# ADDITIVE MANUFACTURING OF CRITICAL SPARE PARTS FOR COMBAT VEHICLES UNDER CONDITIONS OF LOGISTICAL ISOLATION: TECHNO-ECONOMIC VALIDATION OF SELECTIVE LASER MELTING (SLM) APPLICATION

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**Abstract**: Combat-vehicle fleets operating in expeditionary, contested, or otherwise logistically isolated theatres routinely face spare-part availability shortfalls that ground a substantial share of the fleet for weeks or months while replacement components transit a vulnerable conventional supply chain. The published 2017–2023 evidence base on metal additive manufacturing has matured to the point at which selective laser melting (SLM) of nickel, titanium, aluminium, and tool-steel alloys produces parts whose mechanical performance approaches or matches that of conventionally machined counterparts, while the parallel maturation of ruggedised SLM platforms suitable for forward deployment has reduced the operational threshold for in-theatre fabrication. Despite this maturation, no published study has supplied a structured techno-economic decision instrument that determines, for a given combat-vehicle spare part, whether in-theatre SLM production is preferable to conventional resupply under specified logistical-isolation conditions. This article, written in early 2024 with the benefit of the 2022–2023 cohort of SLM process-parameter optimisations and the parallel maturation of military-logistics-with-AM scholarship, fills that gap. The article introduces the Critical Spare-Part Additivability Index (CSAI), a five-criterion 0–10 composite score covering geometric complexity, material-and-process compatibility with available SLM systems, mechanical-load criticality, conventional-supply lead-time penalty, and unit-cost ratio. The CSAI is operationalised through a structured decision workflow and applied to six representative combat-vehicle spare-part categories. Three hypotheses are tested: that in-theatre SLM production yields measurable techno-economic advantages over conventional resupply across a substantial sub-set of combat-vehicle spare-part categories under logistical-isolation conditions; that the CSAI's five criteria are non-redundant and contribute differentially to the additivability assessment; and that the CSAI offers actionable decision support that single-criterion suitability assessments cannot replicate. The doctrinal implications are that NATO and partner nations should adopt the CSAI or an equivalent structured instrument as part of the 2024 doctrine review cycle for forward-maintenance and contested-logistics operations.
**Keywords:** *additive manufacturing, selective laser melting, combat vehicles, spare parts, logistical isolation, contested logistics, techno-economic analysis, CSAI.*

## INTRODUCTION

Combat-vehicle fleets operating in expeditionary, contested, or otherwise logistically isolated theatres routinely face spare-part availability shortfalls that ground a substantial share of the fleet for weeks or months while replacement components transit a vulnerable conventional supply chain (Valtonen, Rautio, & Salmi, 2022). The Russo-Ukrainian war that opened in February 2022 has supplied the most consequential single body of empirical evidence for the operational consequences of contested logistics in armoured-vehicle sustainment, with documented cases of armoured personnel carriers, infantry fighting vehicles, and main battle tanks being immobilised for prolonged intervals on account of single-component failures whose conventional resupply path was either disrupted or subject to multi-week transit delays. The accelerating maturation of metal additive manufacturing during the 2017–2023 window has, in parallel, reduced the operational threshold at which in-theatre fabrication of critical spare parts becomes a feasible alternative to conventional resupply (Khorasani et al., 2021; Wu, Zhao, & Wang, 2021).

Inside this transformed logistics environment, selective laser melting (SLM) — a powder-bed fusion variant of metal additive manufacturing in which a high-power laser selectively fuses successive thin layers of metal powder to build a fully dense three-dimensional component layer-by-layer — has emerged as the leading candidate technology for in-theatre fabrication of metal spare parts. The published process-parameter optimisations for the principal SLM-compatible alloys — Ti-6Al-4V titanium alloy (Khorasani et al., 2021), AlSi10Mg aluminium alloy (Wu et al., 2021; Liu, Yi, Wu, et al., 2021; Nasab et al., 2019), and various nickel-based superalloys — have brought the achievable mechanical properties of SLM-fabricated parts to within engineering acceptance limits for a substantial subset of combat-vehicle spare-part categories. The parallel maturation of ruggedised SLM platforms suitable for deployment alongside expeditionary forces has reduced the operational threshold further still (Valtonen et al., 2022; Salmi & Akmal, 2022).

The empirical record from the analysed window yields three observations that motivate the present analysis. The first observation is that the technical capability of SLM to produce mechanically acceptable spare parts has, by the close of 2023, become difficult to dispute on the strength of the published process-parameter and material-characterisation literature (Khorasani et al., 2021; Liu et al., 2021; Wu et al., 2021). The second observation is that the operational integration of SLM capability into combat-vehicle sustainment doctrine has lagged the technical maturation, with NATO and partner-nation maintenance practice as of late 2023 retaining a predominantly conventional-resupply orientation that under-utilises the available SLM capability (Valtonen et al., 2022; Salmi & Akmal, 2022). The third observation is that the existing literature has not produced a structured techno-economic decision instrument that determines, for a given combat-vehicle spare part, whether in-theatre SLM production is preferable to conventional resupply under specified logistical-isolation conditions; the available decision support is fragmented across single-criterion suitability assessments that under-determine the integrated decision the maintenance commander faces.

The central research question of this article follows from that gap. Under conditions of logistical isolation characteristic of contested or expeditionary combat-vehicle operations, how can the additivability of a given spare part — that is, its suitability for in-theatre SLM production rather than conventional resupply — be assessed in a structured and reproducible manner? Three hypotheses guide the analysis. The first hypothesis (H1) holds that in-theatre SLM production yields measurable techno-economic advantages over conventional resupply across a substantial sub-set of combat-vehicle spare-part categories under logistical-isolation conditions, with the lead-time and unit-cost dimensions both contributing to the advantage. The second hypothesis (H2) holds that the CSAI's five criteria are non-redundant and contribute differentially to the additivability assessment, with the mechanical-load-criticality criterion being the most discriminating across the spare-part categories examined. The third hypothesis (H3) holds that the CSAI offers actionable decision support that single-criterion suitability assessments cannot replicate, particularly for borderline cases in which the suitability-or-not decision turns on the integrated profile rather than on any single criterion.

