

Towards Integrating Maintenance, Repair, and Overhaul (MRO) Aspects into Sustainability-Driven Design of Aircraft Structures: Inspectability Assessment of Hat-Stiffened Panels

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Abstract

Despite the growing importance of Maintenance, Repair, and Overhaul (MRO) in aviation, affecting operational costs, environmental impact, social sustainability, and circular economy potential, MRO is still mainly treated as a downstream operational process rather than a key driver of aircraft structural design. Current design methodologies primarily focus on performance, weight, materials, and manufacturing, while maintainability and repair-related considerations remain largely overlooked during early-stage design. To address this gap, this study proposes a Design for Maintainability (DfM)-based approach for integrating MRO considerations into the conceptual design of aircraft structures. A set of semi-quantitative MRO-oriented metrics is introduced to evaluate critical MRO-related characteristics, including inspectability, accessibility, repair feasibility, and replacement strategies, enabling their future integration into holistic sustainability frameworks covering environmental, economic, social, circularity, and performance aspects. The methodology is demonstrated through a case study of a hat-stiffened aircraft panel, where alternative material configurations are comparatively assessed using the proposed metrics, with emphasis placed on inspection-related considerations. The results show that incorporating MRO-driven criteria during design can reveal important trade-offs between structural performance and lifecycle sustainment, supporting the development of more sustainable, maintainable, and circular aircraft structures.

Keywords: Aviation, Sustainability, Design, MRO, NDT

1. Introduction

The aviation sector is currently operating under unprecedented pressure to drastically reduce its environmental footprint and mitigate its contribution to pressing societal challenges, including global climate change and resource scarcity [1]. This urgency is heavily driven by stringent international regulatory targets, most notably the commitment to achieve net-zero carbon emissions by 2050 [2], while, at the same time, major aviation research initiatives like Clean Aviation [3] are trying to foster innovation in relevant fields. Consequently, sustainability is no longer a peripheral operational consideration but has become a central, defining pillar of modern aerospace engineering. At the same time, research consistently indicates that early-stage design decisions lock in approximately 70% to 80% of a product's total environmental footprint and lifecycle cost [4]. In this environment, in order to address urgent climate imperatives, the aviation sector embraced eco-design, proactively integrating environmental aspects into product development to minimize negative lifecycle impacts [5]. While this approach successfully prioritized ecological responsibility in early-stage engineering, it falls short of capturing the full spectrum of long-term operational constraints. A modern approach demands

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transitioning to a broader Sustainability-Driven Design (SDD) paradigm that embeds comprehensive environmental, economic, social, and circular considerations directly into the conceptual design phase alongside structural performance.

While eco-design initiatives have made commendable progress by utilizing Life Cycle Assessment (LCA) to minimize environmental impacts (e.g., [[6][7][8][9]]), this one-dimensional focus is no longer sufficient in the design process. Consequently, recent research has expanded to evaluate economic trade-offs [10] and embed circular economy principles into early aviation design phases [11]. Current holistic SDD methodologies are trying to formalize these diverse dimensions into a unified, quantifiable sustainability indices that can be used as an early-stage design criterion. To manage these inherently conflicting objectives, the state-of-the-art relies heavily on Multi-Criteria Decision-Making methodologies [12][13][14] coupled with Computer-Aided Engineering (CAE) frameworks [15].

Yet, despite the sophistication of these advanced modeling frameworks, a major operational blind spot persists regarding long-term component sustainment and its profound impact on holistic sustainability for the aviation sector. Maintenance, Repair, and Overhaul (MRO) aspects are still typically treated as downstream operational consequences of design decisions rather than as proactive, design-relevant drivers at early stages. In practice, early-stage design characteristics of aviation structures and systems strongly influence inspection efficiency, repair strategies, accessibility, and replacement philosophy, all of which directly affect operational resilience, total lifecycle cost and environmental impact [16]. This represents a critical oversight, given that MRO activities typically account for 10% to 20% of a commercial aircraft's direct operating costs, creating a massive financial and environmental burden over its multi-decade lifespan [17].

Recognizing this intrinsic link between an aircraft's physical architecture and its operational sustainment, Design for Maintainability (DfM) serves as the dedicated engineering discipline addressing these constraints. The current state of the art in DfM has evolved from a reactive, post-design evaluation into a proactive, multi-disciplinary process integrated directly into early design. To achieve this, modern methodologies leverage Model-Based Systems Engineering (MBSE) to proactively embed Reliability, Availability, and Maintainability (RAM) requirements into the foundational system architecture [18]. At the computational level, state-of-the-art DfM employs hybrid genetic algorithms to simultaneously optimize industrial system design and dynamic maintenance planning, creating Pareto frontiers that help designers find the absolute best trade-off between minimizing Life Cycle Cost (LCC) and maximizing Total Operational Reliability (TOR) [19]. Furthermore, advanced DfM relies extensively on 3D Computer-Aided Design (CAD), Digital Mock-Ups (DMU), and virtual reality to map out constraints such as visual, reach and footstep zones before physical prototyping occurs [20]. Beyond physical ergonomics, the scope of DfM has broadened to include comprehensive multi-criteria indicators calculated via AHP (Analytic Hierarchy Process) and ANP (Analytic Network Process) [21], quantitative inputs like MTBF (Mean Time Between Failures) to verify safety and testability [22] and pioneering "eco-maintainability" metrics that allow designers to trade off maintenance time against environmental impact scores [23]. Finally, these early-stage design efforts are increasingly augmented by machine learning and statistical data analytics, which predict task durations, optimal maintenance intervals, and inspection probabilities to mitigate operational unpredictability throughout the product's lifespan [24],[25].

Despite advancements, a critical disconnect persists during conceptual aircraft development, as current Sustainability-Driven Design frameworks overlook maintainability, while Design for Maintainability (DfM) methodologies often lack to take into account broader design trade-offs. Consequently, decisions frequently lock in future lifecycle burdens, a vulnerability is compounded by the rapid introduction of novel materials alongside legacy inspection and repair methodologies that remain highly labor-intensive and misaligned with emerging industry demands [26]. Without explicitly integrating qualitative MRO metrics into early-stage sustainability trade-offs, the industry's ability to support truly holistic and operationally relevant design decisions remains severely limited.

To address this gap, this study elevates Maintenance, Repair, and Overhaul considerations into a proactive early-stage conceptual design driver, as illustrated in Figure 1. The research proposes the systematic embedding of MRO aspects in the holistic sustainability assessment of aviation structures. Specifically, it formulates novel qualitative metrics and normalizes them alongside traditional structural,

economic, and environmental pillars to enable concurrent trade-off analyses long before high-fidelity models are finalized. This expanded framework is practically applied to a hat-stiffened aviation panel, selected specifically because its closed-profile architecture and multi-material alternatives impose a large design space of trade-offs. By systematically exploring this structural design space, the research demonstrates how early maintainability integration actively drives optimal and sustainable aerospace engineering.



