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Data-Driven Circularity in the Aerospace Sector: A Research Perspective on Cognitive MRO and Generative Design

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General Introduction

The realization of a Circular Economy in the aerospace sector is currently challenged by two critical information gaps: a Semantic Interoperability Gap (the inability to translate human language into machine data) and a Passive Data Gap (the inability to translate physical wear into design revisions). This research paper addresses these challenges in two distinct parts.

Part A focuses on "Semantic Interoperability and the Cognitive MRO," proposing a Semantic Knowledge Graph to bridge the linguistic divide between MRO technicians and design engineers.

Part B focuses on "Generative Design and the Active Digital Product Passport," introducing a Generative Circular Feedback Loop and the "R-Index" to transform static reports into active design agents.

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Part A: Semantic Interoperability and the Cognitive MRO Data Pipeline

Abstract— The realization of a Circular Economy in the aerospace sector is currently challenged by a critical Interoperability Gap. While Engineering Design relies on structured, parametric data (e.g., CAD tolerances), Maintenance, Repair, and Operations (MRO) data often exists as unstructured, free-text logs written by technicians. This linguistic disconnect prevents the automated feedback loops required for circular design. This paper proposes a Semantic Knowledge Graph framework specialized for Landing Gear MRO. By utilizing Natural Language Processing to mine unstructured Shop Visit Reports and mapping them to formal Engineering Ontology, we create a "Digital Bridge." This bridge translates subjective failure descriptions into objective design constraints, enabling a closed-loop data flow that directly informs Design for Remanufacturing (DfRem).

Keywords—*Circular Economy; Semantic Knowledge Graph; Aerospace MRO; Data Interoperability; Unstructured Data Mining; Design for Remanufacturing (DfRem); Landing Gear*

I. INTRODUCTION

The realization of Circular Economy in the aerospace industry relies fundamentally on the closure of information loops. For high-value assets such as Landing Gears, which account for a significant portion of aircraft maintenance costs and embodied materials—the ability to feed End-of-Life (EoL) performance data back into early-stage product design is critical. Ideally, the EoL of one product generation should serve as the Cradle of data for the next, informing Design for Remanufacturing (DfRem) decisions that extend component lifecycles and reduce material waste [1]. As emphasized by Paletti et al. [8] in their analysis of the ISO 59004:2024 standard, the aerospace sector must transition from recycling to higher-value retention strategies such as remanufacturing.

However, a profound Semantic Interoperability Gap currently prevents this closure. As illustrated in our conceptual analysis, the aerospace ecosystem is divided into two linguistically distinct worlds. On one side, the Engineering Design domain operates on highly structured, parametric data (e.g., CAD geometries, finite element tolerances). On the other side, the Maintenance, Repair, and Operations (MRO) domain—where the actual circularity decisions occur—operates largely on unstructured, natural language data.

When a landing gear strut is inspected after 20,000 cycles, the technician's insights are often captured in free-text logbooks or Shop Visit Reports in PDF format. A mechanic might record, "Found heavy pitting on the bogie pivot pin, suspect galvanic reaction." While this entry contains high-value circularity intelligence, it remains computationally invisible to the Design Engineer's database, which expects quantitative inputs like surface roughness or material degradation rate [2].

Consequently, vast repositories of circular knowledge remain trapped in data silos, inaccessible to the algorithms meant to optimize future designs. We define this as the Unstructured Data Problem in Circular Aerospace. Brunton and Kutz [7] note that the future of aerospace engineering lies in the fusion of physics-based models and data-driven insights. Building on this perspective, we propose a framework that fuses physical design parameters with data-driven linguistic insights from MRO logs.

This paper proposes a solution to bridge this semantic gap: a Semantic Knowledge Graph framework tailored for Landing Gear MRO. By applying Natural Language Processing to mine unstructured text and mapping extracted entities to a formal Engineering Ontology [11], we create a "Digital Translator." This framework converts subjective maintenance texts into objective design constraints, enabling a standardized, automated feedback loop that empowers engineers to design landing gears

that are not only robust but inherently optimized for circularity and remanufacturing.