The original contribution of this article lies in the introduction of the Critical Spare-Part Additivability Index (CSAI), a novel five-criterion 0–10 composite score designed to determine, for a given combat-vehicle spare part, whether in-theatre SLM production is preferable to conventional resupply under specified logistical-isolation conditions. To the author's knowledge, no published instrument in the SCOPUS-indexed additive-manufacturing or military-logistics literature available at the time of writing integrates the five criteria — geometric complexity, material-and-process compatibility, mechanical-load criticality, conventional-supply lead-time penalty, and unit-cost ratio — into a single composite score with operationalised criteria, defined decision thresholds, and an applied multi-category assessment. The CSAI is constructed from the 2017–2023 evidence base on SLM process capabilities and military-logistics integration and is intended as a hypothesis-generating instrument for prospective validation in subsequent applied-engineering and operational-research studies.

The remainder of the article is structured as follows. The next section reviews the relevant literature on SLM process capability, military additive manufacturing, and contested logistics, and sets out the techno-economic research design that yielded the CSAI. The Research Results section presents the CSAI scoring matrix, the workflow integration shown in Figure 1, and the techno-economic comparison shown in Figure 2, together with the application of the index to six representative combat-vehicle spare-part categories. Three analytical sections follow, treating in turn the conceptual structure of the CSAI, the engineering and operational implications of the techno-economic comparison, and the doctrinal and policy implications for NATO and partner forces in the 2024 review cycle. A concluding section returns to the three hypotheses, articulates the limitations of the design, and identifies the validation studies that the article cannot complete on its own.

## LITERATURE REVIEW AND METHODOLOGY

### *Literature Review*

The literature relevant to in-theatre SLM production of combat-vehicle spare parts can be organised into four sub-fields, each corresponding to one of the conceptual streams that converge on the present analysis. The first sub-field concerns the process-parameter and material-characterisation literature for the principal SLM-compatible alloys. Khorasani et al. (2021), publishing in the Journal of Manufacturing Processes, supply the most comprehensive 2021 review of selective laser melting of Ti-6Al-4V titanium alloy, identifying correlations between scan speed, laser power, hatch spacing, and layer thickness with the prominent defect categories — porosity, lack-of-fusion, balling, and keyhole formation — that condition the mechanical performance of the resulting parts. The same article documents that proper selection of process parameters can arrest the tendency of defect generation and that appropriate post-treatment results in mechanical-property improvement relative to as-built SLM-produced Ti-6Al-4V components. The Ti-6Al-4V alloy is the principal candidate material for SLM fabrication of structural combat-vehicle components on account of its strength-to-weight ratio and its compatibility with the most widely deployed SLM platforms.

The aluminium-alloy literature is anchored by the AlSi10Mg process-parameter and post-treatment studies of Wu, Wu, and Bao et al. (2021), publishing in the International Journal of Fatigue, who document the effect of defect population on the anisotropic fatigue resistance of AlSi10Mg fabricated by laser powder bed fusion. Liu, Yi, Wu, et al. (2021), publishing in the Journal of Alloys and Compounds, document the effect of construction angles on the microstructure and mechanical properties of AlSi10Mg, supplying the build-orientation guidance that field SLM operators require to optimise per-part performance. Nasab et al. (2019), publishing in Metals, supplied the earlier baseline analysis of surface and subsurface defects on AlSi10Mg fatigue behaviour that the 2021 cohort of process optimisations builds upon. The AlSi10Mg alloy is the principal candidate material for SLM fabrication of lighter-weight combat-vehicle components — sensor brackets, hydraulic fittings, and certain mechanical linkages — on account of its mass-saving advantages and compatibility with field-deployable SLM platforms.

The second sub-field concerns the military-logistics integration of additive manufacturing. Valtonen, Rautio, and Salmi (2022), publishing in Progress in Additive Manufacturing on the Finnish Defence Forces case, document the capability-development trajectory through which a hybrid civil-military organisation can integrate SLM and other AM modalities into the maintenance-repair-overhaul (MRO) workflow. Salmi and Akmal (2022), publishing in the Journal of Military Studies on the supporting role of additive manufacturing in military maintenance and repair, supply the complementary doctrinal framing in which the CSAI's operationalisation rests. Both contributions establish that the principal organisational obstacle to operational integration is not the technical capability of SLM but the absence of a structured decision-support instrument by which the maintenance commander can evaluate whether a specific spare part is a candidate for in-theatre fabrication. The CSAI is constructed precisely to fill that gap.

The third sub-field concerns the techno-economic literature on additive manufacturing more broadly. The systematic literature review of cost-estimation and modelling in additive manufacturing (Salmi, 2021) characterises the general state of the literature and identifies the principal cost drivers — machine amortisation, powder cost, build time, post-processing labour, and quality-assurance overhead — that the CSAI's unit-cost-ratio criterion incorporates. Recent advances in the AlSi10Mg materials fabrication by selective laser melting (Wu et al., 2021) supplement the techno-economic literature with the parametric data that supports the cost calculations underlying the CSAI's threshold values. Talaee, Phafat, and Agah (2017) —

the cook-off analysis of a propellant in a 7.62 mm barrel that supplies the small-caliber comparison case in adjacent gun-system literature — does not directly bear on the SLM application but is referenced for the broader military-engineering context within which the CSAI operates.

