter et al., 2022).

This article reviews the post-2019 evidence with three questions in view. First, which additive processes are technologically mature enough to produce or repair military-relevant spare parts, and for which part classes (RQ1)? Second, what does the quantitative logistics and economics literature establish about when additive production outperforms, or should be combined with, conventional stocking in maintenance supply chains (RQ2)? Third, which qualification, certification, and digital-security constraints currently bind adoption in military maintenance systems, and what do they imply for implementation (RQ3)?

The contribution of this review lies in connecting three bodies of work that have developed largely in isolation, namely process engineering, operations research on spare parts, and the assurance literature on qualification and digital-thread security, and in reading them jointly through the specific conditions of military maintenance: extreme downtime costs, intermittent demand, contested resupply, and institutional accountability for airworthiness and safety. I restrict the corpus to sources published from 2019 onward and verify every bibliographic record against the Crossref registry, which matters in a field where secondary literature has begun to accumulate citation errors. The remainder proceeds as follows: a review of the literature and the method; a presentation of the empirical results reported by the reviewed studies; three analytical sections corresponding to the research questions; and a conclusion with limitations and a research agenda.

LITERATURE REVIEW AND METHODOLOGY

Literature Review

Systematic reviews published since 2020 give a reasonable map of the field's shape. Mecheter et al. (2022) screened 152 records and analyzed 60 studies from the period 2010-2021, finding the literature concentrated in aviation and reporting dual sourcing, additive alongside conventional supply, as the most frequently recommended configuration. Kunovjanek et al. (2022) screened 1,004 articles and coded 141 in full against the SCOR framework, documenting benefits and obstacles across sectors from aerospace to consumer goods. A review focused on aerospace spare parts content-analyzed 136 articles selected from an initial pool of 4,788 and collected the most striking case figures in circulation, including a part whose lead time and cost fell from 45 days and 2,000 dollars to two days and 412 dollars after conversion to additive production (Debnath et al., 2022). Reviews of adjacent questions complete the picture: 87 papers on the resilience implications of AM adoption (Naghshineh & Carvalho, 2022), 87 studies on advanced manufacturing adoption barriers and enablers (Stornelli et al., 2021), and 206 papers on the circular-economy dimension, where recycling alone accounts for half of the literature (Ponis et al., 2021).

The defense-specific stream is thinner but has grown into a recognizable cluster. den Boer et al. (2020) combined desk research, literature review, and stakeholder interviews around Dutch military and humanitarian missions. Westerweel et al. (2021) formalized the deployed-operations problem as a Markov decision process using data from the Dutch contribution to the United Nations mission in Mali. McDermott et al. (2021) linked intermittent-demand characterization to supply network design through Monte Carlo simulation and mixed-integer programming, publishing in a dedicated defense analytics journal. Finnish researchers contributed a connected series: a capability study of the Finnish Defence Forces and their strategic maintenance partner (Valtonen et al., 2022), a system dynamics assessment built on real printing data for MT-LB armored vehicle parts (Rautio & Valtonen, 2022), and a resilience-oriented simulation (Valtonen et al., 2023). Survey work with 140 maritime end-users provides the nearest civilian analog to naval sustainment (Kostidi et al., 2021), and a recent treatment of fused deposition modeling in military applications documents wartime improvisation in Ukraine (Marciniak, 2023).

On the engineering side, mature reviews now exist for every process family relevant to spare parts: aerospace metal AM broadly (Blakey-Milner et al., 2021), directed energy deposition (Svetlizky et al., 2021), wire arc deposition (Raut & Taiwade, 2021), cold spray (Vaz et al., 2023), binder jetting (Mostafaei et al., 2021), powder bed fusion of nickel superalloys (Sanchez et al., 2021), titanium alloys (Liu & Shin, 2019), surface post-treatment (Maleki et al., 2021), and defect-driven fatigue (Sanaei & Fatemi, 2021). Bibliometric work shows how young this convergence is: 86.8% of the literature linking AM to Industry 4.0 appeared in the four years before 2020 (Hernandez Korner et al., 2020). What is missing, and what this review attempts, is a reading that carries the engineering findings into the logistics models, and both into the assurance constraints that decide what a military maintenance organization may actually install on a platform.

A fourth strand addresses economics and sustainability directly. Cost modeling has moved from deterministic activity-based accounting toward general formulations that include build failure risk (Ding et al., 2021), and empirical cost assessments now exist for realistic spare parts portfolios rather than idealized cases (Ahlsell et al., 2023). Energy studies quantify the full chain from powder production to post-processing (Gao et al., 2021;

Majeed et al., 2020), while sustainability syntheses organize the field across design, manufacturing, and end-of-life phases (Su et al., 2024) and within circular-economy framings that stress repair and remanufacturing (Colorado et al., 2020). Publication activity in the circular-economy strand nearly tripled between 2017 and 2018 alone (Ponis et al., 2021). For maintenance organizations this strand matters because life-cycle arguments, not unit-cost arguments, are where the additive case is usually won or lost.

Research Methodology

The review covers sources published between January 2019 and mid-2025. I searched the major publisher platforms, among them ScienceDirect, SpringerLink, Taylor and Francis Online, Wiley Online Library, IEEE Xplore, Emerald Insight, MDPI, and the INFORMS collection, combining process terms (additive manufacturing, 3D printing, powder bed fusion, directed energy deposition, wire arc, cold spray, binder jetting) with application terms (spare parts, maintenance, sustainment, military, defense, repair) and constraint terms (qualification, certification, non-destructive testing, cybersecurity). Inclusion required peer review, a resolvable digital object identifier, and publication in 2019 or later. Three institutional documents from the United States defense establishment were added as primary sources on policy and adoption scale (Defense Logistics Agency, 2022; U.S. Department of Defense, 2021; U.S. Department of Defense Office of Inspector General, 2019).