Figure 1 - Integration of MRO considerations to the design of sustainable aviation parts.

The remainder of this paper is structured as follows. Section 2 details the proposed methodology, first establishing the overarching MRO-Enabled Sustainability Framework (Section 2.1) and subsequently defining the formal formulation of the novel MRO metrics (Section 2.2). Following this formulation, Section 2.3 provides a detailed mapping of these specific metrics directly to the holistic sustainability framework. This methodological foundation culminates in Section 2.4, which outlines the hat-stiffened panel case study utilized for practical validation, and Section 2.5, which describes the inspection assessment methodology including the NDT methods considered, the assessment workflow, and the qualitative scoring scale adopted. Subsequently, Section 3 presents the results and discussion, providing the inspection-pillar assessment first at design level (Section 3.1), then refined to include the influence of joining methods (Section 3.2), followed by a comparative analysis between the two assessment levels (Section 3.3). Finally, Section 4 synthesizes the core findings, acknowledges the limitations of the current study, and outlines directions for future research.

2. Methodology

2.1 MRO-Enabled Sustainability Framework

To effectively integrate maintainability into Sustainability-Driven Design, the industry has to fundamentally shift on how maintenance success is quantified. Currently, maintenance efficiency is evaluated using reactive, lagging Key Performance Indicators that merely measure how personnel cope with operational realities, while traditional RAMS analysis remains a sidelined late-stage verification task. To map this disconnection, this section establishes the theoretical nexus between RAMS objectives and DfM processes in order to elevate maintainability into a proactive conceptual design driver. It is proposed that starting from the traditional RAMS (Reliability, Availability, Maintainability, and Safety) engineering framework and the metrics proposed, Maintainability must be elevated from a downstream operational consequence to an upstream, early-stage design driver. As presented before, Design for Maintainability (DfM) operationalizes this paradigm shift by proactively integrating physical MRO constraints into the conceptual and preliminary design phases.

This establishes a continuous bidirectional feedback loop in which RAMS modeling dictates when intervention is theoretically required, the MRO ecosystem defines the physical constraints of executing it and DfM optimizes the aircraft's architecture to satisfy those realities, while real-world MRO data,

such as unscheduled removal rates, shop findings and fleet service experience, feeds back to validate and refine design predictions across the component's full service life. The complete MRO-enabled sustainability framework is depicted in Figure 2.

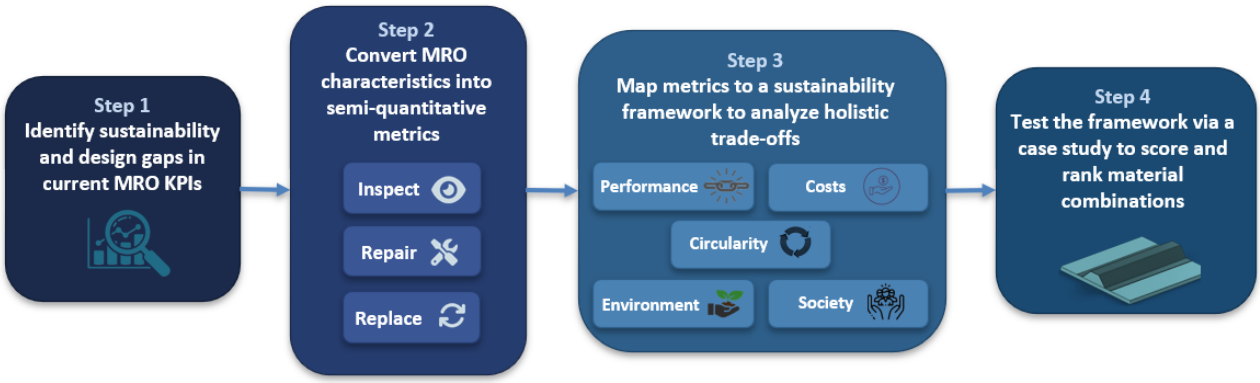


Figure 2 - Schematic representation of the proposed MRO-enabled sustainability framework.

The proposed MRO-Enabled Sustainability Framework subsequently operationalizes these principles across the Inspect, Repair, and Replace phases, with emphasis placed on the first pillar (inspectability).

To demonstrate the systemic flaws necessitating this new approach, the existing relevant industry indicators are detailed below in Tables 1-5 :

Table 1 - Existing mechanical and operational related KPIs.

Metric / Source	Description	Metric / Source	Description
Mean Time Between Failures (MTBF) [27]	Measures the average active flight time between unscheduled structural failures to highlight maintenance frequency long after architectural decisions are permanently locked in.	**Aircraft-on-Ground (AOG) Rate [28]**	Tracks urgent maintenance events that ground an aircraft to evaluate operational disruptions and significant economic losses.
Mean Time To Repair (MTTR) [27]	Quantifies the total labor hours and ground downtime required to resolve a defect by essentially measuring the physical burden placed on mechanics rather than the inherent maintainability of the component.	**Planned vs. Unplanned Maintenance Ratio [29]**	Compares the number of days an aircraft is unavailable due to planned maintenance versus unplanned events (e.g., delays or cancellations). It is tracked at both the fleet and individual aircraft levels.
Availability [30]	Evaluates the component's impact on overall operational readiness by calculating the ratio of active flight time against total system downtime.	**Maintenance Turnaround Time (TAT) [31]**	Compares the number of days an aircraft is unavailable due to planned maintenance versus unplanned events at both the fleet and individual levels.
Mission Capable Aircraft Rate (MCR) [32]	Measures the proportion of assigned hours an aircraft is designated as ready for its mission to improve scheduling and crew readiness.	**Unplanned Engine Removals (UER) [29]**	Tracks unscheduled engine removals requiring shop visits due to issues that cannot be resolved directly on wing.

Table 2 - Existing economic related KPIs.

Metric / Source	Description	Metric / Source	Description
Maintenance Cost Per Flight Hour (CPFH) [33]	Standardizes maintenance expenses per flight hour to guide critical airline decisions regarding fleet renewal and	**Inventory per unit of Fixed Asset (I/FA) [34]**	Compares variable inventory levels against total fixed assets to indicate lean operational efficiency and optimal resource

	operational budgeting.		utilization.
Maintenance Cost to Replacement Cost Threshold [35]	Defines the maximum economical repair boundary before full component replacement becomes the financially optimized lifecycle strategy.	**Supplier On-Time Delivery Rate [36]**	Evaluates supply chain reliability to ensure smooth daily operations and minimize indirect purchasing costs.
Unscheduled Removal Rate (URR) [37]	Tracks unexpected failures requiring immediate removal to highlight the cascading financial penalties of emergency spare parts and unplanned downtime.	**MRO Outsourcing vs. In-House Cost Ratio [38]**	Compares third-party service expenditures against internal operations to help airlines strategically optimize their aftermarket logistics.
Proportion of Labor Cost [39]	Measures human resource expenses against total maintenance costs to emphasize the necessity of controlling labor burdens on modern aircraft.	**Inventory per unit of Fixed Asset (I/FA) [34]**	Compares variable inventory levels against total fixed assets to indicate lean operational efficiency and optimal resource utilization.