II. LITERATURE REVIEW AND GAP ANALYSIS

The digital transformation of the aerospace supply chain is often viewed through the lens of Big Data. However, for the Circular Economy, the challenge is not only the *volume* of data, but its *variety* and *integrity*. The transition from a linear to a circular model requires the convergence of three disparate research streams: Knowledge Management in MRO, Natural Language Processing for industrial text, and Ontology-based interoperability. According to the UNECE specifications for Digital Product Passports [6], interoperability is the primary barrier to adoption.

A. *The "Data Graveyard" in Aerospace MRO*

MRO activities generate vast amounts of technical data. Keivanpour [1,2] notes that while modern aircraft are equipped with sensors (structured data), the most valuable insights regarding EoL recoverability often reside in human-generated reports (unstructured data). Technicians inspect components for complex failure modes—such as fretting corrosion in landing gear struts—and document their findings in free-text logs. However, current research indicates that major part of industrial data remains unanalyzed, forming Data Graveyards. The lack of structured feedback from these logs to the design phase is a primary barrier to "Design for Remanufacturing" (DfRem), as engineers lack empirical evidence to justify design changes [3]. Recent works by Jo [4] have demonstrated the efficacy of LLMs in retrieving compliance data for MRO tasks. However, while their system focuses on *retrieving* existing manual data for repair execution, it does not address the *generation* of feedback data to improve future component design, which is the primary focus of this research.

B. *Semantic Knowledge Graphs (SKGs) and Ontologies*

Semantic Knowledge Graphs have emerged as a powerful tool for Industry 4.0. Unlike rigid relational databases (SQL), SKGs [12] utilize graph structures to link disparate entities through meaningful relationships. In the aviation domain, several ontologies have been proposed to standardize maintenance terminology. Liu et al. [5] successfully utilized LLMs to construct knowledge graphs from aerospace requirement documents. Nevertheless, a significant gap remains in applying this methodology to *post-operational* data. Unlike their focus on pre-design requirements, our proposed framework applies

graph construction to unstructured *End-of-Life (EoL)* reports to close the circularity loop.

The *Digital Twin Ontology* attempts to unify data formats [10]. However, existing ontologies tend to focus on operational scheduling (e.g., When is the next service due?) rather than physical degradation capability (e.g., "Is this surface remanufacturable?"). There is a notable scarcity of ontologies specifically tailored to the complex material physics of Landing Gear EoL processing.

C. NLP for Industrial Text Mining

Recent advancements in NLP, particularly Transformer-based models like BERT [9] (Bidirectional Encoder Representations from Transformers), have revolutionized text mining. Studies have demonstrated the efficacy of NLP in extracting named entities (e.g., part numbers, failure dates) from maintenance logs. However, a critical limitation remains: most current NLP applications in MRO are diagnostic (aimed at fixing the current fault) rather than generative (aimed at improving future design). There is limited literature on bridging the output of NLP models directly into parametric CAD constraints.

D. Synthesis: The "Semantic Interoperability Gap"

Despite progress in these individual fields, a critical "Semantic Gap" persists at their intersection:

1. The Linguistic Divide: Design engineers speak in *parameters* (e.g., Tolerance < 0.05mm), while MRO technicians speak in *observations* (e.g., "Surface looks rough"). Current systems lack the translation layer to convert the latter into the former.
2. Contextual Loss: Standard NLP approaches extracting keywords but often lose the *causal context* required for circularity (e.g., knowing *why* a part failed, not just *that* it failed).
3. The Missing Feedback Loop: There is no established framework that automatically triggers a Design Alert based on the semantic trends found in unstructured text.

This paper addresses these gaps by proposing a domain-specific Landing Gear Knowledge Graph. Unlike generic text mining tools, our framework specifically maps unstructured degradation descriptions to formal engineering design parameters, thereby operationalizing the Digital Thread for the Circular Economy (Figure 1).