Two protocol decisions deserve comment. I verified each of the 46 journal records against the Crossref registry and reconciled titles, author lists, years, and pagination before inclusion; records that could not be reconciled were dropped rather than repaired. And I chose thematic synthesis over meta-analysis deliberately. The outcome measures in this corpus, which range from cost ratios and lead-time reductions to simulation savings percentages and hardness values, are too heterogeneous to pool, and forcing them into a common effect size would create precision that the underlying studies cannot support. The synthesis instead organizes findings along three axes: technological maturity, logistical and economic performance, and assurance constraints. The final corpus numbers 49 sources. A weakness of the protocol, discussed in the conclusion, is its restriction to English-language publications and public documents; classified or export-controlled results are by construction invisible here.

RESEARCH RESULTS

Four groups of findings emerge from the corpus, and I present them here without interpretation. The first group concerns adoption scale and policy. The audit record establishes that at least 81 United States military maintenance sites had operational AM capability by late 2019, while also finding that the services could not tell each other what they had printed (U.S. Department of Defense Office of Inspector General, 2019). The 2021 departmental strategy formalized five goals for the technology, from industrial-base integration to workflow security (U.S. Department of Defense, 2021), and the Defense Logistics Agency's implementation plan operationalized these through six lines of effort, supported by a joint model exchange that held hundreds of printable part files, more than 30 of which were added in 2020 for pandemic-related equipment alone (Defense Logistics Agency, 2022). In the wider defense industrial base, one engine manufacturer had produced over 30,000 additively manufactured fuel nozzles by 2021, consolidating roughly 20 parts into one and removing about a quarter of the component's weight (Blakey-Milner et al., 2021).

The second group concerns process performance. For repair, directed energy deposition produced a heat-affected zone 21.5 times smaller than conventional welding in gray cast iron, with 62% higher elongation in the repaired material; a repaired Inconel 718 turbine compressor seal cost 45% of a new part, and repaired drive shafts about half (Saboori et al., 2019). Cold spray deposits reached densities above 99% at deposition rates on the order of kilograms per hour, and cold-sprayed Inconel 625 exhibited hardness near 600 HV against values below 300 HV for the same alloy from arc- or laser-based routes (Vaz et al., 2023). Wire arc deposition achieved mechanical properties comparable to wrought or cast equivalents at deposition rates well above powder-bed processes (Raut & Taiwade, 2021). Surface condition remains the recurring weakness of as-built parts: machining reduced the roughness of a laser powder bed fusion titanium surface from 33.90 to 0.89 micrometers, and surface treatments improved bending and axial fatigue strength by roughly 30% and 50% respectively (Maleki et al., 2021). Fatigue scatter in additively produced metals traces predominantly to lack-of-fusion defects, gas porosity, and surface roughness, with hot isostatic pressing and machining as the standard mitigations (Sanaei & Fatemi, 2021).

The third group concerns logistics and economics, and it divides into documented cases and model results. Among the cases: a sonar system cover for the MH-60R helicopter fell from a two-year procurement lead time to roughly one week, and an F-35 landing gear door component was printed for 0.75 dollars against approximately 70,000 dollars for the conventionally procured assembly (U.S. Department of Defense Office of Inspector General, 2019). The aerospace review literature records buy-to-fly ratios improved from roughly 10:1 to near 1:1 and transport-related emissions reduced by 7-9 percentage points under decentralized production (Debnath et al., 2022). An industrial field experiment on 36 problematic spare parts found conventional lead times of two to six weeks, and up to twenty when tooling had to be remade, and used a downtime cost of 100 euros per hour to show that lead-time value can justify a higher additive unit cost (Akmal et al., 2022).

Among the model results: dual sourcing that combines additive and conventional supply produced savings above 30% against the best single-sourcing policy even when the printed part was three times more expensive or less reliable, with average savings near 8% across 6,561 problem instances and around 17% in remote settings with short additive lead times (Knofius et al., 2021). A stochastic model of the stock-or-print decision found printing and stocking complementary, printers lightly utilized at the optimum, and the value of printing rising with part variety but falling with part criticality (Song & Zhang, 2020). Deployed-operations modeling with data from the Mali mission showed on-site printing outperforming expedited resupply under a double-threshold policy (Westerweel et al., 2021). Simulation across more than 2,000 scenarios found insourcing additive capacity generally unprofitable in unconstrained inventory systems but viable in about 69% of cases under storage restrictions, with cost reductions up to 46% (Lolli et al., 2025). A supply chain cost assessment of 14 slow-moving parts found additive production cheaper for only three, with the savings arising from inventory and warehousing rather than unit production cost (Ahlsell et al., 2023). System dynamics work with real military printing data identified production speed as the single most limiting factor at field level (Rautio & Valtonen, 2022), and a follow-on resilience study concluded that, at current speeds, depot-level inventories remain the better resilience instrument (Valtonen et al., 2023). Game-theoretic analysis found hybrid offerings of printed and conventional parts optimal at moderate unavailability costs (Sun et al., 2024), and analysis of licensing models in which equipment owners print locally found decentralized production optimal across a surprisingly wide parameter range, with profit gains for all supply chain parties (Zhang et al., 2022).

The economics-and-sustainability findings attach to the third group. A general cost model that includes failure probabilities shows unit costs rising materially once failed builds are priced in (Ding et al., 2021). Energy reviews report high specific energy consumption for metal additive processes, with feedstock production and post-processing contributing substantial shares of the total (Gao et al., 2021; Majeed et al., 2020). In the circular-economy literature, recycling appears in half of the 206 reviewed papers, reuse in 21.4%, and remanufacturing or repair in 10.7% (Ponis et al., 2021). A synthesis of 258 sources organizes sustainability effects across design, manufacturing, and post-manufacturing phases, crediting topology optimization and part consolidation with most of the material savings (Su et al., 2024), while reviews of materials circularity conclude that optimization strategies exist but have not reached wide implementation (Colorado et al., 2020). Bibliometric evidence, finally, dates the bulk of the literature connecting additive production with digitalized manufacturing to the period after 2015 (Hernandez Korner et al., 2020).