Table 3 – Existing environmental related KPIs.

Metric	Description
Facility Energy and Utility Consumption [40], [41]	Tracks energy and water use during manufacturing and maintenance to identify areas where reducing consumption lowers environmental impacts and greenhouse gas emissions.
Hazardous Waste Volume [42]	Measures the toxic waste generated from maintenance processes such as painting and cleaning to highlight the necessity of pollution prevention programs and reduce off-site disposal costs.
Fleet Energy Efficiency [43]	Evaluates how effective maintenance management improves fuel economy and reduces total costs by analyzing specific fuel consumption per transport volume to determine overall operational efficiency.

Table 4 - Existing circularity related KPIs.

Metric	Description	Metric	Description
Used Serviceable Material (USM) Utilization Rate [44], [45]	Evaluates the financial and environmental benefits of utilizing recycled aircraft components to achieve high recovery values and significant cost efficiencies compared to purchasing new parts.	**Composite Material Recycling Rate [46]**	Highlights the fundamental challenge of recovering complex polymeric structures due to a severe lack of large-scale industrial recycling methods.
Component Teardown Yield [47]	Assesses the proportion of an aircraft successfully recovered and dismantled at its end of life to demonstrate practical rates of direct reuse and recycling.	**Circularity Performance Indicator (CPI / CEI) [48]**	Evaluates component-level circularity by calculating the ratio of a recycled material's specific stiffness to a reference virgin material. It accounts for material degradation after recycling loops to ensure high mechanical quality.
Landfill Diversion Rate [41]	Tracks the proportion of aircraft waste successfully diverted from landfill disposal through advanced reuse and recycling to drive toward a zero-waste objective.	**Design-for-Disassembly Score [49]**	Assesses the operational difficulty and time required to dismantle a structure to ensure high material sorting capabilities and optimized end of life recovery.
Material Recovery Rate	Quantifies the proportion of aircraft mass successfully	**Life Extension Rate [50]**	Evaluates the potential to extend component lifespans and

at End-of-Life (EOL) [44]	recovered and diverted from landfills during decommissioning.		minimize premature waste through the strategic application of predictive maintenance and advanced health monitoring systems.

Table 5 - Existing circularity social related KPIs

Metric	Description	Metric	Description
Safety Incident / Accident Rate (SMS Effectiveness) [51]	Tracks workplace injuries among aviation technicians to highlight the effectiveness of safety systems in proactively managing occupational risks and reducing severe equipment mishaps.	**Technician Fatigue & Shift-Related Incident Rate [52]**	Tracks fatigue levels in maintenance crews caused by extended hours and inadequate rest to help implement strategic mitigations that systematically reduce the risk of human error.
Maintenance Error Rate / Human Factors Rate [53]	Tracks frequency of maintenance errors caused by human factors to address the root organizational conditions and supervision gaps driving these failures.	**Workforce Attrition / Technician Retention Rate [54]**	Tracks the rate at which qualified technicians leave maintenance organizations to underscore the industry's need for strategic interventions and better workforce planning.
Regulatory Compliance Rate [55]	Tracks the frequency of regulatory deviations alongside skill-based errors to address the root organizational conditions causing systematic compliance failures.	**Safety Management System (SMS) Maturity Score [56]**	Assessing implementation effectiveness of safety frameworks to indicate an organizational shift from reactive compliance toward proactive systematic learning.
Technician Utilisation (Wrench Time) [57]	Measures the percentage of shift time technicians spend on active physical maintenance versus nonproductive downtime to highlight opportunities for improved operational steering.		

As demonstrated across these five domains, relying solely on operational-related indicators makes proactive sustainability impossible, as the data required for these metrics does not exist during early-stage geometric conceptualization. In addition, a fragmented metrics landscape is observed, with metrics that are not connected between the presented pillars.

Overcoming this deficiency requires establishing a new theoretical foundation that actively bridges the gap between aerospace engineering and downstream MRO execution. Below the three phases are presented in a discreet way:

Phase 1: Inspect

A long-term sustainable aviation component fundamentally requires the rapid and accurate identification of structural degradation. This proactive approach is exceptionally critical in modern aerospace engineering due to the mechanical behavior of advanced lightweight composites. Unlike traditional metallic structures that exhibit visual cues of fatigue such as yielding or denting, advanced composites may exhibit more often internal – nonvisible damage mechanisms. Consequently, the inherent visual detectability of the structure is drastically reduced. This material behavior forces a heavy reliance on complex NDT methodologies. If the component is not proactively designed to accommodate these NDT methods by avoiding attributes such as complex mixed-material interfaces or overly thick layered geometries, the inspection process becomes exceptionally time-consuming and energy-intensive. Therefore, it is proposed that early-stage design must treat inspection efficiency and in particular NDT compatibility as a primary structural constraint.

Phase 2: Repair

When inspection confirms that damage is detected and remains within the allowable repair envelope,

the component architecture must support localized structural restoration without unnecessary removal of serviceable material. This requires early-stage consideration of aspects such as repair accessibility, compatible joining and patching methods, controlled load-path recovery, and sufficient clearance for tooling, surface preparation, curing, and post-repair inspection. Complex interfaces, inaccessible geometries, and incompatible material combinations may increase repair time, energy consumption, tooling requirements, and material waste. Therefore, repairability must be treated as a primary design constraint, ensuring that standardized and repeatable repair procedures can restore structural performance with minimum resource consumption and operational downtime.

Phase 3: Replace

When damage exceeds the permissible repair threshold, or when repair is no longer technically or economically viable, the system architecture must enable controlled removal and replacement of the affected component. This requires modular interfaces, accessible fasteners or reversible joints, defined separation boundaries, and minimum disturbance to adjacent load-bearing structures, systems, and surface treatments. Designs based on permanent bonding, highly integrated geometries, or destructive disassembly can significantly increase material loss, maintenance duration, and aircraft downtime. Therefore, replaceability must be incorporated during early-stage design to enable rapid component exchange, preserve surrounding structural integrity, and support the subsequent off-wing repair, remanufacturing, or recycling of the removed part.

2.2 MRO Metrics Definition

Building upon the established three functional domains, this section defines the specific evaluation metrics required to execute the maintainability framework. These proposed metrics are designed to translate the physical, logistical, and environmental burdens of the hangar floor into standardized criteria that can guide early-stage engineering decisions and are depicted in Table 6.

