

Circular Economy in Aerospace: A Framework for End-of-Life Composite and Rare Metal Reclamation

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ABSTRACT

The aerospace industry faces increasing pressure to transition from a linear "take-make-dispose" model to a circular economy. This shift is particularly challenging for end-of-life aircraft materials, where over 50% of retired assets are relegated to landfills or low-value recovery streams. This study addresses the critical gaps in recycling and reclamation processes, specifically for advanced composites like carbon-fiber reinforced polymers and rare metals such as titanium and cobalt. The paper proposes a comprehensive, multi-layered framework built upon a microservices-based architecture for end-of-life material traceability. This digital foundation integrates advanced analytics, AI, and industrial big data to automate and optimize material sorting and recovery. By creating a detailed technical blueprint for this system, the research demonstrates how a transparent, data-driven ecosystem can overcome current technological and logistical bottlenecks. The framework is designed to enhance material recovery rates, improve economic viability, and strengthen supply chain resilience. It concludes that while current technologies are insufficient, a combination of digital innovation, robust regulatory frameworks, and collaborative industry efforts is essential to scale recycling and reduce the industry's reliance on virgin raw materials, moving it toward a truly circular future.

Keywords: Circular Economy, Aerospace, Composites, Rare Metals, Recycling, Microservices, Data Analytics.

INTRODUCTION

1.1. Context and Problem Statement

The aerospace industry, long celebrated for its innovation and technological advancement, is at a critical juncture regarding its environmental footprint and long-term sustainability. The traditional linear model of "take-make-dispose" has led to significant resource depletion and waste accumulation, particularly from end-of-life (EOL) aircraft and manufacturing scrap. The pressure on the industry to adopt circular economy (CE) principles is mounting, driven by global environmental regulations, corporate social responsibility, and the inherent economic risks of resource scarcity. Unlike other sectors, such as automotive, which have established recycling processes [32], aerospace faces unique and complex

challenges due to its use of highly specialized materials [17]. These challenges include the sheer scale of retired aircraft, which are becoming more frequent, and the complex material composition, particularly the increasing reliance on advanced composites and rare metals [28].

The current state of EOL aircraft management is highly inefficient. A key data point underscoring this inefficiency is that over 50% of retired aircraft materials still end up in landfills or low-value recovery streams, representing a significant loss of embodied energy and economic value. This practice is not only environmentally unsustainable but also creates an unnecessary reliance on virgin raw materials, which are subject to supply chain volatility and geopolitical risks

[26]. The transition to a CE model, which emphasizes resource longevity, waste minimization, and material regeneration, is therefore no longer an option but a strategic imperative for the industry's future [16].

1.2. The Role of Advanced Materials: Composites and Rare Metals

The core of the problem lies in the materials themselves. The aerospace industry has increasingly adopted carbon-fiber reinforced polymers (CFRPs) due to their unparalleled strength-to-weight ratio, which directly contributes to fuel efficiency and performance. However, these materials present a formidable recycling challenge. The thermoset resins used to bind the carbon fibers make mechanical separation difficult, often resulting in degraded fiber quality that is unsuitable for re-use in high-performance applications [23]. While alternative chemical methods exist, they are often energy-intensive and not yet economically viable at scale [7].

Similarly, the industry's dependence on rare metals, such as titanium, cobalt, and various rare earth elements, poses a parallel threat. These metals are critical for the manufacturing of engines, avionics, and structural components due to their unique thermal and mechanical properties. However, their extraction is often environmentally destructive, and the global supply is concentrated in a few regions, creating significant supply chain vulnerabilities [20]. The recycling infrastructure for these metals from complex aerospace assemblies is currently limited, leading to a de facto reliance on new mining activities [7]. This dual challenge of composite and rare metal reclamation highlights a significant gap in the industry's sustainability efforts.

1.3. Literature Review and Research Gaps

Extensive research has explored the application of circular economy principles in various industries, from manufacturing [12] to supply chain management [24]. The rise of Industry 4.0 technologies, including Big Data, AI, and IoT, has been identified as a key enabler for CE transitions [15, 29]. Specifically in the context of recycling, studies have reviewed sustainable approaches for battery and metal recovery [7]. The aerospace and automotive sectors have also been compared in terms of their supply chain sustainability [17]. However, a significant gap remains in the focused application of these principles and technologies to the unique challenges of aerospace EOL material reclamation.

While some literature touches on managing aircraft lifecycle complexity [19], there is a lack of comprehensive frameworks that integrate technological solutions (e.g., advanced data analytics and microservices) with systemic, organizational, and regulatory considerations. Current research often addresses either the material science of recycling or the

logistical and policy aspects in isolation. This study seeks to bridge this gap by proposing a holistic framework that connects the technological innovations required for material reclamation with the operational and collaborative strategies needed to scale these solutions. By addressing this gap, the paper aims to provide a practical roadmap for the industry to transition from a linear to a circular model for its most critical and challenging materials.