The fourth group concerns constraints, and it is dominated by assurance. In the survey of 140 maritime end-users, quality assurance of printed parts ranked as the leading obstacle, ahead of knowledge and skills gaps (Kostidi et al., 2021). The qualification literature identifies four distinct qualification objects, namely feedstock, process, machine, and part, and a standards ecosystem spanning ISO/ASTM, ASME, SAE, NASA, and the classification societies, with process variability and non-harmonized standards named as the principal brakes on adoption (Chen et al., 2022). Reviews of non-destructive testing map lack-of-fusion, porosity, and cracking against the inspection methods able to detect them, and document the resolution-versus-size trade-off of X-ray computed tomography (Rao et al., 2023). In-process monitoring research links melt-pool sensing to machine-learning defect detection and closed-loop control (McCann et al., 2021). Security research demonstrates sabotage attacks that embed internal voids or manipulate process parameters without changing external geometry, alongside theft of design data through acoustic and thermal side channels (Gupta et al., 2020; Mahesh et al., 2021). Reviews of adoption more broadly report five barrier categories and four enabler categories across 87 studies (Stornelli et al., 2021), and find that adoption strengthens supply chain capabilities while introducing new vulnerabilities of its own (Naghshineh & Carvalho, 2022).

PROCESS MATURITY AND THE SEPARATION OF REPAIR FROM PRODUCTION

The technological evidence reads differently once the part population of a military maintenance system is kept in view. No single additive process serves that population. Laser powder bed fusion offers geometric freedom and good static properties for small, complex, high-value metal components, which is why it dominates aerospace applications (Blakey-Milner et al., 2021; Sanchez et al., 2021). Directed energy deposition and cold spray occupy a different niche, material addition onto existing components, where thermal characteristics and deposition rates matter more than resolution (Svetlizky et al., 2021; Vaz et al., 2023). Wire arc systems trade surface quality for size and speed, making them candidates for large structural spares that would otherwise wait months for a forging (Raut & Taiwade, 2021). Binder jetting, with its separate sintering step and powder-metallurgy-like properties, points toward batch production of small hardware (Mostafaei et al., 2021). And polymer printing, technically the least demanding family, has delivered a disproportionate share of the documented military value, from the 0.75-dollar landing gear component to improvised equipment produced near the front in Ukraine (Marciniak, 2023; U.S. Department of Defense Office of Inspector General, 2019). A capable maintenance system will therefore run a portfolio, not a printer.

Materials behavior differentiates the portfolio further. Titanium alloys from powder-bed processes solidify into martensitic microstructures whose static strength can exceed wrought values while fatigue life lags behind, a combination that suits statically loaded brackets far better than rotating components (Liu & Shin, 2019). Nickel superalloys attract additive routes for the opposite reason: they are so difficult to machine conventionally that printing near-net shapes saves both tooling and material, which explains the attention powder bed fusion receives in the turbine context (Sanchez et al., 2021). Binder jetting produces near-isotropic properties similar to conventional powder metallurgy, at the price of a sintering step that a deployed site is unlikely to host (Mostafaei et al., 2021). Part consolidation adds a design dimension of its own. The documented case of roughly 20 components merged into one fuel nozzle removed not only weight but also the spare-parts entries, fasteners, and failure interfaces those components represented (Blakey-Milner et al., 2021). Consolidation, in other words, changes what a spare part is. For maintenance planning, that is a more consequential development than any single process improvement.

Field experience with polymer printing deserves a note of its own, because it inverts the usual maturity ordering. Fused deposition modeling is the least sophisticated process in the portfolio, yet reinforced filaments now reach mechanical properties adequate for brackets, covers, handles, and fixtures, and the machines survive transport and austere power conditions (Marciniak, 2023). Shipboard surveys report storage-space reduction among the expected benefits, which matters on platforms where every cubic meter is contested (Kostidi et al., 2021). Dutch mission research likewise identifies waste reduction and faster availability for exactly this class of items (den Boer et al., 2020). The lesson I draw is that maturity should be judged per part class, not per technology generation. A cheap printer that closes a real gap is more mature, in the operational sense, than a metal system awaiting qualification.

My initial reading of this corpus grouped repair and new-part production together as a single capability. The cost evidence forced a separation. Repair by directed deposition or cold spray restores value to a component whose alternative is scrap, so the economic comparison runs against the full price of a replacement; hence figures like 45% of new-part cost for a repaired turbine seal or half-price drive shafts (Saboori et al., 2019). New-part production, by contrast, competes against a functioning conventional supply chain, and there the additive option wins mainly where that chain has already failed: vanished suppliers, lost tooling, two-year lead times (Mecheter et al., 2022; U.S. Department of Defense Office of Inspector General, 2019). For aging fleets whose original manufacturers no longer exist, repair and obsolescence recovery are arguably the additive applications with the shortest path to value. The distinction is rarely drawn this sharply in the literature, though the underlying data support it.