To evaluate these metrics during the conceptual design phase where high-fidelity empirical data does not yet exist, a qualitative scoring methodology is implemented. Structural configurations are assessed using a discrete ordinal scale ranging from 1 to 5. Within this scale, a score of 1 represents poor maintainability characterized by a high resource burden, while a score of 5 indicates excellent maintainability with minimal operational penalty. This assessment relies on structured expert elicitation and professional aerospace engineering judgment to assign representative values. Furthermore, while the framework formally defines metrics across all three operational pillars to provide a comprehensive theoretical foundation, the practical assessment and case study within this paper will focus exclusively on the Inspect phase. This targeted scope is driven by pressing operational bottlenecks and severe detectability challenges inherently associated with modern composite structures.

Table 6 - Proposed MRO metrics.

Pillar	Metrics	Description	Application
Inspect	**Visual Detectability Score**	Evaluates how easily the material shows physical signs of internal damage without the use of equipment.	Metals yield and dent to provide an immediate visual cue for a high score whereas composites, especially when under low-energy impact, frequently may not have visible impact damage resulting in a low score yet, despite getting severe delamination and matrix cracking.
	NDT Complexity Score	Measures how complex the process of inspection is.	Metals scan cleanly and rapidly for a high score whereas mixed material interfaces and layered composite plies require slow and highly complex scans resulting in a low score.
	Cost Intensity Score	Evaluates the financial burden tied to inspecting the material, including the capital cost of required NDT equipment, specialized technician training (e.g., NDT Level III), consumables,	Aluminum panels inspected with inexpensive visual aid receive a high score whereas complex composites requiring expensive ultrasonic machines and highly paid specialists drastically increase the financial burden for a low score.

		and the continuous Quality Assurance (QA) calibration of diagnostic tools.	
	Time Intensity Score	Evaluates the time required to accurately set up and scan a unit area of the material, interpret results and formally assure the quality of the inspection results.	Metals allow for rapid continuous sweeps yielding a high score whereas layered materials like composites require slow meticulous scans and lengthy data analysis to confidently identify hidden voids for a low score.
	Energy Intensity Score	Evaluates the operational energy footprint required to execute the specific inspection process demanded by the material, as well as power the diagnostic systems necessary for Quality Assurance (QA) data processing.	Basic inspections on metals draw negligible power for a high score whereas inspecting composites often requires automated robotic machines that create a significant energy footprint for a low score.
Repair	**Preparation Complexity Score**	Evaluates how much preparation is required before the material is ready for structural repair.	Thermoplastics that can be melted directly and metals requiring simple drilling receive a high score whereas thermosets requiring massive step sanding to expose individual plies and strict clean room level dust control. Also, thermosets can be hardly repaired with thermoplastic spraying or more difficult with bonded repair patches. Therefore, they get a low score
	Hazardous Substances/ Materials Score	Evaluates the occupational health hazard to the MRO technician executing the repair.	Thermoplastic welding and metal riveting involving essentially zero toxic liquid chemicals achieve a high score whereas thermosets exposing mechanics to toxic unmixed epoxy resins carcinogenic primers and hazardous solvents result in a low score.
	Cost Intensity Score	Evaluates the direct financial cost of the repair process, focusing specifically on consumable materials, structural patches, specialized tool wear and the expenditure required for post-repair QA testing (e.g., secondary NDT sweeps).	Aluminum repairs utilizing inexpensive standard rivets and sheet metal receive a high score whereas thermoset repairs requiring expensive repairs needing seconds cure cycles and single use consumable bagging materials result in a low score.
	Time Intensity Score	Evaluates the time required to complete the structural repair and secure final airworthiness certification, which directly drive Aircraft-on-Ground (AOG) downtime.	Metal riveting or thermoplastic induction welding completed in minutes to a few hours yield a high score whereas thermoset repairs requiring multi hour overnight curing cycles under heat blankets keep the aircraft grounded significantly longer for a low score.
	Energy Intensity Score	Evaluates the power consumed by MRO equipment during the execution of the repair through the required post-repair QA verification.	Operating rivet guns that consume negligible power yields a high score whereas curing a thermoset composite patch requiring industrial vacuum pumps and high amperage heat blankets running continuously for several hours results in a low score.
Replace	**Replacement Complexity Score**	Evaluates whether the hat stiffener can be cleanly detached without destroying the base material of the skin.	Riveted metals and welded thermoplastics that can be cleanly separated receive a high score whereas co-cured permanently bonded thermosets that cannot be

			separated without destroying the fibers force the entire panel to be scrapped resulting in a low score.
	Recyclability	Evaluates if the base material can be recycled at the end of the aircraft's life.	Aluminum alloys and thermoplastics possessing high value circularity achieve a high score whereas thermosets that cannot be melted down and must be shredded into low grade filler or sent to a landfill, meaning very limited possibility of recyclability, receive a low score.
	Hazardous Substances/ Materials Score	Evaluates the ecological toxicity and hazardous waste generation associated with the physical removal, disposal, and scrapping of the component.	Drilling out aluminum rivets or utilizing localized thermoplastic welding to produce clean non-toxic recyclable byproducts yields a high score whereas mechanically grinding heavily bonded thermoset panels generates hazardous chemically contaminated scrap mandating strict landfill disposal for a low score.
	Cost Intensity Score	Evaluates the financial burden of replacing the structural component, including the cost of the Minimum Replaceable Unit (MRU) and end-of-life disposal fees, as well as the QA testing required to verify structural continuity.	Replacing a riveted aluminum stringer is inexpensive and generates valuable scrap for a high score whereas breaking a co-cured thermoset stringer forces the purchase of an entirely new panel alongside hazardous waste disposal fees for a low score.
	Time Intensity Score	Evaluates the labor hours required to physically detach the damaged component, install the replacement and execute meticulous QA verification of aerodynamic tolerances and joint integrity.	Drilling out metal fasteners or remelting thermoplastic welds taking minimal time receives a high score whereas mechanically grinding out a heavily bonded thermoset stringer without damaging the underlying skin is a painstaking hours long process resulting in a low score.
	Energy Intensity Score	Evaluates the macro-level energy required to extract the component, power the diagnostic tools needed for installation QA and possibly process it into its respective end-of-life recycling or disposal stream.	Removing and melting down pure metal or thermoplastic parts in an optimized energy efficient recycling loop yields a high score whereas shredding complex mixed material panels in specialized industrial facilities requires massive mechanical energy for very little and limited return resulting in a low score.