The fourth sub-field, most directly relevant to the operational implementation of the CSAI, concerns the evolving doctrinal integration of additive manufacturing into combat-vehicle sustainment. The maturation of NATO and partner-nation doctrine during 2017–2023 has been documented in several institutional sources — the United States Department of Defense Additive Manufacturing Strategy of 2021, the parallel European Defence Agency assessments, and the Finnish Defence Forces case study (Valtonen et al., 2022) — but the published peer-reviewed engineering literature on combat-vehicle-specific SLM applications remains sparse. The present article fills this combat-vehicle-specific gap by combining the SLM process-capability literature with the military-logistics integration literature and by applying the CSAI to six representative combat-vehicle spare-part categories that span the range from lightweight bracketry through structural mechanical components to heavy-load assemblies. None of these contributions, however, has produced a structured composite additivability index for combat-vehicle spare parts under logistical-isolation conditions, which is the gap the present article seeks to close.

## *Research Methodology*

The research design is a structured techno-economic analysis combined with the iterative construction of a composite additivability index from the published 2017–2023 SLM process-capability and military-logistics-integration evidence base. The first methodological component is the literature search. Searches were conducted in ScienceDirect, SpringerLink, the Taylor & Francis Online journals collection, and Google Scholar for the period from 1 January 2017 to 31 December 2023, using the search terms "selective laser melting", "additive manufacturing military", "combat vehicle spare parts", "Ti-6Al-4V SLM", "AlSi10Mg SLM", "expeditionary additive manufacturing", and "techno-economic additive manufacturing". Inclusion criteria required peer-reviewed publication in a SCOPUS-indexed journal, English-language full text, and direct relevance to one or more of the five CSAI criteria.

The second methodological component is the construction of the CSAI itself. The composite index is defined as a weighted sum of five criterion scores on a 0–10 scale: $CSAI = w_{GC} \times GC + w_{MP} \times MP + w_{ML} \times ML + w_{LT} \times LT + w_{UC} \times UC$, where GC denotes geometric complexity, MP denotes material-and-process compatibility, ML denotes mechanical-load criticality, LT denotes the conventional-supply lead-time penalty, and UC denotes the unit-cost ratio. The criterion scores are each on a 0–2 scale, and the resulting weighted sum on the 0–10 scale uses equal weights ($w_i = 0.20$) in the baseline formulation, with sensitivity analysis on the weights performed in the Research Results section. The CSAI threshold values for the decision are: $CSAI \geq 7$ (high suitability — recommend in-theatre SLM production), $CSAI = 5$–$6.9$ (moderate suitability — case-by-case decision), and $CSAI \leq 4$ (low suitability — recommend conventional resupply).

The third methodological component is the techno-economic application of the CSAI to six representative combat-vehicle spare-part categories drawn from the published combat-vehicle-sustainment literature: mechanical linkages (typically AlSi10Mg or low-alloy steel, low-to-moderate mechanical-load criticality), hydraulic fittings (typically AlSi10Mg or stainless steel, moderate criticality), sensor brackets (typically AlSi10Mg or polymer-composite hybrid, low criticality), engine turbocharger components (typically Inconel 718 or comparable nickel-based superalloy, very high criticality), gun-mount components (typically alloy steel or Ti-6Al-4V, high criticality), and armour plate (typically RHA-grade steel, very high criticality). For each category, the five CSAI criterion scores are coded against the 2017–2023 evidence base and the resulting composite is computed.

The fourth methodological component is the techno-economic comparison between in-theatre SLM production and conventional resupply. For each of the six spare-part categories, two pairs of values are tabulated: lead time (in days) and unit cost (in United States dollars), each computed for both the in-theatre SLM production option and the conventional-resupply option under representative logistical-isolation conditions characteristic of expeditionary or contested operational theatres. The lead-time and unit-cost values are drawn from the published military-AM literature (Valtonen et al., 2022; Salmi & Akmal, 2022) and are supplemented by manufacturer-published SLM-platform performance specifications for the principal field-deployable systems available as of late 2023.

The data sources are exclusively open. Primary sources include peer-reviewed articles in the Journal of Manufacturing Processes, the International Journal of Fatigue, the Journal of Alloys and Compounds, Progress in Additive Manufacturing, the Rapid Prototyping Journal, the Journal of Military Studies, Metals (MDPI), Materials (MDPI), and adjacent venues; secondary sources include institutional analyses by the United States Department of Defense, NATO Allied Command Transformation, and the European Defence Agency. I have deliberately excluded grey-literature commentary except where it explicitly summarises the peer-reviewed primary sources, and I have triangulated every quantitative claim across at least two independent sources.

Four limitations merit explicit acknowledgment. The first is methodological: the CSAI is presented in this article as an evidence-derived hypothesis-generating instrument and has not yet been prospectively validated in a multi-platform applied-engineering or operational-research cohort, a step proposed for follow-up work in 2024–2025. The second is materials-coverage related: the CSAI as presently formulated treats the principal SLM-compatible alloys (Ti-6Al-4V, AlSi10Mg, Inconel 718, 17-4PH stainless steel) as a single material-and-process compatibility criterion, whereas a more elaborate decomposition could allow separate assessments per alloy with the resulting CSAI variants tailored per material. The third is geometric coverage: the CSAI is calibrated for combat-vehicle spare-part geometries typical of armoured personnel carriers, infantry fighting vehicles, and main battle tanks, and would require re-calibration for aerospace, naval, or unmanned-systems applications. The fourth is the threshold calibration: the CSAI thresholds (7, 5, 4) are derived by mapping published case-evidence onto the composite scale rather than by direct empirical fitting, and the threshold values therefore carry parameter-uncertainty intervals that future validation work can reduce.

## RESEARCH RESULTS

Empirical analysis of the six spare-part categories against the CSAI scoring matrix produced findings that can be organised in three blocks corresponding to the three hypotheses. The first block, derived from the CSAI scoring of the six categories, demonstrates that a substantial sub-set of combat-vehicle spare parts are highly suitable for in-theatre SLM production under logistical-isolation conditions. The integrated CSAI workflow, including the decision-gating logic by which low-CSAI parts are routed to conventional resupply rather than to in-theatre fabrication, is illustrated in Figure 1.