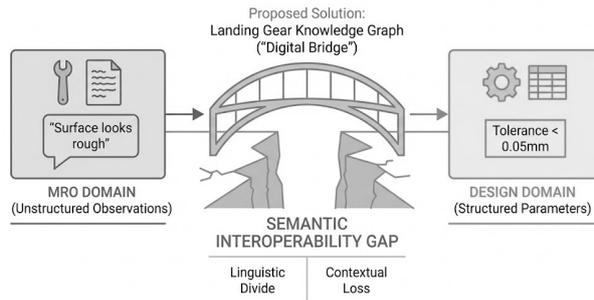


Figure 1: The Semantic Interoperability Gap in Circular Aerospace

III. CONCEPTUAL FRAMEWORK

To understand the fundamental barrier to a circular aerospace economy, it is necessary to analyze the disconnect between the operational and design domains. As illustrated in Figure 2, the industry is currently divided into two linguistically incompatible environments. The MRO domain is dominated by Human Intelligence, where data is generated by technicians and inspectors relying on heuristic experience. This environment produces unstructured, qualitative, natural language data; for example, a mechanic might document a finding as *"Found heavy pitting on the bogie pivot pin; suspect galvanic reaction due to moisture trap."* While semantically rich, this data exists as undefined text strings—computationally "invisible" "blobs" that lack mathematical definition. On the other hand, the Engineering Design domain is governed by Computational Intelligence, primarily driven by CAD software and Finite Element Analysis (FEA) solvers. This world operates strictly on structured, quantitative parameters. A design database anticipates specific numerical inputs, such as `Surface_Roughness` or `Material_Loss_Rate`. Consequently, a fundamental incompatibility arises: design software cannot interpret adjectives. It has no mechanism to process qualitative descriptors like "heavy" or "suspect," and without a convertible numerical value, the technician's critical insight is effectively rejected by the system.

This "Semantic Interoperability Gap" creates as a void where circularity fails.

First, there is a Linguistic Divide where no direct translation layer exists to convert observational jargon into parametric constraints, forcing engineers to rely on estimation rather than field reality. Second, there is a critical Contextual Loss; while standard keyword searches might flag the word "corrosion," they often discard the causal context—such as the phrase *"due to moisture trap"* which is the most vital piece of feedback for preventing future failures. Finally, this results in a Silent Loop;

because the Design domain cannot "hear" the MRO domain, design flaws are often repeated in the next generation of components. To bridge this chasm, this research proposes a Semantic Knowledge Graph acting as a "Digital Translator." By utilizing an ontology to map vague terms like "*Heavy Pitting*" to specific nodes (e.g., *Corrosion_Severity_Level_3*) linked to design constraints, we can effectively convert subjective opinion into objective, actionable design data.

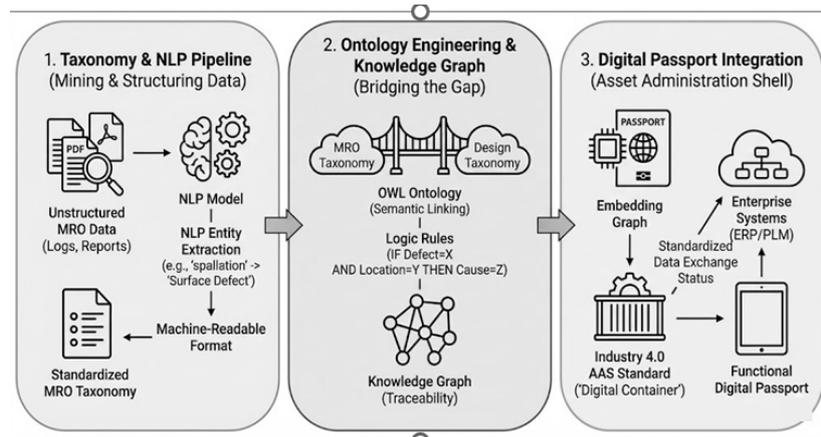


Figure 2: The proposed Conceptual framework

IV. APPLICATION PERSPECTIVE

To demonstrate the practical utility of the proposed framework, this study shows an example of application via a historical dataset of "Shop Visit Reports" concerning the Nose Landing Gear Main Fitting, a high-value critical component (Figure 3). The objective was to validate the "Digital Bridge" capability: transforming unstructured rejection logs into actionable DfRem constraints. The process begins with the ingestion of raw, unstructured data from the MRO environment. In a typical linear economy scenario, a technician might record a fatal flaw in a free-text logbook as follows:

"Unit removed due to heavy pitting corrosion found on the bogie pivot pin bore during overhaul. Cadmium plating has delaminated. Depth exceeds manual limits. Component scrapped."

In a standard data environment, this entry is archived as a static PDF; the word "scrap" is recorded, but the causal intelligence—specifically *why* the circular loop failed—is lost to the Data Graveyard.

Under the proposed framework, this raw text is processed through an NLP pipeline tailored for aerospace syntax. The system first performs Named Entity Recognition to isolate critical tokens: the defect ("heavy pitting"), the location ("bogie pivot pin bore"), and the surface condition ("plating

delaminated"). Crucially, the NLP engine identifies the causal linkage implied in the text: the delamination of the plating led to the exposure of the substrate, resulting in corrosion that exceeded repair limits.

This extracted intelligence is then instantiated into the Semantic Knowledge Graph, where it is mapped against Engineering Ontology. The graph logic identifies that the "Bogie Pivot Pin Bore" is a geometric feature defined by specific tolerance parameters in the CAD model. The system flags a conflict: the standard repair manual allows for a re-boring of 0.25mm, but the "heavy pitting" detected by the technician implies a material loss greater than 0.50mm, rendering the part non-circular (i.e., waste).

To close the loop, the Knowledge Graph triggers an automated Circular Design Alert sent back to the engineering environment. Instead of simply recording the scrap event, the system generates a generative design constraint for the next product iteration:

"Increase material allowance on Pivot Pin Bore boss by 2.0mm to accommodate deep re-boring operations for future lifecycles."

Furthermore, it suggests a material substitution, recommending a switch from Cadmium to Zinc-Nickel plating to prevent the delamination mode identified in the logs. By translating the technician's "scrap report" into a parametric "remanufacturing allowance," the framework ensures that future Main Fittings are designed with the inherent capacity to survive multiple service lives, thereby achieving true industrial circularity.

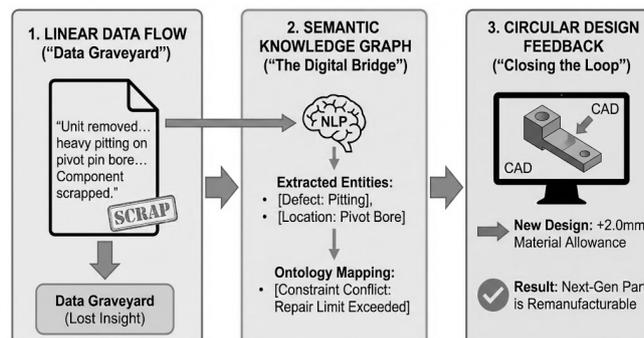


Figure 3: Translating MRO text to Circular design

Despite the demonstrated efficacy of the framework in bridging the linguistic divide, scaling this "Digital Bridge" from a pilot study to industrial practice faces substantial socio-technical barriers.

Firstly, while the framework enables technical circularity (DfRem), the environmental and economic net benefits remain theoretical. A rigorous Life Cycle Assessment (LCA) coupled with Technoeconomic Analysis (TEA) is required to validate

that the energy expended in the digital remanufacturing workflow does not outweigh the embodied carbon savings of material reuse.

Secondly, the integration of probabilistic AI outputs into deterministic engineering domains presents a profound challenge for Airworthiness Certification. Regulatory bodies (e.g., FAA, EASA, Transport Canada) demand verifiable validation paths for design changes; currently, a design modification triggered by stochastic NLP text mining lacks the established certification basis required for flight-critical hardware like landing gears.