2.3 Towards integration of the metrics to holistic sustainability framework

To successfully integrate maintainability into the conceptual design phase, the proposed MRO metrics must be systematically embedded into a existing holistic sustainability assessment framework. According to the foundational methodology outlined in prior studies by the authors for the aviation sector [12], [13], overall sustainability is mathematically formulated as an aggregated metric that actively balances five primary pillars. The established holistic sustainability index in this framework, operates as a comprehensive decision-making tool designed to quantify and optimize inherently conflicting design objectives

The five pillars evaluate respectively: mechanical performance through parameters such as total deformation, economic viability through total lifecycle cost spanning material extraction to disposal, environmental impact through lifecycle carbon dioxide equivalent emissions, circularity performance through closed-loop material recovery potential, and social impact through Social Life Cycle Assessment of occupational and societal hotspots across the supply chain. To consolidate these diverse units into a single comparable value, the framework applies min-max normalization to bound

each pillar's output between zero and one, then aggregates the normalized scores using a Multi-Criteria Decision-Making approach. Specifically, the Analytic Hierarchy Process (AHP) establishes stakeholder-driven weightings through pairwise comparison, which are combined with the normalized scores via a Weighted Sum Model (WSM) to yield a unified scalar Sustainability Index (SI), as defined in [12],[13].

$$SI = P \times K_P + E \times K_E + C \times K_C + CIRC \times K_{CIRC} + SOC \times K_{SOC} \leq 1 \quad (1)$$

While this baseline formulation captures material characteristics, manufacturing footprints, and structural constraints, it lacks maintainability data necessary to reflect the true lifecycle footprint. The qualitative metrics defined in the previous section are therefore mapped directly onto the established sustainability pillars, bridging theoretical design and physical sustainment. This mapping, that is depicted in **Σφάλμα! Το αρχείο προέλευσης της αναφοράς δεν βρέθηκε.**, produces an MRO-Enabled Sustainability Index that integrates physical sustainment constraints alongside traditional aerodynamic and manufacturing metrics into a single decision-making criterion, enabling engineers to conduct concurrent trade-off analyses that identify architectures optimized not only for flight performance but also for lifecycle inspectability, repairability, and replaceability.



Figure 3 - Integration of proposed MRO metrics from different pillars to the holistic sustainability method

The mechanical performance pillar absorbs the majority of the operational execution metrics, specifically incorporating the Visual Detectability Score, the NDT Complexity Score, the Preparation Complexity Score, the Replacement Complexity Score, and the Time Intensity Score. The Cost Intensity Score naturally aligns with the economic viability pillar by capturing the direct financial expenditures of maintenance operations, whereas the Energy Intensity Score feeds directly into the environmental impact pillar by quantifying the power consumption of diagnostic and repair equipment. Furthermore, the Hazardous Substances and Materials Score is allocated to the social impact pillar to explicitly account for the occupational health risks and toxicity exposure posed to maintenance personnel. Finally, the Recyclability metric is embedded within the circularity performance pillar to evaluate the true end-of-life material recovery potential. This systematic allocation ensures that every facet of the physical maintenance reality is accurately translated into its corresponding sustainability impact.

2.4 Case Study: Hat-Stiffened Panel

To practically demonstrate and validate the proposed MRO-Enabled Sustainability Framework, a hat-stiffened panel is adopted as a representative aircraft structural component due to its widespread application in fuselage and wing structures, as well as its strong sensitivity to material and joining choices, as illustrated in Figure 4.

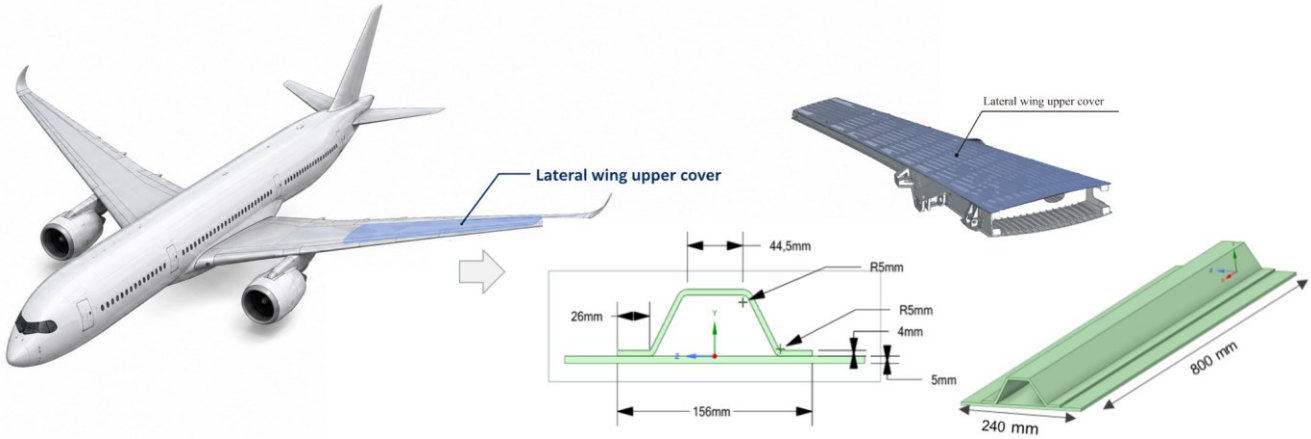


Figure 4 - Geometry and dimensions of a hat-stiffened panel.

The panel consists of a load-carrying skin reinforced by a longitudinal hat-shaped stiffener, designed to withstand representative in-plane and out-of-plane loading scenarios typical of aircraft structural applications. The baseline geometry, loading conditions, and structural performance are derived from previously published work [12],[13].

This baseline parameterization defines the geometry through a skin (reference thickness of 5 mm) and a stringer (reference thickness of 4 mm) separated by a distinct crown width (reference of 44.5 mm). Building upon this established baseline, multiple design configurations are generated by varying the material systems assigned to the skin and stiffener—ranging from traditional metallic alloys (Aluminum 2024-T3, Ti-6Al-4V) to advanced composites (pristine CFRP, PEEK)—as well as the joining and bonding techniques used at their interface, as depicted in Table 7.

Table 7 - Material configurations on skin and stringer components.

No.	Hat	Stringer	Available Joining Methods
1	Aluminum 2024 T3	Aluminum 2024 T3	Mechanical fastening; adhesive bonding; hybrid bonded-fastened joining
2	Carbon Fiber-Reinforced Composite (thermoset)	Aluminum 2024 T3	Adhesive bonding; hybrid bonded-fastened joining
3	Aluminum 2024 T3	Carbon Fiber-Reinforced Plastic (thermoset)	Adhesive bonding; hybrid bonded-fastened joining
4	Carbon Fiber-Reinforced Plastic (thermoset)	Carbon Fiber-Reinforced Plastic (thermoset)	Adhesive bonding; co-bonding / co-curing; hybrid bonded-fastened joining
5	Ti-6Al-4V	Carbon Fiber-Reinforced Plastic (thermoset)	Adhesive bonding; hybrid bonded-fastened joining
6	Carbon Fiber-Reinforced Thermoplastic Polymer (PEEK)	Carbon Fiber-Reinforced Thermoplastic Polymer (PEEK)	Fusion welding / induction welding / resistance welding; mechanical fastening; hybrid welded-fastened joining

While the geometric envelope and primary structural requirements (such as safety factors and total deformation) are preserved, these variations lead to distinct structural architectures with vastly different implications for MRO characteristics. The hat-stiffened panel's closed-profile geometry presents inherent and well-documented operational challenges, as the internal cavity restricts visual access and complicates internal corrosion or delamination inspections, often requiring specialized non-destructive testing or complex repair strategies compared to open-profile stiffeners. Consequently, while the design space remains consistent with prior structural optimizations, it is effectively extended in this study to explicitly explore the influence of foundational material and joining choices on the MRO embedded sustainability design.