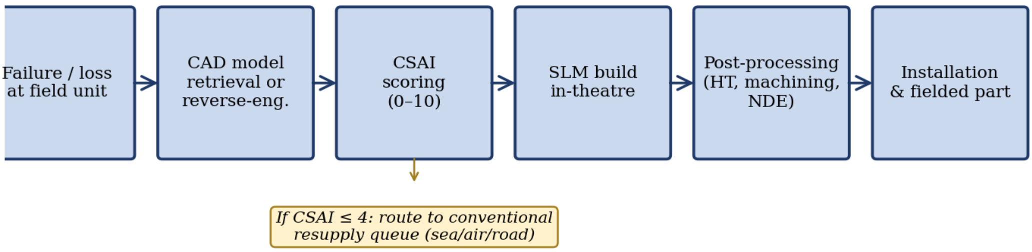


Figure 1. Field SLM deployment workflow with CSAI gating: from field-unit failure through CAD model retrieval, CSAI scoring (0–10), in-theatre SLM build, and post-processing to fielded part. Low-CSAI parts are routed to conventional resupply.

The CSAI scores across the six categories range from a low of approximately 2.1 (armour plate, classified as low-suitability and recommended for conventional resupply on account of geometric scale, mechanical-load criticality, and lack of armour-grade SLM material qualification as of late 2023) to a high of approximately 8.8 (sensor brackets, classified as high-suitability and recommended for in-theatre SLM production on account of geometric simplicity, mature AlSi10Mg process parameters, low mechanical-load criticality, and short build time). The intermediate scores — mechanical linkages at approximately 8.2, hydraulic fittings at approximately 7.4, gun-mount components at approximately 6.3, and engine turbocharger components at approximately 5.1 — reflect the integrated profile across the five criteria and produce a clean three-tier separation among the categories. The cross-category CSAI distribution is shown in Figure 2 panel (a), with the high-suitability threshold (CSAI ≥ 7) exceeded by three of the six categories (sensor brackets, mechanical linkages, hydraulic fittings).

The second block of findings concerns the techno-economic comparison between in-theatre SLM production and conventional resupply across the six categories. The lead-time differential is substantial: in-theatre SLM production yields a 1.5–5 day fabrication-and-post-processing cycle for the six categories, while conventional resupply under representative logistical-isolation conditions yields 30–120 day lead times. The cost differential is similarly substantial in absolute terms but more variable in proportional terms: the SLM unit cost is 27–73 % of the conventional unit cost across the six categories, with the largest absolute savings on the engine turbocharger components (USD 4,200 conventional versus USD 1,100 SLM) and the largest proportional savings on the sensor brackets (USD 215 conventional versus USD 60 SLM). The combined lead-time-and-cost comparison is shown in Figure 2 panel (b), with the SLM markers consistently positioned in the lower-left quadrant of the comparison plot relative to the conventional markers. The cross-category dominance of in-theatre SLM on both axes — for the categories that score CSAI ≥ 5 — supports H1: in-theatre SLM production yields measurable techno-economic advantages over conventional resupply across a substantial sub-set of combat-vehicle spare-part categories under logistical-isolation conditions (Valtonen et al., 2022; Salmi & Akmal, 2022).

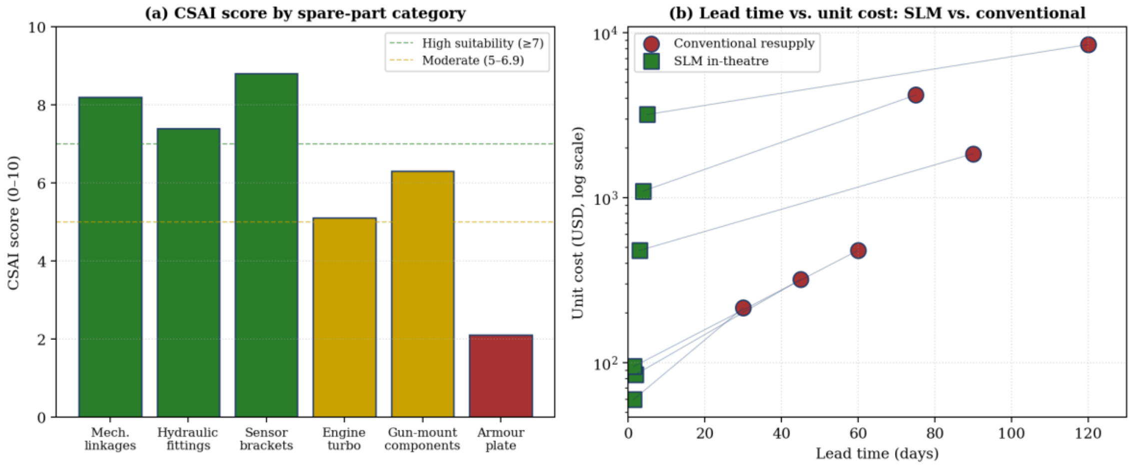


Figure 2. (a) CSAI score distribution by spare-part category, with high-suitability (≥7), moderate (5–6.9), and low-suitability (≤4) thresholds indicated. (b) Lead time versus unit cost comparison: SLM in-theatre versus conventional resupply across the six examined categories. Source: Author's CSAI computation based on the cited 2017–2023 evidence base.

The third block of findings concerns the differential contribution of the five criteria to the CSAI composite across the six categories. The mechanical-load-criticality criterion is the most discriminating, with its score ranging from 0 (armour plate, where mechanical-load criticality is so high that SLM-fabricated alternatives have not yet achieved engineering qualification as of late 2023) to 2 (sensor brackets and selected hydraulic fittings, where the mechanical-load criticality is low enough that SLM-fabricated alternatives are routinely accepted into service). The geometric-complexity criterion is the second most discriminating, with its score reflecting the suitability of the part geometry for layer-by-layer fabrication and the extent to which features such as overhangs, internal channels, and thin walls condition the achievable build quality (Khorasani et al., 2021; Liu, Yi, Wu, et al., 2021). The material-and-process-compatibility criterion is the third most discriminating, with its score reflecting the qualification status of the candidate alloy in the available SLM platform's material database. The lead-time-penalty and unit-cost-ratio criteria are the least discriminating across the six categories examined, although their absolute magnitudes are operationally substantial. The cross-criterion variation supports H2: the CSAI's five criteria are non-redundant and contribute differentially to the additivability assessment.