Finally, the proposed "closed-loop" information flow encounters significant resistance regarding Data Confidentiality and Intellectual Property (IP). Original Equipment Manufacturers (OEMs) are often hesitant to expose sensitive fleet failure data within a shared digital ecosystem due to competitive risks. Addressing this requires moving beyond centralized knowledge graphs toward privacy-preserving architectures, such as Federated Learning, where insights can be derived collaboratively without raw proprietary data ever leaving the OEM's secure firewall.

V. CONCLUSION AND FUTURE DIRECTIONS

The pursuit of a Circular Economy in aerospace is currently limited not by a lack of data, but by a lack of *meaning*. As this research has shown, the "Semantic Interoperability Gap" between the linguistic world of MRO technicians and the parametric world of design engineers creates a broken feedback loop, trapping valuable circularity insights in unstructured Data Graveyards. This paper has proposed a SKG framework. By synergizing NLP with domain-specific ontologies, we have demonstrated the capability to transform subjective maintenance logs into objective, queryable design constraints. This Digital Bridge effectively operationalizes the Digital Thread, allowing End-of-Life performance data to automatically influence DfRem without human intervention.

Looking forward, this research opens several critical avenues for future investigation. First, while this study focused on textual data, MRO reports are inherently multimodal, often containing photographs and acoustic signals alongside written logs. Future work will aim to integrate Computer Vision into the Knowledge Graph, allowing the system to correlate a text description of "pitting" with a visual quantification of the defect's surface area.

Second, the rapid evolution of Large Language Models (LLMs) offers a new horizon for "Generative Maintenance." We propose moving beyond static ontologies to dynamic LLM-Agents capable of conversing with technicians in real-time to standardize data entry at the source. Finally, to ensure industrial

scalability, future iterations of this framework must be harmonized with global interoperability standards, such as the Asset Administration Shell (AAS) and ASD S1000D, ensuring that this Active Feedback Loop can function across the heterogeneous IT landscapes of global aerospace supply chains.

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Part B: Generative Design and the Active Digital Product Passport

Abstract—The aerospace industry faces a critical information gap between End-of-Life (EoL) Maintenance, Repair, and Operations (MRO) and early-stage product design. Currently, critical wear-and-tear data from landing gear overhaul—such as corrosion hotspots and fatigue cracking—remains trapped in static reports (Passive Storage), failing to inform future design iterations. This paper proposes a Generative Circular Feedback Loop that transforms the Digital Product Passport (DPP) from a static repository into an Active Feedback Agent. By utilizing AI-driven computer vision and an R-Index (Remanufacturability Index) scoring model, we demonstrate how real-time MRO data from landing gear struts can automatically trigger Generative Design revisions in CAD environments. The proposed framework aims to maximize repair yield and minimize material waste in next-generation aerospace components.

Keywords—Circular Economy; Aerospace Supply Chain; Generative Design; Digital Product Passport (DPP); Artificial Intelligence (AI); Landing Gear MRO; Design for Remanufacturing (DfRem)

VI. INTRODUCTION

The aviation industry is at a critical stage in its pursuit of the "Net-Zero 2050" mandate. While significant advances have been made in operational efficiency and sustainable aviation fuels (Scope 1 emissions), the embodied carbon of high-value aerospace components remains a persistent challenge (Scope 3). Today's airplanes are high-tech, but current EoL management practices remain largely linear and outdated.

This is particularly evident in Landing Gear (LG) systems—complex assemblies of high-strength steels, titanium, and hazardous hydraulic fluids that are subjected to extreme impact loads and environmental corrosion [1]. Currently, the lifecycle of a landing gear follows a predominantly linear path. Despite the advent of Industry 4.0 and smart sensors in the operational phase, the transition to the EoL phase is characterized by a profound information disconnect. When a landing gear component enters an MRO facility for overhaul, it generates a wealth of empirical data regarding wear patterns, corrosion hotspots, and fatigue limits [2]. However, this critical intelligence is typically captured in static technical logs or isolated PDF reports—a phenomenon we define as the Static PDF Problem.

