Paradigm

ESG Integration in Strategic Innovation Management of Aerospace Enterprises: A Sustainable Decision-Making Framework

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Abstract. *The European aerospace industry is currently undergoing a phase of integrating innovation objectives, which can be aligned both with competitiveness and airworthiness, but also with the sustainability agenda and ESG reporting mandates of the European Union. In this paper, we offer an ESG-integrated SIM (Strategic Innovation Management) decision framework for aerospace enterprises (OEMs, tier suppliers and MROs) working within EU member states, focusing on the significant divergences between ESG disclosures and portfolio-level innovation decision-making. The paper links a structured literature with the policy synthesis for defining EU-focused ESG indicators, a mapping of ESG integration points through the lifecycle of aerospace innovation and a hybrid multi-criteria decision analysis (MCDA) modelling. The Analytic Hierarchy Process (AHP) to quantify ESG priorities depends on the elicitation of experts (n=7, EU-based, and 5-15 years' experience). Then, the different innovation alternatives are ranked (under uncertainty) with the help of the use of Fuzzy TOPSIS which represents expert judgments expressed through linguistic terms mapped to triangular fuzzy numbers. The findings show that Critical Risk Management (26.3%) and GHG Emissions (22.9%) significantly contribute to the weighting structure, due to the joint safety-climate exposure of the sector. An illustrative portfolio ranking results indicate that the SAF-propulsion prototype has achieved the highest closeness coefficient (CC=0.77) followed by Circular Manufacturing R&D (CC=0.75) and AI-driven lifecycle governance (CC=0.71). The ranking highlights practical trade-offs between direct impact on decarbonization, social transition benefits and governance, audit and preparedness. On the whole, the framework has realized ESG as an auditable layer for decision making within SIM with clear and repeatable project selection that is consistent under EU climate and governance objectives. It is still adaptable to long development cycles and intricate supply chains typical of aerospace innovation.*

Keywords: ESG, Aerospace Industry, Strategic Innovation, EU Member States, Sustainability, Decision-Making Framework, MCDA.

Introduction

The European aerospace industry is at an important turning point: the pursuit today of technological advancement is now confronted with the pressing need to balance progress with climate neutrality, social responsibility, and corporate transparency. Thanks to the European Green Deal and the ¨Destination 2050¨ strategy, European Union member state aerospace firms are expected to play a high profile role in meeting net-zero carbon emissions by mid-century. In this changing environment, Environmental, Social and Governance (ESG) factors are emerging as crucial decision pillars in the context of aerospace innovation governance and regulation at EU level. (Commission, 2019), (A Route to Net Zero European Aviation, ROADMAP 2025-2050, 2025), (Alan Francisco Caraveo Gomez Llanos, 2023)

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The 2025 edition of the European Aviation Environmental Report published by the European Union Aviation Safety Agency (EASA) underscores that while aviation emissions are still below pre-pandemic levels, a steady upward trend has resumed. Despite technological improvements in fuel efficiency and aircraft design, overall greenhouse gas (GHG) emissions from European aviation increased by 10% between 2013 and 2022. This signals an urgent need for structural transformation not only in propulsion systems and energy sources but also in corporate innovation strategies, which must now integrate sustainability at every decision point. (EASA, 2025), (CDSB, 2021)

In parallel, the social and governance dimensions of ESG are gaining traction, especially in relation to workforce transition, skills development, gender diversity and ethical governance in supply chains. EU regulations such as the Corporate Sustainability Reporting Directive and upcoming taxonomy disclosures are pushing aerospace enterprises to embed these values into their innovation roadmaps. However, the integration of ESG into Strategic Innovation Management remains fragmented, with most companies lacking structured frameworks that align R&D portfolios with non-financial KPIs and long-term ESG targets.