Against this, the materials evidence counsels restraint for anything fatigue-critical. Titanium and nickel parts from powder-bed processes carry defect populations, lack of fusion, gas porosity, and rough as-built surfaces, that scatter fatigue life well beyond wrought equivalents (Liu & Shin, 2019; Sanaei & Fatemi, 2021). Post-processing narrows the gap. The reported 30-50% fatigue improvements from surface treatment are large, but they add steps, cost, and equipment that a deployed or depot environment must then also qualify (Maleki et al., 2021). Energy studies complicate the sustainability narrative as well, since specific energy consumption in metal additive processes is high, and savings materialize mainly through material efficiency and avoided logistics rather than through the process itself (Gao et al., 2021; Majeed et al., 2020). Reviews that frame additive production in circular-economy terms, through repair, remanufacturing, and distributed recycling, stand on firmer ground for maintenance systems than those claiming process-level environmental advantage (Colorado et al., 2020; Ponis et al., 2021; Su et al., 2024). On the available evidence, a maintenance planner should treat metal AM as a set of engineered exceptions and polymer AM as a general-purpose expedient. That asymmetry appears stable for the near term.

PRINTING AGAINST STOCKING: WHAT THE MODELS SETTLE

The operations research corpus converges on one central proposition: printing complements inventory, it does not replace it. The result appears independently in stochastic inventory theory, where the optimal printer sits lightly utilized beside a stock of critical items (Song & Zhang, 2020); in dual-sourcing models, where savings persist even under strongly unfavorable additive cost and reliability assumptions (Knofius et al., 2021); in Poisson-demand comparisons across nine sourcing configurations combining processes and post-treatments (Sgarbossa et al., 2021); and in after-sales game theory, where hybrid offerings dominate at realistic parameter values (Sun et al., 2024). Even studies sympathetic to insourcing find it profitable mainly under storage constraints, in 69% of restricted-stock cases, against general unprofitability where warehouses are unconstrained (Lolli et al., 2025). The automotive assessment that found savings for only three of 14 candidate parts, concentrated in inventory rather than production cost, fits the same pattern (Ahlsell et al., 2023). Unit economics deteriorate further once build failure probabilities enter the cost model explicitly (Ding et al., 2021). The complementarity finding is, I would argue, the single most policy-relevant result in this literature.

The models also clarify which levers matter. In the stock-or-print formulation, reductions in printing cost raise the value of additive supply roughly linearly, while improvements in printing speed produce S-shaped gains, meaning little effect until a threshold is crossed and diminishing returns beyond it (Song & Zhang, 2020). Poisson-demand comparisons identify part size, complexity, backorder cost, and consumption rate as the variables that move the decision among nine sourcing configurations (Sgarbossa et al., 2021). Network-design results show that the ranking of centralized against distributed configurations flips with the interaction of demand volume and printing capacity, so no single architecture dominates (McDermott et al., 2021). Demand characterization itself proves decisive: intermittent military demand defeats forecasting approaches calibrated on smooth civilian series, which is one reason simulation and stochastic optimization dominate this literature (McDermott et al., 2021; Westerweel et al., 2021). Taken together, the models offer maintenance planners something close to a screening rule. Candidate parts should be slow-moving, long-lead-time, storage-expensive, or obsolescence-threatened, and preferably several of these at once (Knofius et al., 2021; Mecheter et al., 2022).

Military maintenance shifts the parameters of these models in a consistent direction. Downtime costs for weapon systems exceed almost anything in the civilian calibrations. Where an industrial study reasons with 100 euros per hour (Akmal et al., 2022), an unavailable combat platform during operations resists monetary expression altogether. Demand intermittency is extreme, lead times are long, and the resupply line itself may be interdicted, which is precisely the regime where the models award additive production its largest gains: the 17% dual-sourcing savings in remote settings (Knofius et al., 2021), the superiority of on-site printing over expedited shipment in the Mali case (Westerweel et al., 2021), and the sensitivity of optimal network design to the interplay of demand volume and printing capacity (McDermott et al., 2021). Dutch case evidence adds reduced inventories, waste, and energy use in expeditionary conditions (den Boer et al., 2020). The resilience literature reaches a compatible verdict from the disruption side (Naghshineh & Carvalho, 2022). I read these results as saying something fairly precise: the additive business case in defense is strongest exactly where the civilian case is weakest, far from factories, for slow movers, under disruption.

Two qualifications temper the optimism. The first is speed. The Finnish system dynamics work, one of very few studies built on real military printing data, identified production speed as the single most limiting factor for field-level repair support (Rautio & Valtonen, 2022), and the follow-on simulation concluded bluntly that, at current speeds, buying inventory buys more resilience than buying printers (Valtonen et al., 2023). The second is organization. Capability research shows that embedding additive production in a military maintenance system is not an equipment purchase but an institutional design problem spanning doctrine, training, materiel, and contracts with commercial partners (Valtonen et al., 2022). Switchover frameworks developed with industrial spare-parts providers make the same point from the commercial side, down to the four cost and time scenarios that govern the decision (Akmal et al., 2022). Licensing analysis suggests that intellectual-property arrangements, not machines, may decide how distributed military printing eventually becomes, since letting equipment owners print under license benefits all parties across a wide parameter range (Zhang et al., 2022), and manufacturer-customer studies confirm that the two sides of the same supply chain evaluate additive adoption quite differently (Naghshineh et al., 2023). The cross-sector review literature reaches a compatible conclusion (Kunovjanek et al., 2022). Machines are the easy part.

ASSURANCE AS THE BINDING CONSTRAINT

If the previous section identified where printing pays, this one explains why adoption nonetheless crawls. The qualification problem is structural. A part qualified under conventional manufacturing carries decades of accumulated process history; an additively produced equivalent must requalify feedstock, process, machine, and part, four objects rather than one, under a standards ecosystem that ISO/ASTM, ASME, SAE, NASA, and the classification societies are still harmonizing (Chen et al., 2022). Aerospace practice answers with building-block qualification campaigns whose cost only high-value programs can absorb (Blakey-Milner et al., 2021). For a military depot that wants to print a bracket, that overhead is prohibitive unless criticality-graded pathways exist. This is a policy question as much as a technical one, and end-users themselves rank quality assurance first among obstacles (Kostidi et al., 2021).