This creates a blind spot for design engineers. The CAD teams responsible for the next generation of landing gears rarely receive feedback on why the current generation failed to be remanufactured. Consequently, design flaws that delay circularity—such as geometries that trap corrosive de-icing fluids or surfaces that are inaccessible to laser cladding tools—are repeated [3].

This paper proposes a conceptual framework for a shift from this Passive Data Storage to an Active Feedback Agent. We introduce the Generative Circular Feedback Loop, a framework that integrates Digital Product Passports (DPP) with AI-driven defect analysis. By treating the landing gear's EoL status not as a grave but as a data source, we aim to close the semantic gap between the hangar floor and the design studio. This research focuses on two core contributions:

- The "R-Index" Logic Engine: A quantifiable scoring model that uses computer vision to assess the "Remanufacturability" of landing gear components based on defect criticality (e.g., distinguishing between surface plating wear and deep trunnion fatigue).
- The Generative Feedback Mechanism: A conceptual workflow where low R-Index scores automatically trigger "Design for

Remanufacturing" (DfRem) alerts, prompting Generative AI agents to suggest geometry revisions that extend the asset's lifecycle. By discussing this framework through a landing gear case study, we demonstrate that the future of circular aerospace lies in transforming waste data into generative design wisdom.

VII. LITERATURE REVIEW AND GAP ANALYSIS

The transition toward a Circular Aerospace Economy requires the convergence of three domains: sustainable and resilient supply chain management, digital twin technologies, and generative artificial intelligence. While each field has matured independently, the intersection remains underexplored in this industry.

A. Circular Economy in High-Value Aerospace Components

The aerospace sector is shifting from a linear "take-make-dispose" model to a closed-loop system, particularly for high-value components which utilize critical raw materials (titanium, high-strength steel). Keivanpour [1,4] emphasizes that circularity in engineering must move beyond simple recycling to value retention processes like remanufacturing and refurbishment. In the context of EoL aircraft, Keivanpour and Ait-Kadi [2] identified that the primary bottleneck is not the lack of recycling technology, but the lack of *information transparency* regarding the residual value and material history of components (See also [5]). For landing gears, which face rigorous safety fatigue limits, the decision to remanufacture vs. recycle is often conservative due to a lack of precise wear data [3].

B. Digital Twins in MRO 4.0

To address this data opacity, the concept of the Digital Twin (DT) has gained prominence. Defined by Grieves and Vickers [6] as a virtual representation of a physical asset, DTs have become standard in MRO (Maintenance, Repair, and Operations). Tao et al. [7] expanded this capability, proposing Digital Twin-driven Product Design. However, current applications of DT in landing gear maintenance are predominantly operational focused on predicting when a part will fail (Predictive Maintenance) rather than informing how the part should be *redesigned* to prevent that failure in the future. Recent work by Li et al. [8] demonstrates the power of Deep Learning in detecting corrosion in landing gears, yet this data is rarely fed back into the CAD environment.

C. Generative AI and Cognitive Design

The emergence of Generative AI offers a new pathway for Cognitive Design [9]. Unlike traditional topology optimization,

which focuses on weight reduction, Generative AI can optimize for multiple constraints, including disassemblability and repairability. However, a review of recent literature suggests that most generative design algorithms operate on theoretical constraints (e.g., load cases) rather than empirical EoL data (e.g., actual corrosion from field operations).