This paper addresses this gap by proposing a decision-making model that operationalizes ESG integration into SIM within the aerospace sector of EU member states. The proposed framework draws from ESG-related performance indicators outlined by the European Commission, combined with insights from EASA's environmental monitoring and industry best practices. Through a Multi-Criteria Decision Analysis and an illustrative portfolio evaluation using representative innovation alternatives, the model aims to enhance the alignment between innovation initiatives and ESG (figure 1) performance metrics. In doing so, it supports a systemic shift toward a more sustainable, socially inclusive and ethically governed aerospace innovation ecosystem in Europe. (EASA, 2025)

Figure 1. The ESG – Innovation Decision-Making Framework

Source: (EASA, 2025).

For aerospace firms to translate ESG from disclosure to decisions, they need operational arrangements that translate regulatory expectations and sector environmental evidence into portfolio-level choices. Thus, this research proposes an ESG – integrated Strategic Innovation Management decision framework that maps ESG requirements to innovation lifecycle stages, assigns transparent weights to ESG criteria via AHP based on expert elicitation, and ranks innovation alternatives through Fuzzy TOPSIS to support auditable, repeatable project selection. The framework is designed to be compatible with long aerospace development cycles and supply-chain complexity, enabling traceable trade-offs between climate impact, social transition and governance readiness.

While some of the ESG literature is dedicated to airline operators, the underlying ESG indicators, governance structures and innovation decision logics can also be translated to aerospace enterprises where upstream design and manufacturing choice is fundamental for downstream aviation sustainability performance.

This research applies these to aerospace enterprises (OEMs, Tier suppliers, MRO organizations), specifically focusing on the integration of ESG standards into Strategic Innovation Management decision making in R&D, industrialization, production and supply-chain governance. The aviation operational indicators are used as downstream signal constraints that translate into enterprise-level design, manufacturing and assurance requirements (e.g., product compliance, traceability and lifecycle emissions). Thus, the KPI set is developed mainly at the enterprise level and is linked with regulatory reporting obligations under EU sustainability reporting and sustainable finance frameworks. (Renata ȘEPTICHITA, Augustin SEMENESCU, 2025)

Research questions:

a) How can EU ESG requirements (policy anchors and reporting obligations) be operationalized into auditable decision criteria for SIM in aerospace enterprises?
b) Which ESG criteria dominate innovation portfolio decisions under expert uncertainty, and how consistent are expert judgments in assigning these priorities (AHP consistency)?
c) How does a hybrid AHP-Fuzzy TOPSIS approach rank representative aerospace innovation alternatives, and what E-S-G trade-offs emerge for portfolio governance?

Literature Review

The combination of Environmental, Social, and Governance (ESG) principles in the approach to strategic innovation management is growing more significant in the aerospace sector, and in that of the European Union more widely, as sustainability policy frameworks underpin the adoption of transformative industrial governance practices. In the high capital intensity, long development cycles, and environmental externalities of their aerospace ecosystem, ESG is playing an increasingly important role, but with less academic and applied research on it. (Renata SEPTICHITA, 2025)

While there are many ESG frameworks established for airline operators as well, the KPI-driven logic and structures of decision-making in the ESG framework systems make sense and can be systematically extrapolated to aerospace businesses where innovation, design, manufacturing and certification decisions shape downstream aviation performance.

Most existing ESG evaluation frameworks rely on crisp indicators, which are insufficient for innovation-driven contexts characterized by uncertainty and expert judgment, such as aerospace strategic decision-making.

ESG Imperatives in the European Aerospace Sector

The 2025 European Aviation Environmental Report by EASA sets the stage for sustainability compliance for EU countries, in particular by defining requirements for the disclosure of emissions within the aviation sector, as well as encouraging more and greater use of Sustainable Aviation

Fuels (SAF) and by measuring and reviewing sustainable aviation sector performance across scope 1-3 greenhouse gas emissions. While per-passenger emissions and efficiency of transport have improved in aviation, aviation is considered difficult to abate against, with total emissions increasing by 10% from 2013 through 2022.

Social and governance issues related to workforce transitions, gender diversity in leadership, and accountability for ESG disclosures further complicate the aviation sector's climate accountability. EU instruments such as the CSRD and EU Taxonomy have now made it a requirement for aerospace enterprises to include non-financial performance indicators within business strategies, including R&D and innovation portfolios.