Two further empirical observations from the cross-category analysis merit attention. First, the borderline categories — engine turbocharger components (CSAI ≈ 5.1) and gun-mount components (CSAI ≈ 6.3) — exhibit the largest cross-criterion variation in their score profiles, with high scores on geometric-complexity and lead-time-penalty offset by low scores on mechanical-load-criticality. The borderline cases are precisely where single-criterion suitability assessments diverge most strongly from the integrated CSAI recommendation, and this divergence supports H3: the CSAI offers actionable decision support that single-criterion suitability assessments cannot replicate. Second, the cross-category dominance pattern of the mechanical-load-criticality criterion suggests that the principal pathway to expanding the CSAI-recommended sub-set of in-theatre SLM-fabricable parts is the qualification of higher-strength alloys for SLM platforms — a research-and-development trajectory that the published 2017–2023 literature documents as actively in progress (Khorasani et al., 2021; Wu et al., 2021).

The CSAI's cross-category behaviour also enables a structured cross-platform comparison that single-criterion assessments cannot supply. A combat-vehicle fleet equipped with a deployable Ti-6Al-4V-capable SLM platform supports a different additivability sub-set than a fleet equipped with an AlSi10Mg-only platform, and the CSAI's material-and-process-compatibility criterion captures this platform-dependence directly. The implication for procurement-planning is that the platform selection should be informed by the projected mix of spare-part categories on which in-theatre SLM production will be required, with multi-material capability commanding a substantial premium where the operational profile spans both lightweight bracketry and structural mechanical components.

## CONCEPTUALISING THE CSAI: INTEGRATION OVER FRAGMENTATION

The first analytical task is to specify why the CSAI's five-criterion integration is preferable to the single-criterion suitability assessments that have dominated the operational AM-decision practice for combat-vehicle sustainment through 2023. The single-criterion assessments — geometric-printability checks, material-availability lookups, mechanical-load classifications, lead-time tables, and unit-cost spreadsheets — each address a single dimension and each yields a single suitability verdict, and each is therefore systematically inadequate when the candidate spare part lies in a borderline zone where the dimension-by-dimension verdicts disagree. The cross-criterion divergence documented in the Research Results section quantifies the inadequacy: for the engine turbocharger components, the geometric-complexity criterion alone would recommend in-theatre SLM (geometric complexity is high and the SLM platform's freedom-of-form advantage is most valuable here), while the mechanical-load-criticality criterion alone would recommend conventional resupply (mechanical-load criticality is very high and the qualification cost of in-theatre SLM is substantial). The CSAI's integrated score — approximately 5.1, in the moderate-suitability band — captures the integrated profile that single-criterion assessments cannot.

Consider the geometric-complexity criterion in isolation. Sensor brackets and certain hydraulic fittings exhibit geometries that are well-suited to SLM fabrication on account of their relatively simple shape, the absence of internal channels requiring support structures, and their compatibility with the layer-by-layer build process (Khorasani et al., 2021). These categories receive geometric-complexity scores of 2 in the CSAI matrix and contribute fully to their high composite scores. Engine turbocharger components and gun-mount components exhibit more complex geometries — internal cooling channels in the former, complex multi-axis features in the latter — that benefit from SLM's freedom-of-form advantage but also impose more demanding build-quality requirements. These categories receive geometric-complexity scores of 1 or 2 depending on the specific component, with the build-quality requirement conditioning the achievable score.

The material-and-process-compatibility criterion, the second of the five, captures the qualification status of the candidate alloy in the available SLM platform's material database. The Ti-6Al-4V alloy (Khorasani et al., 2021) and the AlSi10Mg alloy (Wu et al., 2021; Liu, Yi, Wu, et al., 2021; Nasab et al., 2019) are both fully qualified across the principal field-deployable SLM platforms available as of late 2023, and their compatibility scores are correspondingly 2. The Inconel 718 alloy (used in engine turbocharger components) is qualified on the larger production-floor SLM platforms but only partially qualified on the field-deployable platforms, and its compatibility score is 1. Armour-grade RHA steel is not qualified on any field-deployable SLM platform as of late 2023, and its compatibility score is 0. The cross-alloy variation in the compatibility score is the principal reason that armour plate scores so low in the overall CSAI assessment.

The mechanical-load-criticality criterion, the third of the five, captures the engineering acceptance threshold below which an SLM-fabricated part can be installed without engineering review and above which engineering review and qualification testing are mandatory. The criterion's three-point ordinal scale — 0 (very high criticality, qualification required), 1 (moderate criticality, partial qualification acceptable), 2 (low criticality, no engineering review required) — captures the operational risk that the maintenance commander assumes when authorising the installation of an in-theatre-fabricated part. The mechanical-load-criticality criterion is the most discriminating across the six categories examined, and its score profile drives the cross-category CSAI variation in a way that the other four criteria, taken individually, do not.

The conventional-supply-lead-time-penalty criterion, the fourth of the five, captures the operational cost of the alternative — that is, the operational impact of waiting for conventional resupply rather than producing the part in-theatre. The criterion's score depends on both the absolute lead time and the operational consequence of the immobilisation that the lead time produces. A 90-day lead time on a part whose absence grounds an entire combat platoon is far more operationally costly than the same 90-day lead time on a part whose absence grounds a single non-essential subsystem. The criterion is therefore evaluated in operational-impact-weighted terms rather than in absolute lead-time terms, with the resulting score reflecting the integrated operational cost.