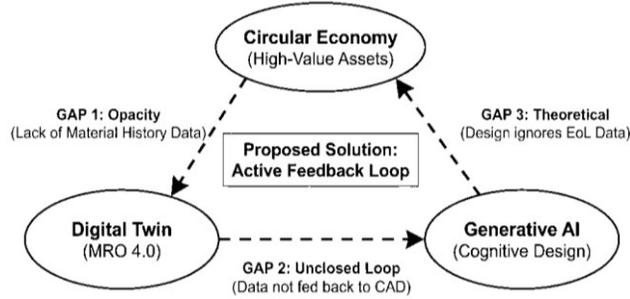


Figure 1: Literature Gap analysis in Circular Aerospace

III. CONCEPTUAL FRAMEWORK: THE "ACTIVE FEEDBACK AGENT"

The proposed framework (Figure 2) illustrates the fundamental information disconnect in current aerospace EoL management, identified here as "The Static PDF Problem." In this figure (left), the diagram shows a linear, broken loop where MRO 4.0 data (e.g., rejection reasons like "Wall thickness < 0.5mm") is captured but immediately "siloes" into a Static Digital Passport (often a cloud-based PDF repository). Essentially, there is "No Loop Back for DfRem" (Design for Remanufacturing), leaving the Design Engineer disconnected from real-world degradation data. Future Goal (Right) proposed model transforms the passport into an Active "Feedback Agent." In this closed loop, rejection data is not merely stored but processed by an "Active Digital Passport" acting as an IE Feedback Agent.

This agent pushes actionable insights directly to the Design Engineer, enabling Continuous Improvement and informing future design iterations based on empirical failure modes.

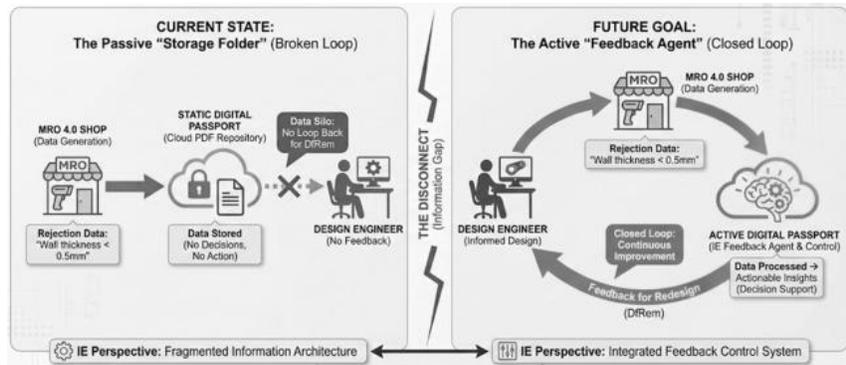


Figure 2: The proposed conceptual framework, Current state and future goal

To operationalize the feedback loop, we developed the Remanufacturability Index (R-Index), a dynamic scoring system driven by automated inspection. The process follows three phases:

- **Phase 1 (Data Input):** Automated Blue-Light Inspection captures the physical geometry of the worn landing gear component, digitizing surface topology and defects.
- **Phase 2 (Logic Engine):** The "Defect Analysis & Criticality Check" algorithm sorts defects into two distinct logical paths:
 - ✓ **Fatal Flaw Logic:** Identifies nonrecoverable structural compromises (e.g., Root Fatigue or Deep Stress Cracking in the trunnion). This triggers a "Penalty: Set Score to 0," immediately classifying the part as scrap/recycle.
 - ✓ **Repairability Penalty Logic:** Identifies recoverable defects (e.g., surface wear or corrosion on the chrome plating). The system applies a weighted penalty (e.g., "-5 to -15 points") based on the required repair effort (such as laser cladding), resulting in a passing score.
- **Phase 3 (Dynamic Output):** The Digital Product Passport displays a real-time score (e.g., 92/100) and an actionable status (e.g., "APPROVE FOR REMAN"), replacing static logs with decision-ready data.