The joining methods considered in the present case study were selected on the basis of material compatibility and their relevance to current aerospace structural practice. For the metallic aluminum/aluminum configuration, the available solutions include conventional mechanical fastening, adhesive bonding, and hybrid bonded-fastened joining, since all three routes are industrially feasible and lead to distinctly different inspection scenarios. For the metal–thermoset composite configurations, namely CFRP/Al and Ti/CFRP, adhesive bonding and hybrid bonded-fastened joining were retained as the most representative options, as they reflect the usual need to transfer load efficiently while mitigating the limitations associated with direct through-thickness fastening of laminated composite parts. Actually, for the metal-composite parts, the metallic layers bring possibilities in terms of mechanical joints to be utilized. In the fully thermoset CFRP/CFRP configuration, the joining design space is broader and includes secondary adhesive bonding, co-bonding or co-curing, and hybrid bonded-fastened concepts, thereby covering both integrally manufactured and assembled structural solutions. However, in the latter case, welded joints may not work since they degrade the thermoset material properties. Finally, for the thermoplastic CFRTP/PEEK concept, welding-based approaches were considered the most characteristic joining route, particularly induction, resistance, or fusion welding, while mechanical fastening and hybrid welded-fastened solutions were also retained as technically feasible alternatives. These joining options were not introduced merely as manufacturing details, but as structural variables directly influencing inspectability, since they modify the location and nature of the critical interface, the dominant damage mechanisms, and the applicability and burden of the corresponding NDT route.

2.5 Inspection Assessment

In the present work, the analysis is limited to the first pillar of the proposed MRO framework, namely inspection, as an initial step toward the integration of maintainability into the sustainability-driven assessment of the hat-stiffened panel concepts. This choice is motivated by the fact that inspection is the first operational stage through which damage must be identified before any repair or replacement decision can be made. In the case of hat-stiffened panels, this issue is further complicated by the closed-profile geometry of the stiffener, which restricts access to the internal regions and to the skin–stringer interface. As a result, inspectability is not treated here as a material property alone, but as a design-dependent characteristic arising from the combined effect of material selection, joining concept, and feasible inspection route.

2.6 NDT methods considered

To evaluate the inspection pillar, five non-destructive testing methods were considered, as illustrated in Table 8: ultrasonic testing (UT), radiographic testing (RT), dye penetrant testing (PT), eddy current testing (ET), and magnetic particle testing (MT). These methods were selected because they are included in the NDT comparison framework developed for this study and cover both surface-sensitive and volumetric inspection approaches. Their role in the present methodology is not to provide a standalone comparison of inspection technologies, but to support the evaluation of how each design configuration can be inspected in practice.

Table 8 - The examined NDT method.

NDT method	Abbreviation
Ultrasonic testing	UT
Radiographic testing	RT
Dye penetrant testing	PT
Eddy current testing	ET
Magnetic particle testing	MT

These methods are compared using a common set of practical criteria, including difficulty of application, cost, defect detectability, result accuracy, inspection time, personnel requirements, geometric compatibility, accessibility, safety and health aspects, equipment needs, recordability, preparation time, calibration requirements, sensitivity to external factors, and dependence on material system. These criteria provide the basis for distinguishing between inspection routes that are relatively straightforward and those that become more demanding when hidden interfaces, layered composites, or dissimilar-material joints are involved.

2.6.1 Assessment Workflow

The inspection assessment was carried out in a stepwise manner in order to compare the candidate's hat-stiffened panel concepts on a common basis. The procedure begins with the identification of the NDT methods that are potentially applicable to each material configuration. This initial screening is then refined by considering the joining method, since the joint architecture directly affects the accessibility of the critical inspection region, the type of damage expected to occur, and the suitability of the corresponding inspection route.

For each design alternative, only the NDT methods considered technically relevant are retained for the assessment. These methods are then evaluated against the five inspection metrics defined in the previous subsection, namely Visual Detectability, NDT Complexity, Cost Intensity, Time Intensity, and Energy Intensity. In this way, the inspectability of a design is assessed not only through the material system of the skin and stringer, but through the complete design solution, including the joining concept and the inspection route required in practice. It is useful to mention here that process complexity refers to the extent of special equipment, extensive training and/or preparation needed for each NTD method.

A qualitative five-level scale was adopted for all five metrics in order to ensure a consistent comparison between designs and is depicted in Table 9. In all cases, a score of 5 corresponds to the most favorable inspectability condition, while a score of 1 corresponds to the least favorable one. Therefore, higher values indicate easier, simpler and efficient inspection. The same scale is used throughout the design-by-design assessment, allowing both criterion-wise comparison and overall ranking of the candidate panel designs.

Table 9 - Five-point scoring scale for MRO inspection metrics.

Metric Examined	Scale 1 to 5				
	1	2	3	4	5
Visual Detectability	Not visible	Poorly visible	Partly visible	Mostly visible	Readily visible
NDT Complexity	Very complex	Complex	Moderate	Simple	Very simple
Cost Intensity	Very high cost	High cost	Moderate cost	Low cost	Very low cost
Time Intensity	Very time-consuming	Time-consuming	Moderate	Fast	Very fast
Energy Intensity	Very high energy demand	High energy demand	Moderate energy demand	Low energy demand	Very low energy demand

The scoring process was applied at the level of each relevant set of hat stiffened material set–joining technology set – NDT method applied combination. The resulting ratings were first examined separately for each metric and subsequently compared across the six panel concepts. This approach makes it possible to identify not only which configurations are more inspectable overall, but also the reason for their performance, for example whether a concept is penalized mainly by poor visual detectability, high NDT complexity, or increased time and cost burden.