The unit-cost-ratio criterion, the fifth of the five, captures the relative unit cost of in-theatre SLM production compared to conventional resupply. The criterion's score reflects both the absolute unit costs and the cost-justification threshold that the procurement framework imposes. A part whose SLM unit cost is 30 % of the conventional unit cost is highly cost-effective and scores 2; a part whose SLM unit cost is 60–80 % of the conventional unit cost is marginally cost-effective and scores 1; a part whose SLM unit cost exceeds the conventional unit cost is not cost-effective and scores 0. Across the six categories examined, the unit-cost-ratio scores are uniformly favourable for SLM production (the average ratio is approximately 0.42), with the cost advantage being a robust feature of the in-theatre SLM option under the analysed logistical-isolation conditions.

Three further conceptual points follow from the CSAI's five-criterion structure. The first is that the composite index does not collapse into a single physical variable; the five criteria address categorically different dimensions and require distinct sources of input data. The second is that the CSAI is calibrated for combat-vehicle spare parts and would require re-calibration for aerospace, naval, or unmanned-systems applications, with the corresponding thresholds and criterion weights re-fitted to the applicable operational context. The third is that the CSAI is intended as an enabling rather than a binding instrument: a CSAI score of 7 is a recommendation for in-theatre SLM production, not a mandate, and the maintenance commander retains the authority to override the CSAI recommendation on the basis of additional context — security, classification, intellectual property, or operational tempo — that the CSAI does not directly model.

## ENGINEERING AND OPERATIONAL IMPLICATIONS: CONTESTED LOGISTICS AND THE CSAI

The second analytical task is to translate the CSAI cross-category results into engineering and operational implications for combat-vehicle sustainment under contested-logistics conditions. Three implications follow directly from the cross-category results documented in the Research Results section. The first is that a deployable SLM platform supporting Ti-6Al-4V and AlSi10Mg alloys can, on the strength of the CSAI assessment, address approximately half of the combat-vehicle spare-part categories examined here under logistical-isolation conditions, with the additional conventional-resupply requirement reduced to the categories that score CSAI ≤ 5 (Valtonen et al., 2022; Salmi & Akmal, 2022). The implication for the operational maintenance footprint is that an SLM-equipped maintenance unit can substitute in-theatre fabrication for approximately half of the spare-part demand that would otherwise transit the conventional supply chain, with the resulting reduction in supply-chain vulnerability and the corresponding improvement in fleet readiness.

The second engineering implication is that the build-time-and-post-processing cycle for SLM fabrication of combat-vehicle spare parts under field conditions is short enough — 1.5–5 days for the six categories examined — to support same-week sustainment of operational combat-vehicle fleets. The cycle includes the build itself (typically 8–48 hours depending on part size and SLM platform throughput), the heat-treatment and stress-relief steps (typically 4–12 hours), the precision-machining of mating surfaces and tolerance-critical features (typically 4–24 hours), and the non-destructive evaluation (NDE) and dimensional-acceptance testing (typically 2–8 hours). The operational implication is that an SLM-equipped maintenance unit can return a combat vehicle to service within a week of identifying the failed component, compared to the 30–120 day lead time that conventional resupply would impose under the analysed logistical-isolation conditions.

The third engineering implication concerns the build-volume and throughput limitations of field-deployable SLM platforms. The build envelopes of typical field-deployable SLM systems available as of late 2023 are in the range of 250 × 250 × 300 mm to 500 × 280 × 365 mm, which is sufficient for the three high-CSAI categories (sensor brackets, mechanical linkages, hydraulic fittings) and most of the moderate-CSAI categories but insufficient for the larger components in the engine turbocharger and gun-mount categories. The implication is that the deployment of larger-build-volume SLM systems — which exist as of late 2023 but are heavier, less mobile, and more demanding of power and thermal-management infrastructure — would expand the CSAI-recommended sub-set of in-theatre fabrication candidates but at substantial logistical cost.

Two further engineering observations from the cross-category analysis merit attention. First, the post-processing-cycle component of the lead time is the largest single contributor to the SLM lead-time floor: the build itself is typically 8–48 hours, but the post-processing extends the total cycle to 1.5–5 days. The implication for engineering investment is that field-deployable post-processing infrastructure — heat-treatment ovens, precision machining equipment, and NDE instrumentation — should be co-deployed with the SLM platform itself if the lead-time advantage is to be fully realised. Second, the CSAI computation requires inputs that are partly outside the standard maintenance-data flow as of late 2023: the geometric-complexity assessment requires CAD-model availability or reverse-engineering capability; the material-and-process-compatibility assessment requires up-to-date alloy-qualification data; and the unit-cost-ratio assessment requires accurate per-build cost models that reflect the field-deployment context. The operational adoption of the CSAI therefore requires a parallel investment in CAD-library development, alloy-qualification data sharing across NATO partners, and field-deployment cost-model refinement.

The combined engineering and operational implication is that the CSAI offers a structured framework within which the maintenance commander can make consistent in-theatre-SLM-or-conventional-resupply decisions, and that the operational adoption of the CSAI substantially improves the fleet readiness under logistical-isolation conditions. The Russo-Ukrainian conflict's continuing demonstration of contested logistics conditions provides an empirical context in which the CSAI's value can be validated through deployment, and the 2024 NATO doctrine review cycle is the appropriate institutional moment for the formal adoption of the CSAI or an equivalent structured instrument.

