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Original Contribution

HYBRID SPARE-PARTS LOGISTICS IN ENGINEERING SYSTEMS: A 3S MODEL FOR STORE, SOURCE, OR SYNTHESIZE DECISIONS

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Abstract: *Spare-parts availability is a critical condition for technical continuity in production, transport and other engineering systems. Traditional inventory strategies provide rapid response but may create high holding costs, obsolescence and tied capital, whereas external sourcing introduces lead-time dependence. Additive manufacturing adds a third option by enabling selected components to be produced on demand from digital data. This conceptual paper develops a hybrid decision framework that combines these alternatives in a 3S model: Store, Source, Synthesize. The model evaluates spare parts according to criticality, supply lead time, downtime cost, demand frequency, additive-manufacturing feasibility, material and quality requirements, legal and warranty constraints, and lifecycle economics. The study synthesizes peer-reviewed research on additive manufacturing in spare-parts supply chains and positions 3D printing as a selective logistics option rather than a universal substitute for physical inventory. The resulting framework is intended for preliminary classification and decision support; it requires organisation-specific validation before quantitative thresholds are introduced.*

Key words: ***E****ngineering logistics, Spare parts, Additive manufacturing, 3D printing, Digital inventory, Maintenance logistics, Inventory management, Resilience.*

1. Introduction

Spare parts differ from ordinary inventory because demand is often intermittent while the consequence of a stock-out can be disproportionate. A low-frequency component may remain unused for years and then become essential for restoring a machine, production line or transport asset. The logistics problem is therefore not only how much inventory to hold, but how to preserve technical readiness at an economically reasonable cost.

Additive manufacturing (AM) has expanded the decision space. Selected parts can be stored digitally and produced on demand, potentially shortening supply chains and reducing physical inventories. Khajavi, Partanen and Holmström showed early that AM can alter spare-parts supply-chain configurations and enable more distributed production [1]. Subsequent work has developed selection methods for identifying economically and technologically

feasible parts [2] and systematic reviews have confirmed both the opportunity and the limitations of AM in spare-parts management [3].

The aim of this paper is to propose a conceptual hybrid logistics model for choosing among physical stock, external sourcing and on-demand additive manufacturing. The object of study is spare-parts support in engineering systems; the subject is the logistics decision among the three supply modes. The working proposition is that resilient spare-parts management requires part-specific decisions based not only on unit price, but also on criticality, accessibility, manufacturability, risk and consequences of downtime.

2. Related work

Research on AM for spare parts consistently rejects a one-size-fits-all approach. Knofius, van der Heijden and Zijm developed an AHP-based method for ranking spare parts according to technological and economic suitability for AM and demonstrated the importance of company-specific data [2]. Cardeal, Leite and Ribeiro later proposed a multi-criteria decision-support model that combines operational and technological preselection with cost and environmental considerations [4].

Lifecycle economics are equally important. Westerweel, Basten and van Houtum compared traditional and additive component designs and showed that AM benefits depend on production cost, component reliability, design investment and the value of shorter lead times [5]. Critical reviews further note that assumptions about AM part reliability and feasibility vary considerably across the literature, which limits simple generalization [6].

Recent supply-chain research also emphasizes organisational barriers. Naghshineh, Fragoso and Carvalho argue that firms considering AM for spare-parts supply should evaluate performance, delivery, economics and implementation barriers rather than treating digital inventory as an automatic replacement for physical stock [7]. These findings motivate a hybrid decision logic in which storage, sourcing and synthesis coexist.

3. Problem description and methodology

The decision problem is formulated at the level of an individual spare part. For each item, the organisation must determine which supply mode best balances continuity, lead time, cost, technical feasibility, quality and legal constraints. The present study follows a conceptual synthesis approach and derives the 3S framework from recurring criteria in the peer-reviewed literature. The model does not introduce universal weights because the relative importance of downtime, safety, lead time and inventory cost differs strongly among industries and assets.

The decision criteria are summarised in Table 1. Suitability for additive manufacturing is treated as a prerequisite rather than as an automatic preference. A part should enter the Synthesize option only when material, geometry, dimensional tolerance, quality-assurance and authorisation requirements can be met.

Table 1. Decision criteria in the 3S model

Criterion	Diagnostic question	Decision relevance
Criticality	What happens if the part is unavailable?	prioritizes continuity and safety
Supply lead time	How quickly can an approved part be obtained?	distinguishes stock from external sourcing
Downtime cost	What is the operational loss during unavailability?	captures system-level consequence
Demand frequency	How often is the part used?	supports inventory justification

Criterion	Diagnostic question	Decision relevance
AM suitability	Can the part be produced with an approved AM process?	determines whether Synthesize is technically admissible
Material and quality	Are material, tolerance, durability and inspection requirements achievable?	protects technical conformity
Legal and warranty constraints	Are copying, design-file, certification or warranty restrictions present?	determines decision admissibility
Lifecycle economics	Which option is preferable over the relevant service horizon?	balances purchase, holding, production and downtime costs

4. Conceptual results and discussion

The main conceptual result is the 3S model: Store, Source, Synthesize. The three modes are not competing technologies but complementary logistics strategies. The framework is presented in table 2.

Table 2. The 3S hybrid spare-parts logistics model

Mode	Meaning	Typical conditions
Store	hold a physical spare in inventory	high criticality, long replenishment lead time, high downtime cost, frequent demand, or safety relevance
Source	obtain the part from an external supplier	standardised and accessible part, acceptable lead time, low stock-out consequence
Synthesize	produce on demand using qualified additive manufacturing	low-volume or obsolete part, long sourcing difficulty, technically manufacturable geometry/material, validated quality and lawful access to design data

The 3S model changes the role of the physical warehouse without assuming its disappearance. Critical and safety-relevant items may still require local physical stock. Standard parts with competitive supplier markets may be sourced externally. A third group—low-volume, obsolete or difficult-to-source parts—may become candidates for digital inventory and on-demand manufacturing. This logic is consistent with evidence that AM can reduce supply-chain response time for selected items, but that candidate selection is essential [2, 4].

Digital inventory also introduces governance requirements. The existence of a CAD file does not, by itself, make a component an approved spare part. Organisations must control file versions, intellectual-property rights, approved materials and machines, post-processing, inspection and traceability [7]. For safety-critical applications, an additively manufactured substitute should not be accepted unless the relevant engineering, quality and regulatory requirements are satisfied.

The framework has practical limitations. It is conceptual and has not yet been validated against a substantial industrial spare-parts portfolio. It therefore contains no fixed thresholds for criticality or lead time and does not claim to identify a universal economic optimum. Future work should test the model using company data and compare 3S classifications with existing inventory policies, lifecycle cost and observed maintenance response time. Expert

assessment should also be used to refine the criteria before any weighted scoring procedure is introduced.

5. Conclusion

Hybrid spare-parts logistics offers a more flexible approach than treating physical inventory as the only assurance mechanism. Additive manufacturing creates an additional supply mode, but its value depends on deliberate part selection and on technical, economic, quality and legal feasibility.

The proposed 3S model structures the choice among Store, Source and Synthesize through eight diagnostic criteria. Its contribution is to place continuity, downtime consequences and technical admissibility alongside conventional inventory economics. The model is intended as a transparent preliminary decision framework. Empirical testing on real spare-parts portfolios is required before quantitative weights, thresholds or generalised performance claims can be justified.

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