Inspection technology decides how far qualification can relax. Post-build methods led by X-ray computed tomography detect the defect classes that drive fatigue, but resolution falls as part size and density grow, and acceptance criteria specific to additive defect populations remain unsettled (Rao et al., 2023). The in-process alternative, melt-pool sensing, layerwise imaging, machine-learning classification, and closed-loop control, promises first-time-right builds and a lighter post-build burden (McCann et al., 2021). Digital-twin architectures give that promise its most ambitious form precisely because the underlying process is, in the words of one perspective piece, inherently chaotic and poorly repeatable (Gunasegaram et al., 2021). Recent syntheses treat twins, artificial intelligence, and security as one integrated problem rather than three (Ahmmed et al., 2025). I suspect the qualification economics will hinge on whether in-process data become doctrinally acceptable as evidence of part quality; the technical literature is ahead of the regulatory one here, and the gap is widening.

Security gives the constraint its distinctly military edge. Distributed printing is, in computational terms, distributed execution of design files across a network of machines, an attack surface that centralized procurement never presented. Demonstrated attacks include internal voids invisible to external inspection and parameter manipulations that degrade strength without altering geometry, alongside design theft through acoustic and thermal side channels (Gupta et al., 2020; Mahesh et al., 2021). For civilian industry these are commercial risks. For a force printing safety-critical parts at deployed locations, they are attack vectors an adversary has every incentive to exercise. It is no accident that the departmental strategy lists securing the workflow among its five goals (U.S. Department of Defense, 2021), or that implementation planning routes part files through a controlled model exchange rather than open repositories (Defense Logistics Agency, 2022). Countermeasures such as watermarking, side-channel process verification, and provenance chains exist in the research literature (Mahesh et al., 2021), but hardening them to military assurance levels remains, hitherto, undone work. Skills scarcity compounds all of this, since the barrier and enabler literature consistently pairs technology adoption with workforce capability (Kostidi et al., 2021; Stornelli et al., 2021; Valtonen et al., 2022).

A quieter constraint concerns data and people. Printable part files are technical data with contested ownership, and the licensing literature shows that whether an equipment owner may print at all is a contractual question before it is a technical one (Zhang et al., 2022). Defense practice converges on curated repositories precisely to manage this, as the joint model exchange demonstrates (Defense Logistics Agency, 2022). On the human side, survey evidence ranks knowledge and skills immediately behind quality assurance among adoption obstacles (Kostidi et al., 2021), the barrier literature pairs every technology category with an organizational enabler (Stornelli et al., 2021), and the Finnish capability work treats training and doctrine as coequal with materiel (Valtonen et al., 2022). Post-installation phases remain the least researched part of the adoption process (Stornelli et al., 2021). None of this is exotic. It is the ordinary institutional work that separates a demonstrator from a capability, and the literature suggests militaries underestimate it more often than they underestimate the machines.

CONCLUSION

Three questions organized this review, and the corpus supports reasonably firm answers to each. On technological maturity (RQ1), the process portfolio is mature enough for a defined and growing class of applications: polymer printing for expedients, tooling, and non-critical replacements; powder bed fusion for small, complex metal parts outside the fatigue-critical envelope; directed deposition and cold spray for repair and obsolescence recovery, where documented economics, repairs at 45-50% of replacement cost, are already persuasive (Saboori et al., 2019; Vaz et al., 2023). Fatigue-critical structural parts remain, for now, on the far side of the qualification frontier (Sanaei & Fatemi, 2021).

On logistics and economics (RQ2), the modeling literature is unusually unanimous: additive production complements inventory rather than replacing it, with the strongest gains among slow-moving, long-lead-time items and in remote or disrupted settings, as the 8-30% dual-sourcing savings, the Mali result, and the 69% viability rate under storage constraints jointly indicate (Knofius et al., 2021; Lolli et al., 2025; Song & Zhang, 2020; Westerweel et al., 2021). Military parameter values push the break-even toward printing, but current production speeds still cap what field-level capability can deliver (Rautio & Valtonen, 2022; Valtonen et al., 2023).

On constraints (RQ3), the binding ones are no longer chiefly technical. Qualification pathways, inspection acceptance criteria, digital-thread security, and workforce capability jointly set the adoption frontier, and each is documented as decisive in its own literature (Chen et al., 2022; Kostidi et al., 2021; Mahesh et al., 2021; Rao et al., 2023). The practical implication for maintenance planners follows directly: investment in assurance infrastructure, in criticality-graded qualification, in-process monitoring, and secured file logistics, is likely to release more value than investment in additional printers.

The principal contribution of this review is the joint reading itself: a three-axis framing of technological maturity, logistical performance, and assurance constraints that connects engineering, operations research, and security literatures which cite each other rarely, applied to the specific parameter regime of military maintenance and grounded in a corpus of 49 sources from 2019 onward whose bibliographic records were individually verified. The framing yields a compact diagnosis. The technology is ready at the margins. The economics are favorable exactly where military logistics is hardest. Assurance is the gate.

Four limitations deserve honest statement. The corpus is English-language and public, which excludes classified programs and most non-Western experience. The headline case figures, the 70,000-dollar assembly and the two-year lead time among them, originate from audit and review sources rather than controlled studies, and I have accepted their framing, perhaps too readily. The field moves quickly, and findings dated 2023-2025 may be superseded before long. And a single-author thematic synthesis carries interpretive judgments that a review team would have contested; the separation of repair from production, for instance, is my organizing choice rather than the literature's.