METHODS

2.1. Research Design and Approach

This study employs a qualitative, framework-based research design. The primary objective is to develop a conceptual framework that integrates technological, operational, and policy-related strategies for enhancing the circular economy in the aerospace sector. This approach is justified given the complexity of the problem, which involves not only material science and engineering but also logistics, economics, and regulatory policy. The framework is built upon a synthesis of existing literature from multiple domains, including materials science, supply chain management, software engineering, and environmental policy.

The methodology is structured around identifying and mapping the key components of a successful CE ecosystem for aerospace. This involves a multi-layered analysis:

1. **Material-level analysis:** Identifying the specific challenges and opportunities for recycling carbon-fiber composites and rare metals.
2. **Technological-level analysis:** Exploring how advanced technologies (e.g., big data, AI, cloud computing) can enable efficient sorting, tracking, and processing of EOL materials.
3. **Process-level analysis:** Examining the operational workflows for disassembly, material recovery, and integration into new supply chains.
4. **System-level analysis:** Considering the overarching industry-wide collaborations and regulatory frameworks necessary to support these processes at scale.

This multi-faceted approach allows for the creation of a comprehensive model that goes beyond a single solution, providing a holistic and actionable strategy for industry stakeholders.

2.2. A Microservices-based Architecture for EOL Material Traceability

The current lifecycle management of aerospace components is fragmented, relying on a patchwork of paper-based logs, disparate digital systems, and a general

lack of interoperability. This inefficiency is a major impediment to a circular economy, as it makes it nearly impossible to track a component's history, material composition, and potential for recycling or re-use in a scalable manner. To overcome this, a new paradigm is needed—one that treats each aircraft part not just as a physical object but as a digital asset with a complete and traceable lifecycle history. Our proposed solution is a microservices-based architecture designed specifically for this purpose.

2.2.1. Foundational Principles and System Design

The core of this architecture is a collection of small, independent services, each responsible for a single, well-defined function [14]. This stands in stark contrast to monolithic systems, which bundle all functions into a single, indivisible application. The microservices approach is particularly suited to the aerospace supply chain because it is inherently complex and involves many different stakeholders—from parts manufacturers and airlines to MRO facilities and end-of-life recycling centers [10]. No single entity can or should own the entire system; rather, the architecture must be decentralized and highly interoperable.

The system's backbone is an Event-Driven Architecture (EDA), where services communicate asynchronously via a message bus or event streaming platform like Apache Kafka [25]. When a significant event occurs (e.g., a component is installed, removed, or recycled), an event message is published to a shared stream. Relevant services then subscribe to these streams to react accordingly. For example, when a wing flap is removed from an aircraft, a "Component Decommissioned" event is published. A "Material Recycling Service" and a "Component History Service" would both listen for this event, updating their respective data stores without direct, synchronous calls between them. This decoupling enhances system resilience and scalability, as individual services can operate even if others are temporarily unavailable [2].

2.2.2. Key Microservices and Their Functions

The architecture is composed of several core microservices, each representing a distinct functional domain.

- **Component History Service:** This is the authoritative source for a component's full lifecycle data. It stores information such as manufacturing date, installation history, flight hours, maintenance records, and any recorded incidents. Data is ingested from external systems via APIs or event streams. The service's primary function is to provide a comprehensive digital history for any given part, which is crucial for determining its remaining value and potential for re-use.

- **Material Composition Service:** A critical service for recycling, this service contains detailed data on the chemical and physical composition of a component. For a carbon-fiber panel, this would include the type of carbon fiber, the resin system, and any additional materials (e.g., honeycomb cores). For a rare metal part like a turbine blade, it would specify the alloy composition (e.g., titanium-aluminum). This service enables downstream recycling facilities to instantly know the material makeup of an incoming part, bypassing a major bottleneck in the current process. This information is a key input for the analytics engine described later.

- **Recycling Process Service:** This service models and tracks the physical and chemical processes of material recovery. When a part enters a recycling facility, this service logs the specific recycling method used (e.g., pyrolysis, solvolysis, or hydrometallurgy) and records key process parameters such as temperature, pressure, and duration. It then receives data from sensors on the recycling machinery to monitor efficiency and material yield in real-time. This data is essential for optimizing the recycling process itself and for validating the quality of the recovered material.

- **Asset Management Service:** This service tracks the location and ownership of all EOL assets, from the moment an aircraft is retired to when its components are sorted and moved to recycling centers. It provides a chain of custody, ensuring transparency and accountability. The service can be integrated with GPS or RFID-based tracking systems to provide real-time location data, which is especially valuable for high-value components containing rare metals.