## DOCTRINAL AND POLICY IMPLICATIONS

The third analytical task is to specify what the CSAI implies for combat-vehicle sustainment doctrine and for the policy framework within which procurement, maintenance, and operational deployment decisions are made. Three doctrinal and policy implications stand out. The first is that the combat-vehicle sustainment doctrine should be revised to integrate the CSAI as a primary in-theatre-fabrication-or-resupply decision instrument alongside the conventional supply-chain-driven decision practice. The current doctrinal vocabulary as articulated in NATO STANAGs governing combat-vehicle sustainment and in the equivalent national-level maintenance-engineering standards treats the conventional supply chain as the default option, with in-theatre AM as an exceptional capability invoked only when the conventional option fails. The CSAI's structured decision support inverts this default for the high-CSAI sub-set of spare-part categories, with in-theatre SLM production becoming the default option and conventional resupply becoming the exception (Valtonen et al., 2022). The second doctrinal implication is that the procurement framework for combat-vehicle SLM platforms should be calibrated against the CSAI-projected mix of spare-part categories rather than against a generic AM-capability specification. A force whose operational profile emphasises armoured-personnel-carrier and infantry-fighting-vehicle sustainment will have a different CSAI-projected mix than a force emphasising main-battle-tank sustainment, and the corresponding SLM-platform specification — build envelope, multi-material capability, post-processing infrastructure

— should reflect the projected mix. The implication for procurement-planning is that the CSAI computation should be applied prospectively across the projected operational profile to derive the platform-specification recommendation, with the resulting platform procurement quantitatively justified rather than generically motivated.

The third doctrinal implication concerns the alloy-qualification and CAD-library investment required to support operational SLM deployment. The cross-category CSAI variation documented in the Research Results section reflects, in part, the partial alloy qualification status of higher-strength alloys (Inconel 718, armour-grade steel, Ti-6Al-4V variants for higher-criticality applications) on field-deployable SLM platforms. The implication for the doctrinal framework is that NATO and partner-nation defence research organisations should coordinate the alloy-qualification workload across member states, with the resulting qualification data shared through a NATO-level alloy-qualification database accessible to all member-state SLM-equipped maintenance units. The corresponding CAD-library investment — a centralised, classified CAD repository of qualified spare-part designs for combat-vehicle fleets in service across the Alliance — would, in parallel, expand the CSAI-recommended sub-set substantially relative to the current ad hoc CAD-availability environment (Salmi & Akmal, 2022).

Beyond these specific doctrinal recommendations, the CSAI has implications for the validation research that the next phase of military-AM research needs to undertake. The instrument as presented here is hypothesis-generating rather than fully validated, and the validation requires (1) a multi-platform applied-engineering campaign in which the CSAI is applied prospectively to a representative cohort of combat-vehicle spare parts and the in-theatre-SLM versus conventional-resupply outcomes are tracked across the operational lifetime of the parts, (2) an inter-rater reliability study confirming that the CSAI scoring produces consistent results across different maintenance-engineer coding teams, and (3) a cross-fleet validation extending the CSAI to additional combat-vehicle platforms beyond the armoured-personnel-carrier, infantry-fighting-vehicle, and main-battle-tank categories that the present analysis emphasises. Each of these studies is feasible within a one-to-three-year horizon and could be undertaken by the existing weapon-system test-and-evaluation infrastructure at NATO and partner-nation testing centres.

A final policy implication concerns the integration of the CSAI with the broader contested-logistics, supply-chain-resilience, and forward-maintenance frameworks that NATO and partner nations have developed during 2017–2023. The supply-chain-resilience doctrine, the forward-maintenance concept of operations, and the various contested-logistics task forces across member states each address aspects of the logistical-isolation challenge, but their analytical vocabularies are uncoordinated and partially redundant. The CSAI supplies an integrative decision-support vocabulary that can serve as the connective tissue across these dispersed efforts, allowing the existing investments to compose into a single in-theatre-fabrication-or-resupply decision rather than a fragmented capability inventory. The 2024 review cycle should consider whether the CSAI or an equivalent integrative instrument should be adopted as the Alliance-level analytic baseline for combat-vehicle SLM deployment, and the present article advocates for that adoption.

## CONCLUSION

Combat-vehicle fleets operating in expeditionary, contested, or otherwise logistically isolated theatres routinely face spare-part availability shortfalls whose operational consequences are substantial and whose conventional-supply-chain remediation is increasingly fragile under the conditions that the Russo-Ukrainian war and the parallel multi-theatre operational environment have made the contemporary norm. The published 2017–2023 evidence base on selective laser melting of metal spare parts has matured to the point at which in-theatre fabrication is technically feasible for a substantial sub-set of combat-vehicle spare-part categories, and the parallel maturation of military-logistics-with-AM scholarship has documented the organisational and doctrinal pathways by which in-theatre SLM capability can be integrated into the maintenance-repair-overhaul workflow. This article has accepted the broad analytic framing while arguing that the existing literature has not supplied a structured techno-economic decision instrument that determines, for a given combat-vehicle spare part, whether in-theatre SLM production is preferable to conventional resupply under specified logistical-isolation conditions. The Critical Spare-Part Additivability Index (CSAI) has been advanced to fill that gap.

The first hypothesis, that in-theatre SLM production yields measurable techno-economic advantages over conventional resupply across a substantial sub-set of combat-vehicle spare-part categories under logistical-isolation conditions, finds clear support. The cross-category CSAI distribution documents that three of the six examined categories — sensor brackets, mechanical linkages, and hydraulic fittings — score CSAI $\geq 7$ and are recommended for in-theatre SLM production, with the corresponding lead-time and unit-cost advantages quantified in Figure 2 and substantial across both axes. The hypothesis is therefore confirmed.

The second hypothesis, that the CSAI's five criteria are non-redundant and contribute differentially to the additivability assessment, finds clear support. The cross-criterion variation documented in the Research Results section demonstrates that the mechanical-load-criticality criterion is the most discriminating, the geometric-complexity and material-and-process-compatibility criteria are second-most discriminating, and the lead-time-penalty and unit-cost-ratio criteria are least discriminating across the six examined categories. The hypothesis is therefore confirmed.

The third hypothesis, that the CSAI offers actionable decision support that single-criterion suitability assessments cannot replicate particularly for borderline cases, finds support but with the qualifier that the support is computational rather than operational. The cross-criterion divergence under the borderline categories — engine turbocharger components and gun-mount components — is computationally demonstrated but not yet validated against operational deployment data on a populated combat-vehicle cohort. The hypothesis is therefore conditionally confirmed, with the recommendation that the validation campaign proposed in the doctrinal-implications section be undertaken as the priority follow-up activity.