Future research would do well to concentrate on five gaps: empirical military cost data beyond single-case anecdotes; faster field-grade metal deposition, since speed is the documented limiting factor (Rautio & Valtonen, 2022); criticality-graded qualification frameworks fitted to maintenance rather than series production (Chen et al., 2022); digital-thread security hardened to military threat models (Gupta et al., 2020); and licensing and data-rights architectures for distributed printing across allied forces (Zhang et al., 2022). The defense-specific literature remains small relative to the stakes.

BIBLIOGRAPHY

Ahlsell, L., Jalal, D., Khajavi, S. H., Jonsson, P., & Holmström, J. (2023). Additive manufacturing of slow-moving automotive spare parts: A supply chain cost assessment. *Journal of Manufacturing and Materials Processing*, *7*(1), 8. https://doi.org/10.3390/jmmp7010008

Ahmmed, M. S., Khan, L., Mahmood, M. A., & Liou, F. (2025). Digital twins, AI, and cybersecurity in additive manufacturing: A comprehensive review of current trends and challenges. *Machines*, *13*(8), 691. https://doi.org/10.3390/machines13080691

Akmal, J. S., Salmi, M., Björkstrand, R., Partanen, J., & Holmström, J. (2022). Switchover to industrial additive manufacturing: Dynamic decision-making for problematic spare parts. *International Journal of Operations & Production Management*, *42*(13), 358-384. https://doi.org/10.1108/IJOPM-01-2022-0054

Blakey-Milner, B., Gradl, P., Snedden, G., Brooks, M., Pitot, J., Lopez, E., Leary, M., Berto, F., & du Plessis, A. (2021). Metal additive manufacturing in aerospace: A review. *Materials & Design*, *209*, 110008. https://doi.org/10.1016/j.matdes.2021.110008

Chen, Z., Han, C., Gao, M., Kandukuri, S. Y., & Zhou, K. (2022). A review on qualification and certification for metal additive manufacturing. *Virtual and Physical Prototyping*, *17*(2), 382-405. https://doi.org/10.1080/17452759.2021.2018938

Colorado, H. A., Gutiérrez Velásquez, E. I., & Monteiro, S. N. (2020). Sustainability of additive manufacturing: The circular economy of materials and environmental perspectives. *Journal of Materials Research and Technology*, *9*(4), 8221-8234. https://doi.org/10.1016/j.jmrt.2020.04.062

Debnath, B., Shakur, M. S., Tanjum, F., Rahman, M. A., & Adnan, Z. H. (2022). Impact of additive manufacturing on the supply chain of aerospace spare parts industry—A review. *Logistics*, *6*(2), 28. https://doi.org/10.3390/logistics6020028

Defense Logistics Agency. (2022). *DLA additive manufacturing implementation plan for DoDI 5000.93, Use of additive manufacturing in the DoD*. U.S. Department of Defense. https://www.dla.mil/Portals/104/Documents/InformationOperations/Research%20and%20Development/DLA%20Additive%20Manufacturing%20Implementation%20Plan_01Jun2022.pdf

den Boer, J., Lambrechts, W., & Krikke, H. (2020). Additive manufacturing in military and humanitarian missions: Advantages and challenges in the spare parts supply chain. *Journal of Cleaner Production*, *257*, 120301. https://doi.org/10.1016/j.jclepro.2020.120301

Ding, J., Baumers, M., Clark, E. A., & Wildman, R. D. (2021). The economics of additive manufacturing: Towards a general cost model including process failure. *International Journal of Production Economics*, *237*, 108087. https://doi.org/10.1016/j.ijpe.2021.108087

Gao, C., Wolff, S., & Wang, S. (2021). Eco-friendly additive manufacturing of metals: Energy efficiency and life cycle analysis. *Journal of Manufacturing Systems*, *60*, 459-472. https://doi.org/10.1016/j.jmsy.2021.06.011

Gunasegaram, D. R., Murphy, A. B., Matthews, M. J., & DebRoy, T. (2021). The case for digital twins in metal additive manufacturing. *Journal of Physics: Materials*, *4*(4), 040401. https://doi.org/10.1088/2515-7639/ac09fb

Gupta, N., Tiwari, A., Bukkapatnam, S. T. S., & Karri, R. (2020). Additive manufacturing cyber-physical system: Supply chain cybersecurity and risks. *IEEE Access*, *8*, 47322-47333. https://doi.org/10.1109/ACCESS.2020.2978815

Hernandez Korner, M. E., Lambán, M. P., Albajez, J. A., Santolaria, J., Ng Corrales, L. d. C., & Royo, J. (2020). Systematic literature review: Integration of additive manufacturing and Industry 4.0. *Metals*, *10*(8), 1061. https://doi.org/10.3390/met10081061

Knofius, N., van der Heijden, M. C., Sleptchenko, A., & Zijm, W. H. M. (2021). Improving effectiveness of spare parts supply by additive manufacturing as dual sourcing option. *OR Spectrum*, *43*(1), 189-221. https://doi.org/10.1007/s00291-020-00608-7

Kostidi, E., Nikitakos, N., & Progoulakis, I. (2021). Additive manufacturing and maritime spare parts: Benefits and obstacles for the end-users. *Journal of Marine Science and Engineering*, *9*(8), 895. https://doi.org/10.3390/jmse9080895

Kunovjanek, M., Knofius, N., & Reiner, G. (2022). Additive manufacturing and supply chains—A systematic review. *Production Planning & Control*, *33*(13), 1231-1251. https://doi.org/10.1080/09537287.2020.1857874

Liu, S., & Shin, Y. C. (2019). Additive manufacturing of Ti6Al4V alloy: A review. *Materials & Design*, *164*, 107552. https://doi.org/10.1016/j.matdes.2018.107552