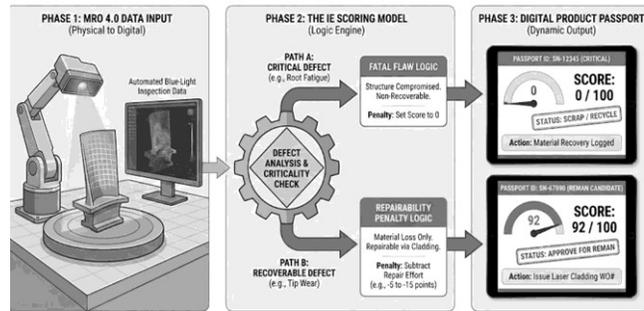


Figure 3: The Remanufacturability Index (R-Index) Framework

Figure 4 demonstrates the "Design Feedback Loop" in action, applied to a landing gear case study. This dashboard has four sections:

1. The Dashboard (Heat Map): The system aggregates fleetwide R-Index data to visualize systemic failure points. The "Heat Map" highlights low-scoring zones (Red < 40) on the assembly, identifying areas that consistently fail MRO repair.
2. The Action (Designer Analysis): The Design Engineer receives a specific alert: "Low R-Index due to inaccessible coating removal." This identifies that the root cause of the scrap rate is not material failure, but "Design Geometry" that prevents effective remanufacturing tools from reaching the surface.
3. DfRem Action (CAD Revision): The designer modifies the geometry (e.g., widening the access angle) to improve accessibility. The "After" model represents an "Enhanced Accessibility" design optimized for the circular economy.
4. The Value: The process validates the business case: "Design Change X" directly leads to an "Increased R-Index & MRO Efficiency," proving that data-driven design can measurably increase repair yield.

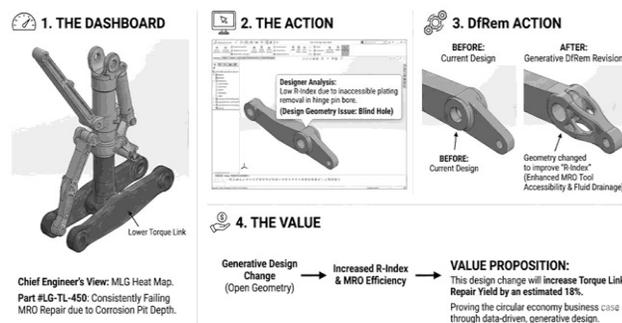


Figure 4: Generative Circular feedback loop for Main Landing gear

IV. Conclusion and Future Directions

The transition from a linear aerospace supply chain to a circular one cannot be achieved through material innovation alone; it requires a fundamental restructuring of how engineering data flows between the operational "Grave" and the design "Cradle." This research has challenged the "Static PDF" paradigm by proposing the Generative Circular Feedback Loop, a framework that transforms the Digital Product Passport from a passive archive into an Active Feedback Agent. Through the development of the Remanufacturability Index (R-Index) and its application to a Landing Gear Main Fitting case study, we have demonstrated that EoL status can be effectively quantified into a numeric score using automated inspection logic. This quantification removes the subjectivity from "scrap vs. repair" decisions and, crucially, allows MRO data to act as a direct constraint for Generative Design algorithms. By automating the identification of geometric features that delay remanufacturing—such as drainage traps or blind holes—this framework provides the missing link between MRO 4.0 diagnostics and CAD-based product development, ensuring that the next generation of landing gears is optimized for multiple lifecycles.

To build upon these findings, future research will focus on scaling the R-Index model from individual structural components to complex, multi-material systems-of-systems, addressing the intricacies of disassembly logic in the presence of hazardous fluids. A critical avenue for investigation involves the integration of Learning architectures, which would allow the AI model to learn from global MRO failure trends without exposing the proprietary intellectual property or sensitive fleet reliability data of Original Equipment Manufacturers (OEMs). Furthermore, we intend to explore the direct link between the R-Index and Additive Manufacturing (AM) workflows, aiming to create a seamless pipeline where the "Active Passport" automatically generates G-code for Direct Energy Deposition (DED) repairs. Finally, a longitudinal Life Cycle Assessment (LCA) is planned to quantify the precise carbon footprint reduction and economic savings achieved by this framework, establishing the robust business case required for industry-wide standardization.

DECLARATION OF AI ASSISTANCE

Drafting and language polishing for this manuscript were supported by Google's Gemini under the author's strict supervision. The author affirms that all core ideas, research design, and conceptual contributions are original.

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