3. Results & Discussion

3.1 Results of the inspection-pillar assessment at design level

The initial assessment of the Inspect pillar was performed at the material-and-configuration level, without considering the influence of the joining method. For each hat-stiffened panel concept, a representative NDT route was selected based on the assumed skin and stiffener materials, the expected damage mechanisms, and the accessibility of the inspected region, as summarized in Table 10. The concepts were assessed using the five previously defined metrics: Visual Detectability, NDT Complexity, Cost Intensity, Time Intensity, and Energy Intensity. A common ordinal scale from 1 to 5 was applied, where a score of 5 represents the most favorable inspection condition and a score of 1 the least favorable. The Overall Inspectability Score was calculated as the unweighted arithmetic mean of the five metric scores.

Table 10 - Baseline inspection-pillar assessment at design level.

Rank	Design	Dominant NDT method	Visual Detect.	NDT Compl.	Cost Int.	Time Int.	Energy Int.	Overall Inspectability Score
1	Al / Al	ET / PT	5	5	5	5	5	5
2	Al / CFRP	ET / UT	4	3	3	3	3	3.2
3	CFRTP / CFRTP	UT	2	3	3	3	3	2.8
4	CFRP / Al	UT	2	2	2	2	2	2
5	Ti / CFRP	UT / RT	2	1	1	1	1	1.2
6	CFRP / CFRP	UT	2	2	1	1	2	1.6

At this level, the results indicate a progressive reduction in inspectability from metallic to hybrid and composite-dominated configurations. The Al/Al concept achieves the highest score due to its compatibility with mature and relatively low-demand methods, such as eddy-current and penetrant testing. The Al/CFRP configuration ranks second. The aluminium region supports relatively direct inspection, while ultrasonic testing is required for the composite stiffener and the dissimilar-material interface. The CFRTP/CFRTP concept follows with an intermediate score. Although internal damage has limited visual detectability, the configuration can be inspected using established ultrasonic methods with moderate complexity and resource demand. The CFRP/Al concept presents lower inspectability because inspection is dominated by the CFRP region and the composite–metal interface, increasing reliance on ultrasonic testing. The CFRP/CFRP configuration receives a lower score due to limited visual detectability and the time and cost associated with detecting internal delamination and skin–stiffener debonding. The Ti/CFRP concept presents the least favorable inspection profile. The titanium–composite interface and the potential need for combined ultrasonic and radiographic inspection substantially increase inspection complexity, cost, duration, and energy demand.

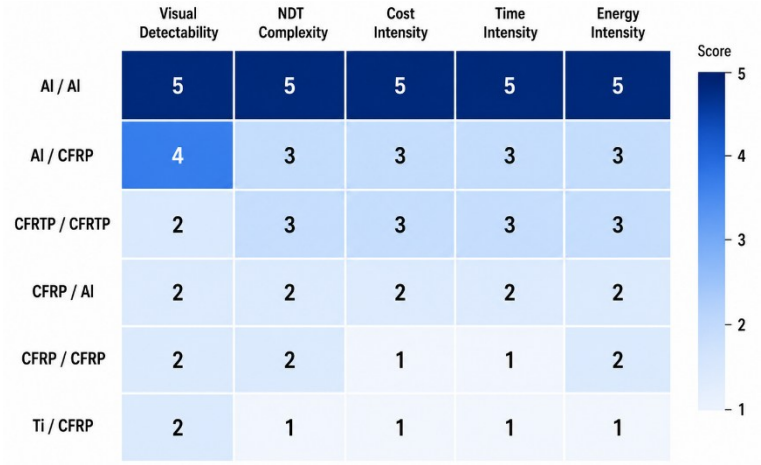


Figure 5 – Mapping of inspectability performance taking into account materials combination in the design of hat-stiffened panel

Overall, the results identify material arrangement, interface characteristics, inspection accessibility, and dependence on NDT as the primary design-level drivers of inspectability. The ranking represents an early-design assessment framework and may change when geometry, thickness, joining method, defect type, and inspection coverage are considered.

3.2 Second-level inspection-pillar assessment including joining-method influence

In the second stage, the assessment was refined by introducing the joining method, as shown in Table 11. This step was necessary because the joint architecture affects the location of the critical inspection zone, the likely damage mechanism, and the burden of the applicable NDT route. The same material configuration can therefore lead to different inspection outcomes depending on whether the interface is mechanically fastened, bonded, hybrid, co-cured, or welded.

Table 11 - Second-level inspection-pillar assessment for each design–joining–NDT combination.

Rank	Design	Joining method	NDT method	Visual Detect.	NDT Compl.	Cost Int.	Time Int.	Energy Int.	Overall Inspectability Score
1	Al / Al	Mechanical fastening	ET	5	5	5	5	5	5
2	Al / Al	Mechanical fastening	PT	5	5	5	5	4	4.8
3	Al / Al	Hybrid bonded-fastened	ET / UT	4	4	4	4	3	4
4	CFRTP / CFRTP	Welding	UT	2	2	4	4	4	3.6
5	Al / CFRP	Hybrid bonded-fastened	ET / UT	4	4	3	3	3	3.4
6	Al / Al	Adhesive bonding	UT	4	3	3	3	3	3.2
7	Al / CFRP	Adhesive bonding	UT	4	3	3	3	3	3.2
8	CFRTP / CFRTP	Hybrid bonded-fastened	UT	2	3	3	3	3	2.8
9	CFRP / Al	Hybrid bonded-fastened	UT	2	3	2	2	2	2.2
10	CFRTP / CFRTP	Adhesive bonding	UT	2	3	2	2	2	2.2
11	CFRP / Al	Adhesive bonding	UT	2	2	2	2	2	2
12	Ti / CFRP	Hybrid bonded-fastened	ET / UT	2	2	2	2	2	2
13	CFRP / CFRP	Hybrid bonded-fastened	UT	1	2	2	2	2	1.8
14	CFRP / CFRP	Adhesive bonding	UT	1	2	2	2	2	1.8
15	Ti / CFRP	Adhesive bonding	UT / RT	2	1	1	1	1	1.2
16	CFRP / CFRP	Co-cured / co-bonded	UT	1	1	1	1	2	1.2

The refined results confirm that the metallic Al/Al concept remains the most favorable case, especially when mechanical fastening is used. In this case, the inspection path remains simple, local, and well established. When the same design is adhesively bonded, the scores decrease because the critical region is shifted from accessible metallic features toward a hidden interface. The hybrid bonded-fastened solution remains highly ranked, but still slightly below the mechanically fastened case.

For the two mixed concepts, the joining effect becomes more visible. In Al/CFRP, the hybrid solution gives the best balance, since the metallic skin still supports local surface or near-surface screening, while ultrasonic testing covers the interface and composite side. In CFRP/Al, the same improvement is smaller, because the external composite skin continues to penalize visual detectability and keeps the assessment dependent on more demanding inspection routes.