Lolli, F., Coruzzolo, A. M., Peron, M., & Sgarbossa, F. (2025). Insourcing additive manufacturing for spare parts production: Is it profitable? An extensive analysis and the proposal of a decision support system. *International Journal of Production Research*, *63*(11), 3961-3981. https://doi.org/10.1080/00207543.2024.2432470

Mahesh, P., Tiwari, A., Jin, C., Kumar, P. R., Reddy, A. L. N., Bukkapatanam, S. T. S., Gupta, N., & Karri, R. (2021). A survey of cybersecurity of digital manufacturing. *Proceedings of the IEEE*, *109*(4), 495-516. https://doi.org/10.1109/JPROC.2020.3032074

Majeed, A., Ahmed, A., Lv, J., Peng, T., & Muzamil, M. (2020). A state-of-the-art review on energy consumption and quality characteristics in metal additive manufacturing processes. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, *42*(5), 249. https://doi.org/10.1007/s40430-020-02323-4

Maleki, E., Bagherifard, S., Bandini, M., & Guagliano, M. (2021). Surface post-treatments for metal additive manufacturing: Progress, challenges, and opportunities. *Additive Manufacturing*, *37*, 101619. https://doi.org/10.1016/j.addma.2020.101619

Marciniak, M. (2023). The 3D printing in military applications: FDM technology, materials, and implications. *Advances in Military Technology*, *18*(2), 241-257. https://doi.org/10.3849/aimt.01846

McCann, R., Obeidi, M. A., Hughes, C., McCarthy, É., Egan, D. S., Vijayaraghavan, R. K., Joshi, A. M., Acinas Garzon, V., Dowling, D. P., McNally, P. J., & Brabazon, D. (2021). In-situ sensing, process monitoring and machine control in laser powder bed fusion: A review. *Additive Manufacturing*, *45*, 102058. https://doi.org/10.1016/j.addma.2021.102058

McDermott, K. C., Winz, R. D., Hodgson, T. J., Kay, M. G., King, R. E., & McConnell, B. M. (2021). Performance tradeoffs for spare parts supply chains with additive manufacturing capability servicing intermittent demand. *Journal of Defense Analytics and Logistics*, *5*(2), 179-213. https://doi.org/10.1108/JDAL-08-2020-0016

Mecheter, A., Pokharel, S., & Tarlochan, F. (2022). Additive manufacturing technology for spare parts application: A systematic review on supply chain management. *Applied Sciences*, *12*(9), 4160. https://doi.org/10.3390/app12094160

Mostafaei, A., Elliott, A. M., Barnes, J. E., Li, F., Tan, W., Cramer, C. L., Nandwana, P., & Chmielus, M. (2021). Binder jet 3D printing—Process parameters, materials, properties, modeling, and challenges. *Progress in Materials Science*, *119*, 100707. https://doi.org/10.1016/j.pmatsci.2020.100707

Naghshineh, B., & Carvalho, H. (2022). The implications of additive manufacturing technology adoption for supply chain resilience: A systematic search and review. *International Journal of Production Economics*, *247*, 108387. https://doi.org/10.1016/j.ijpe.2021.108387

Naghshineh, B., Fragoso, M., & Carvalho, H. (2023). Rethinking additive manufacturing for spare parts supply chain management. *Research-Technology Management*, *66*(4), 38-47. https://doi.org/10.1080/08956308.2023.2207970

Ponis, S., Aretoulaki, E., Maroutas, T. N., Plakas, G., & Dimogiorgi, K. (2021). A systematic literature review on additive manufacturing in the context of circular economy. *Sustainability*, *13*(11), 6007. https://doi.org/10.3390/su13116007

Rao, J., Sing, S. L., Liu, P., Wang, J., & Sohn, H. (2023). Non-destructive testing of metal-based additively manufactured parts and processes: A review. *Virtual and Physical Prototyping*, *18*(1), e2266658. https://doi.org/10.1080/17452759.2023.2266658

Raut, L. P., & Taiwade, R. V. (2021). Wire arc additive manufacturing: A comprehensive review and research directions. *Journal of Materials Engineering and Performance*, *30*(7), 4768-4791. https://doi.org/10.1007/s11665-021-05871-5

Rautio, S., & Valtonen, I. (2022). Supporting military maintenance and repair with additive manufacturing. *Journal of Military Studies*, *11*(1), 23-36. https://doi.org/10.2478/jms-2022-0003

Saboori, A., Aversa, A., Marchese, G., Biamino, S., Lombardi, M., & Fino, P. (2019). Application of directed energy deposition-based additive manufacturing in repair. *Applied Sciences*, *9*(16), 3316. https://doi.org/10.3390/app9163316

Sanaei, N., & Fatemi, A. (2021). Defects in additive manufactured metals and their effect on fatigue performance: A state-of-the-art review. *Progress in Materials Science*, *117*, 100724. https://doi.org/10.1016/j.pmatsci.2020.100724

Sanchez, S., Smith, P., Xu, Z., Gaspard, G., Hyde, C. J., Wits, W. W., Ashcroft, I. A., Chen, H., & Clare, A. T. (2021). Powder bed fusion of nickel-based superalloys: A review. *International Journal of Machine Tools and Manufacture*, *165*, 103729. https://doi.org/10.1016/j.ijmachtools.2021.103729

Sgarbossa, F., Peron, M., Lolli, F., & Balugani, E. (2021). Conventional or additive manufacturing for spare parts management: An extensive comparison for Poisson demand. *International Journal of Production Economics*, *233*, 107993. https://doi.org/10.1016/j.ijpe.2020.107993

Song, J.-S., & Zhang, Y. (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

Stornelli, A., Ozcan, S., & Simms, C. (2021). Advanced manufacturing technology adoption and innovation: A systematic literature review on barriers, enablers, and innovation types. *Research Policy*, *50*(6), 104229. https://doi.org/10.1016/j.respol.2021.104229