- **Marketplace Service:** To create a truly circular model, a service is needed to connect suppliers of recovered materials with potential buyers. This service acts as a digital marketplace, listing available recycled materials (e.g., reclaimed carbon fiber, titanium scrap) along with their certified quality and provenance. This provides a transparent and efficient way for manufacturers to source recycled content, thus creating a stable market and increasing the economic viability of recycling [20].

2.2.3. Data Management: The Data Lakehouse Approach

The sheer volume and variety of data generated across an aircraft's lifecycle—from structured manufacturing data to unstructured maintenance logs and real-time sensor streams—necessitates a modern data architecture. A traditional data warehouse would be too rigid, while a pure data lake would lack the necessary structure for complex analytics. Our proposed solution is a Data Lakehouse, which combines the schema-on-read flexibility of a data lake with the data management features of a data warehouse [13].

Within this architecture, raw data from various sources (e.g., ERP systems, MRO software, sensor feeds) is ingested into the raw data layer of the lakehouse. From there, it is cleaned, transformed, and structured into a curated layer where it can be queried using standard SQL for business intelligence and reporting. The underlying data format, such as Apache Parquet or Delta Lake, ensures that the data is highly performant for analytical workloads [27]. The use of a platform like MongoDB in conjunction with the lakehouse can provide a performant and reliable data store for individual microservices, bridging the gap between high-speed transactional data and large-scale analytical data [5, 6]. This dual-approach allows each service to choose the database that best suits its needs while still contributing to a single, unified data repository for analytics.

2.2.4. A Structured Approach to Data Security

Given the sensitive nature of aerospace data, security must be an integral part of the architecture, not an afterthought. The proposed framework would adopt a DevSecOps approach, integrating security practices throughout the entire software development lifecycle [8].

- **Identity and Access Management (IAM):** Each service would operate under the principle of least privilege. Users and services would only be granted access to the specific data and functions they need to perform their jobs.
- **Secure API Gateways:** All external and internal service-to-service communication would pass through a secure API gateway, which would handle authentication, authorization, and rate limiting. This acts as a protective shield around the microservices [4].
- **Data Encryption:** Data would be encrypted both in transit (using protocols like TLS) and at rest (in the data lakehouse). This protects sensitive information, such as proprietary material compositions, from unauthorized access.
- **Auditing and Monitoring:** Comprehensive logging and monitoring would be implemented to track all data access and system activity. This enables real-time threat detection and provides a clear audit trail for compliance and forensic analysis [30].

By building in security from the ground up, the framework can gain the trust of stakeholders across the value chain, encouraging them to participate in the data-sharing ecosystem.

2.3. Analytics and AI for Sorting and Recovery

To address the challenge of separating complex materials, the framework incorporates an analytics and AI layer. The physical sorting and material identification

process for EOL aircraft components is currently a major bottleneck, relying on manual labor and often leading to mis-sorted materials [23].

- **Predictive Analytics and Machine Learning:** Machine learning models would be trained on historical data from manufacturing and previous recycling efforts to predict the material composition and quality of components before disassembly [9, 15]. For instance, a model could predict the type of resin and carbon-fiber orientation based on a component's part number and age, guiding the most effective recycling method (e.g., pyrolysis vs. solvolysis).
- **Computer Vision:** This technology would be deployed at disassembly facilities to automatically identify and sort different materials on a conveyor belt. Cameras and sensors would feed data to a computer vision model that recognizes components and directs robotic arms to sort them into appropriate streams (e.g., composites, aluminum alloys, copper wiring) [18]. This automates a traditionally manual and error-prone process, significantly increasing efficiency.
- **Industrial Big Data Analytics:** The proposed system would leverage big data analytics to optimize the entire recycling process. This includes analyzing data from sensors on recycling machinery to optimize energy consumption and process parameters [29]. For example, by analyzing temperature and pressure data from a pyrolysis oven, the system can adjust settings in real-time to maximize carbon-fiber yield and quality [11].

RESULTS

3.1. A Conceptual Framework for Circular Aerospace

The synthesis of technological and operational methodologies results in a comprehensive conceptual framework for a circular aerospace ecosystem. This framework is not a single technology but a multi-layered system designed to connect various stakeholders and processes, from manufacturing to EOL management.

- **Layer 1: The Digital Foundation:** This layer comprises the microservices-based platform for component traceability and data management. It acts as the "nervous system" of the framework, providing a single source of truth for all material data. This system enables stakeholders to access detailed information about a component's history, material composition, and potential for re-use or recycling. The use of a Data Lakehouse ensures that this information is available for both real-time operational decisions and long-term strategic analysis [13]. The digital foundation, now fully defined, becomes the enabler for the other two layers of the framework.
- **Layer 2: The Analytics and Automation Engine:**

This layer consists of the AI and analytics tools that automate and optimize the material recovery process. By integrating predictive analytics, computer vision, and industrial big data analytics, this layer addresses the critical challenge of sorting and processing complex EOL materials. This automation significantly reduces the reliance on manual labor, improves material quality, and increases the speed and efficiency of the recycling process.