The two thermoset-dominated concepts remain the weakest cases. In CFRP/CFRP, the co-cured or co-bonded solution leads to the lowest scores, since the critical interface becomes highly integrated

and poorly accessible. In Ti/CFRP, the dissimilar interface and the need for advanced inspection also lead to low scores, even when a hybrid solution is assumed. The CFRTP/CFRTP concept improves significantly when welding is used, confirming that a welded thermoplastic interface is more favorable from an inspection standpoint than an adhesively bonded thermoset interface. Although it does not reach the metallic cases, it becomes the best composite-based option in the refined ranking. Despite these advantages, having thermoplastic composites in the primary structural parts of civil aircrafts needs more elaborate predictive modelling to enhance the uniformity in manufacturing of such composites for structural applications. In near future, if thermoplastic composites are being mature in design -prediction of properties as in thermoset counterparts, aircraft manufacturers may choose more parts in fuselage and wing from thermoplastics.

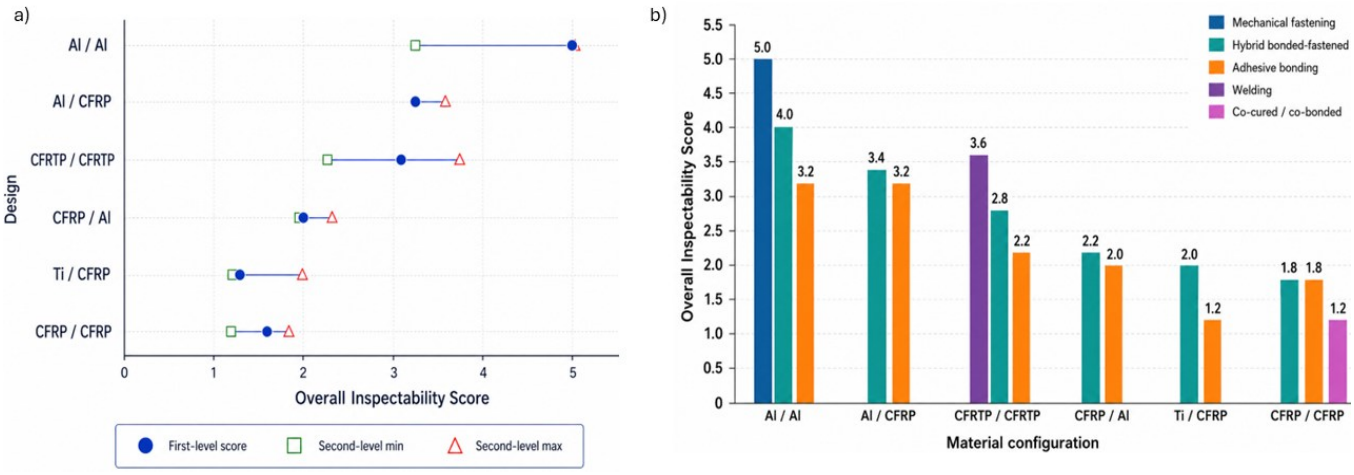


Figure 6– Influence of joining method on inspectability of the hat-stiffed panels design, depicted : (a) in high level per material combination and (b) in low level per material combination and the assess joining technology

3.3 Comparison between the two assessment levels

The first-level assessment provides a baseline ranking based on material configuration and dominant NDT route, without considering the effect of the joining method. It is therefore useful as an initial screening step, showing the general difference between metallic, hybrid, and composite concepts. The second-level assessment refines this picture by introducing the joining method, which directly affects the location of the critical inspection zone and the burden of the applicable NDT route.

The comparison shows that the joining method has limited influence in the metallic case, but a much stronger effect in the hybrid and composite concepts. In particular, bonded and co-cured thermoset interfaces reduce inspectability, whereas welded thermoplastic interfaces provide a more favorable result. This indicates that the first-level ranking is suitable for early concept comparison, while the second-level ranking is needed for a more realistic design evaluation. Overall, the results confirm that inspectability depends on the combined effect of material system, joining concept, and inspection method, rather than on material selection alone.

4. Conclusions & Future Work

This study proposes an MRO-Enabled Sustainability Framework that elevates Maintenance, Repair, and Overhaul considerations from reactive downstream indicators to proactive early-stage design drivers. The framework recontextualizes Maintainability within the RAMS engineering paradigm and operationalizes it through Design for Maintainability principles across three sequential phases: Inspect, Repair, and Replace. Semi-quantitative metrics were defined for each phase and mapped onto the five pillars of an established holistic sustainability index, enabling maintainability to be evaluated concurrently with structural performance, economic, environmental, social, and circularity objectives. A scoring scale based on expert elicitation was adopted to support assessment at the conceptual design stage.

The framework was applied through a hat-stiffened panel case study across six material

configurations, with the practical assessment focused on the inspection phase. The first-level design assessment revealed a clear hierarchy: the Al/Al configuration scored highest (5.0) due to high visual detectability and compatibility with mature, low-burden inspection methods, while the CFRP/CFRP and Ti/CFRP configurations scored lowest (1.2) owing to hidden damage mechanisms and heavy reliance on complex volumetric NDT. The Al/CFRP hybrid (3.2) benefited from metallic skin accessibility, and the CFRTP/CFRTP concept (2.8) outperformed all thermoset-based alternatives despite limited visual detectability. The second-level assessment, incorporating joining method influence, proved that joint architecture is a decisive differentiator for composite concepts. Mechanical fastening preserved the Al/Al maximum score, whereas adhesive bonding reduced it by shifting inspection toward hidden bondline interfaces. Most notably, CFRTP/CFRTP with fusion welding achieved 3.6 to become the highest-ranked composite solution, while CFRP/CFRP with co-curing produced the lowest score of 1.2, confirming that highly integrated thermoset joints create the most challenging inspection conditions. These results establish that inspectability is not determined by material selection alone but by the interdependent combination of material system, joining concept, and inspection route, reinforcing the need for concurrent evaluation during early design.

Despite these highly promising findings, several limitations must be acknowledged regarding the current developmental stage of the framework. The applied one to five scoring methodology relies heavily on structured authors' expertise and professional aerospace engineering judgment rendering the current outputs inherently qualitative. Furthermore, only the Inspect phase was fully assessed and scored within the case study; the Repair and Replace phases, although formally defined with their respective metrics, were not evaluated for the panel configurations considered. Additionally, equal weighting was implicitly assumed across the five-inspection metrics, without the application of a formal prioritization scheme to reflect the relative importance of individual criteria under specific operational scenarios.

Future research efforts must therefore prioritize expanding the practical structural assessment to formally execute the remaining Repair and Replace phases. Once all three operational domains are fully evaluated the resulting maintainability scores must be mathematically integrated into the overarching Multi-Criteria Decision-Making equation to calculate the final Sustainability Index, towards the integration of MRO characteristics to holistic sustainability assessment frameworks for the aviation sector. Ultimately, to maximize the industrial applicability of this approach, future iterations of the framework should seek to transition these qualitative expert scores into fully quantitative empirical data through greater stakeholder participation.

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