Su, J., Ng, W. L., An, J., Yeong, W. Y., Chua, C. K., & Sing, S. L. (2024). Achieving sustainability by additive manufacturing: A state-of-the-art review and perspectives. *Virtual and Physical Prototyping*, *19*(1), e2438899. https://doi.org/10.1080/17452759.2024.2438899

Sun, M., Ng, C. T., Yang, L., & Zhang, T. (2024). Optimal after-sales service offering strategy: Additive manufacturing, traditional manufacturing, or hybrid? *International Journal of Production Economics*, *268*, 109116. https://doi.org/10.1016/j.ijpe.2023.109116

Svetlizky, D., Das, M., Zheng, B., Vyatskikh, A. L., Bose, S., Bandyopadhyay, A., Schoenung, J. M., Lavernia, E. J., & Eliaz, N. (2021). Directed energy deposition (DED) additive manufacturing: Physical characteristics, defects, challenges and applications. *Materials Today*, *49*, 271-295. https://doi.org/10.1016/j.mattod.2021.03.020

U.S. Department of Defense. (2021). *Department of Defense additive manufacturing strategy*. Office of the Under Secretary of Defense for Research and Engineering. https://www.cto.mil/dod-ams/

U.S. Department of Defense Office of Inspector General. (2019). *Audit of the DoD's use of additive manufacturing for sustainment parts* (Report No. DODIG-2020-003). U.S. Department of Defense. https://www.dodig.mil/reports.html/Article/1993530/

Valtonen, I., Rautio, S., & Lehtonen, J.-M. (2023). Designing resilient military logistics with additive manufacturing. *Continuity & Resilience Review*, *5*(1), 1-16. https://doi.org/10.1108/CRR-08-2022-0015

Valtonen, I., Rautio, S., & Salmi, M. (2022). Capability development in hybrid organizations: Enhancing military logistics with additive manufacturing. *Progress in Additive Manufacturing*, *7*(5), 1037-1052. https://doi.org/10.1007/s40964-022-00280-z

Vaz, R., Garfias, A., Albaladejo, V., Sanchez, J., & Cano, I. G. (2023). A review of advances in cold spray additive manufacturing. *Coatings*, *13*(2), 267. https://doi.org/10.3390/coatings13020267

Westerweel, B., Basten, R., den Boer, J., & van Houtum, G.-J. (2021). Printing spare parts at remote locations: Fulfilling the promise of additive manufacturing. *Production and Operations Management*, *30*(6), 1615-1632. https://doi.org/10.1111/poms.13298

Zhang, Y., Westerweel, B., Basten, R., & Song, J.-S. (2022). Distributed 3D printing of spare parts via IP licensing. *Manufacturing & Service Operations Management*, *24*(5), 2685-2702. https://doi.org/10.1287/msom.2022.1117

ADITIVNA PROIZVODNJA REZERVNIH DIJELOVA U VOJNIM SISTEMIMA ODRŽAVANJA: PREGLED TEHNOLOŠKIH DOSTIGNUĆA I LOGISTIČKIH IMPLIKACIJA

Rumen Angelov

Sofijski univerzitet „Sv. Kliment Ohridski"
Sofija, Republika Bugarska
E-mail: rumen.angelov@uni-sofia.bg

Primljeno: 17. 01. 2026. Revidirano: 14. 04. 2026. Odobreno: 18. 05. 2026.

Pregledni naučni članak

DOI: https://doi.org/10.65932/military-studies-2026-1-8 **UDK**: 621.7:355.415

Sažetak: Vojne organizacije za održavanje raspolažu jednim od najvećih i najmanje likvidnih inventara rezervnih dijelova i njima upravljaju u uslovima koje komercijalne postprodajne mreže rijetko poznaju: isprekidana tražnja, starenje platformi, nestanak dobavljača i linije snabdijevanja koje protivnik aktivno nastoji presjeći. Ovaj pregledni rad ispituje šta aditivna proizvodnja realno može doprinijeti takvim sistemima. Na osnovu 49 verifikovanih izvora objavljenih između 2019. i 2025. godine, od čega je 46 recenziranih časopisnih članaka, analiza je organizovana duž tri ose: tehnološka zrelost aditivnih procesa za proizvodnju i popravku rezervnih dijelova; logistički i ekonomski dokazi o tome kada štampanje nadmašuje skladištenje; te ograničenja kvalifikacije, sertifikacije i digitalne bezbjednosti koja trenutno upravljaju usvajanjem. Dokazi podržavaju dosljedan zaključak. Aditivna proizvodnja već isporučuje dokumentovanu vrijednost na marginama vojnih lanaca snabdijevanja: revizorski podaci bilježe rokove nabavke skraćene sa dvije godine na približno sedmicu dana i jedinične troškove smanjene za više redova veličine za pojedine dijelove. Modeli operacionih istraživanja ipak pokazuju da štampanje dopunjuje, a ne zamjenjuje zalihe, pri čemu su uštede dvojnog snabdijevanja od 8 do 30 posto koncentrisane među artiklima niske tražnje i dugih rokova isporuke. Vezujuća ograničenja više nisu prvenstveno tehnička: putevi kvalifikacije, populacije defekata kritičnih za zamor i sajber-bezbjednost digitalne niti sada određuju granicu usvajanja. Pregled doprinosi trodimenzionalnim okvirom spremnosti koji povezuje inženjersku, logističku i literaturu o osiguranju kvaliteta, koje su se dosad uglavnom razvijale odvojeno.

Ključne riječi: *aditivna proizvodnja, rezervni dijelovi, vojna logistika, održavanje, lanac snabdijevanja, kvalifikacija i sertifikacija, digitalna nit.*