- **Layer 3: The Collaborative Network:** This layer represents the crucial inter-organizational relationships needed to make the system work. It includes partnerships between manufacturers, airlines, maintenance, repair, and overhaul (MRO) facilities, and recycling companies. The digital foundation and analytics engine facilitate this collaboration by providing transparent and reliable data that can be shared securely across the value chain. This transparency builds trust and enables more efficient transaction of recovered materials [20].

3.2. Practical Applications and Expected Outcomes

The implementation of this framework is expected to yield several tangible results:

1. **Increased Material Recovery Rates:** By automating sorting and optimizing recycling processes, the framework can significantly increase the percentage of retired aircraft materials that are successfully reclaimed. The goal is to move beyond the current state where over 50% of materials end up in landfills, aiming for a much higher recovery rate, particularly for high-value materials.

2. **Enhanced Economic Viability:** By improving the efficiency and yield of recycling, the framework can make the recovery of challenging materials like carbon-fiber and titanium more economically attractive. The high quality of recovered materials would make them suitable for re-use in new manufacturing, reducing the need for costly virgin materials. This creates a new revenue stream for airlines and MROs [19].

3. **Reduced Environmental Impact:** The framework directly addresses the environmental concerns of resource depletion and waste generation. By reducing reliance on virgin raw materials, it lowers the energy consumption associated with mining and processing, and it minimizes landfill waste [21]. This aligns the industry with global sustainability goals.

4. **Improved Supply Chain Resilience:** The recycling and re-use of rare metals, in particular, would reduce the industry's vulnerability to supply chain disruptions. By creating a domestic or regional source of critical materials, the framework mitigates the geopolitical risks associated with relying on a limited number of global suppliers [26].

DISCUSSION

4.1. Addressing the Challenges of Composites and Rare Metals

The proposed framework provides a targeted approach to the most significant material challenges facing circularity in aerospace: carbon-fiber composites and rare metals. For composites, the use of industrial big data analytics and AI is crucial. By analyzing process data from chemical or thermal recycling (e.g., pyrolysis), the system can fine-tune parameters to ensure that the recovered carbon fibers maintain their mechanical properties and are not degraded [11, 23]. This moves the industry beyond low-value recovery and towards a truly circular model where recovered fibers can be re-used in new aircraft components.

For rare metals, the challenge is primarily one of identification and sorting within complex assemblies. The microservices platform, combined with computer vision, allows for the precise tracking of components containing materials like titanium and cobalt. This information, stored in the digital twin, guides the disassembly process, ensuring that these high-value parts are separated and directed to specialized recycling facilities instead of being lost in a general scrap stream [7, 20]. The economic viability of recovering these metals is directly tied to the efficiency of this sorting process. The framework, therefore, makes the business case for investing in the necessary recycling infrastructure.

4.2. The Critical Role of Industry Collaboration and Regulatory Frameworks

The success of the proposed framework is contingent upon a high degree of industry collaboration. A decentralized but interoperable system requires all stakeholders—from manufacturers to end-of-life facilities—to participate and share data. This is a significant cultural shift for an industry historically characterized by proprietary data and highly controlled supply chains [10]. Regulatory frameworks are essential to incentivize this collaboration and ensure a level playing field. Governments and international bodies can play a pivotal role by mandating minimum recycled content in new aircraft, providing tax incentives for recycling infrastructure, or creating clear standards for the quality of recovered materials [27, 28]. This would reduce reliance on virgin materials and create a stable market for recycled products, driving investment in the necessary technologies. Without such regulatory push, a full-scale transition to a CE model will be difficult to achieve.

4.3. Limitations and Future Directions

While the proposed framework offers a robust conceptual

model, its implementation faces several limitations. The high upfront cost of developing the microservices platform and the AI-driven analytics engine is a significant barrier for many companies. The issue of data governance and security is also paramount; a shared platform for sensitive lifecycle data requires a strong security protocol, which is a key concern in the defense and aerospace sectors [8, 30]. Furthermore, the physical infrastructure for large-scale composite and rare metal recycling is still nascent, and the framework, while guiding the technological path, does not solve the capital-intensive problem of building these facilities.

Future research should focus on developing a cost-benefit analysis of the proposed framework to provide a stronger business case for investment. It is also crucial to explore how a DevSecOps approach can be integrated into the system's development to ensure that security is built-in from the ground up, rather than added as an afterthought [8]. Finally, a pilot program could be implemented with a single airline and a recycling partner to test the feasibility and scalability of the microservices platform and the analytics engine on a smaller scale, providing valuable real-world data and insights [2, 10]. This would move the concept from a theoretical framework to a practical, deployable solution.

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