The principal original contribution of this article is the introduction of the Critical Spare-Part Additivability Index — a five-criterion 0–10 composite decision instrument for in-theatre-SLM-or-conventional-resupply determinations, applied to six representative combat-vehicle spare-part categories — together with the demonstration that the index can be constructed from the verified 2017–2023 SLM process-capability and military-logistics integration evidence base and operationalised through the structured workflow shown in Figure 1 and the techno-economic comparison shown in Figure 2. The CSAI contributes to the military-AM and combat-vehicle-sustainment literature in three ways: it integrates the otherwise fragmented multi-criterion suitability assessment into a single decision-support instrument; it supplies a structured procurement-and-doctrinal vocabulary that NATO and partner-nation maintenance organisations can adopt without abandoning their existing supply-chain infrastructure; and it generates a research agenda — including the multi-platform validation campaign and the alloy-qualification investment outlined in the previous section — that subsequent work can pursue.

The methodological limitations of the analysis are concrete and have been acknowledged: the CSAI is a hypothesis-generating instrument that awaits prospective operational validation; the materials coverage subsumes the principal SLM-compatible alloys into a single criterion that a more elaborate decomposition could disaggregate per-alloy; the geometric coverage is calibrated for combat-vehicle spare parts and would require re-calibration for adjacent military-equipment categories; and the threshold values (7, 5, 4) are derived from published case-evidence rather than from direct empirical fitting. The substantive limitation is that the CSAI is presented in this article as a five-criterion instrument, whereas a more elaborate decomposition with six or seven criteria — incorporating, for instance, intellectual-property considerations and security-classification handling requirements — might capture additional decision dimensions that the present design subsumes into the broader categories.

Three directions for further research follow. First, the CSAI should be subjected to a multi-platform validation campaign on a populated cohort of combat-vehicle spare parts with documented CSAI scores and tracked operational outcomes, with particular attention to the validation of the borderline-case decisions that the present application identifies as most discriminating. Second, the CSAI should be extended to additional combat-vehicle platforms and to adjacent military-equipment categories (artillery, naval, unmanned-systems) to enable cross-platform comparison and to support the migration of the index into multi-domain fleet-management databases. Third, the CSAI's threshold values should be re-calibrated from the validation-campaign data once available, with the resulting validated thresholds replacing the literature-calibrated thresholds used in the present article. Whether the CSAI's analytic value will prove sufficient to justify its incorporation into formal NATO STANAGs and national maintenance-engineering standards is a question this article cannot resolve. Whether the question is worth asking is a question that the empirical record from 2017 through 2023 has placed beyond reasonable dispute.

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# ADITIVNA PROIZVODNJA KRITIČNIH REZERVNIH DIJELOVA BORBENIH VOZILA U USLOVIMA LOGISTIČKE IZOLACIJE: TEHNO-EKONOMSKA VALIDACIJA PRIMJENE SELEKTIVNOG LASERSKOG TOPLJENJA METALA (SLM)

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**Sažetak**: Flote borbenih vozila koje djeluju u ekspedicionim, osporenim ili drugačije logistički izolovanim teatrima rutinski suočavaju se s nedostatkom rezervnih dijelova koji obustavljaju značajan udio flote na sedmicama ili mjesecima dok zamjenske komponente prolaze kroz ranjiv konvencionalni lanac snabdijevanja. Objavljena baza dokaza za period 2017–2023. o metalnoj aditivnoj proizvodnji sazrela je do tačke u kojoj selektivno lasersko topljenje (Selective Laser Melting, SLM) nikl, titanijum, aluminijum i alatno-čeličnih legura proizvodi dijelove čija se mehanička performansa približava ili podudara s konvencionalno obrađenim pandanima, dok je paralelno sazrijevanje ojačanih SLM platformi pogodnih za terenski raspored smanjilo operativni prag za in-theatre fabrikaciju. Uprkos ovom sazrijevanju, nijedna objavljena studija nije obezbijedila strukturirani tehno-ekonomski instrument odlučivanja koji određuje, za dati rezervni dio borbenog vozila, da li je in-theatre SLM proizvodnja povoljnija od konvencionalne resupplyje pod navedenim uslovima logističke izolacije. Ovaj članak, napisan početkom 2024. godine uz korist 2022–2023. kohorte optimizacija SLM procesnih parametara i paralelnog sazrijevanja naučne literature o vojnoj logistici s AM-om, popunjava tu prazninu. U članku se uvodi Indeks aditivnosti kritičnih rezervnih dijelova (Critical Spare-Part Additivability Index, CSAI), pet-kriterijumska 0–10 kompozitna ocjena koja obuhvata geometrijsku kompleksnost, materijalno-i-procesnu kompatibilnost s raspoloživim SLM sistemima, kritičnost mehaničkog opterećenja, kaznu nad vremenom konvencionalne isporuke i odnos jediničnih troškova. CSAI se operacionalizuje kroz strukturirani radni tok odlučivanja i primjenjuje na šest reprezentativnih kategorija rezervnih dijelova borbenih vozila. Testiraju se tri hipoteze: da in-theatre SLM proizvodnja daje mjerljive tehno-ekonomske prednosti u odnosu na konvencionalnu resupplyju kroz značajan podskup kategorija rezervnih dijelova borbenih vozila pod uslovima logističke izolacije; da pet kriterijuma CSAI-ja nisu redundantni i doprinose različito procjeni aditivnosti; i da CSAI nudi akcionu podršku odlučivanju koju jednokriterijumske procjene pogodnosti ne mogu zamjeniti. Doktrinarne implikacije su da NATO i partnerske nacije treba da usvoje CSAI ili ekvivalentni strukturirani instrument kao dio ciklusa revizije doktrine za 2024. godinu za operacije naprednog održavanja i osporene logistike.

**Ključne riječi**: *aditivna proizvodnja, selektivno lasersko topljenje, borbena vozila, rezervni dijelovi, logistička izolacija, osporena logistika, tehno-ekonomska analiza, CSAI.*