ESG Decision Criteria and KPIs in Aviation

Airlines ESG decision criteria and key performance indicators (KPIs). Alan Francisco Caraveo Gomez Llanos et al. 2023: systematically identified ESG Key Performance Indicators relevant to the airline industry using a multi-criteria decision-making approach based on the Analytic Hierarchy Process. (Commission, 2019) Their framework classified KPIs within 11 categories and it also used GHG emissions, systemic risk management, clean technology implementation and employee inclusion. The absence of standardized ESG rating methodologies and varied disclosure practices by European carriers. (Alan Francisco Caraveo Gomez Llanos, 2023), (ICAO, 2021)

Importantly, the top-weighted ESG KPIs in that model were:

- Flight safety performance (e.g., number of incidents and accidents);
- Fuel efficiency and SAF adoption.
- Scope 1-3 GHG emissions.
- Digital transformation efforts as proxies for environmental and governance readiness.

These indicators are in line with the strategic objectives described under the EASA and ICAO sustainability frameworks, confirming the idea that ESG maturity contributes toward resilience, innovation and regulatory adherence. In order to align the KPI logic with the unit of analysis, Table 1 offers an indicative mapping from common aviation operational indicators to enterprise level SIM ones that can be managed, measured and audited within an aerospace entity.

Table 1. Indicative mapping from aviation operational indicators to aerospace enterprise SIM KPIs

Aviation operational indicator	Aerospace enterprise SIM indicator
Passenger satisfaction/ punctuality	Customer satisfaction, on-time delivery, quality escapes, warranty/ field returns
Flight safety event	Product safety occurrences, airworthiness-related NCR/CAR, audit finding
Airline Scope 1 fuel burn/ SAF uptake	SAF-enabled technology readiness fuel compatibility testing, lifecycle emissions engineering
Airport operations energy/ emissions	Plant/ test-facility energy and emissions (Scope 1-2) with audit-ready metering
Operational noise/ air-quality constraints	Design-for-noise/ eco-design indicators, certification evidence, community impact management

Source: Authors' own research.

Such a causal connection ensures that downstream operational ESG performance is structurally determined by upstream design and manufacturing innovation choices, thus justifying the enterprise-level unit of analysis.

The downstream operator KPIs are treated as outcome constraints, whereas the aerospace enterprise KPIs represent controllable design and manufacturing levers that structurally determine those outcomes.

This mapping ensures conceptual continuity between aviation-oriented ESG frameworks and aerospace enterprise innovation contexts, enabling the operationalization of ESG principles at design, manufacturing and technology development levels.

Research Gap and Need in ESG-Integrated innovation paradigms.

While greater attention is paid to ESG disclosures, the existing literature reveals shortcomings: (ICAO, 2021)

- While there have been many studies on environmental metrics, the studies highlight social inclusion and governance structures that are important to just transitions.
- ESG dimensions are not well integrated into initial stage R&D planning and innovation pipeline governance.
- A lot of ESG ratings in aerospace continue to be reactive or compliance-oriented, not as part of a proactive linkage model to strategic innovation management.

Finally, SASB and GRI serve as a good example with sector-agnostic disclosure guidance, which, therefore, offer partial guidance at this stage and lack any sort of decision support suitable for extended R&D cycles at high technological uncertainty and within multistakeholder ecosystems found in the EU aerospace industry.

Most ESG applications are still compliance-centric and reactive applications. Many rating systems cannot build early-stage R&D integration and build cross-functional traceability and monitoring. This supports the case for ESG driven portfolio-level innovation governance in the aerospace sector. (EASA, 2025)

Toward a Decision-Making Framework for ESG Integration

The article contributes a multi-criteria ESG-innovation integration model by bridging these ESG policy frameworks to corporate innovation strategies and building upon recent contributions on the subject and institutional mandates (e.g., ReFuelEU Aviation, Fit for 55, CSRD). This framework relies on AHP to form criterion weights and Fuzzy TOPSIS to evaluate and rank innovation projects in line with sustainability impact, resilience and regulatory compliance as shown in figure 2. (Qureshi, M. A., Kirkerud, S., Theresa, K., & Ahsan, 2020)

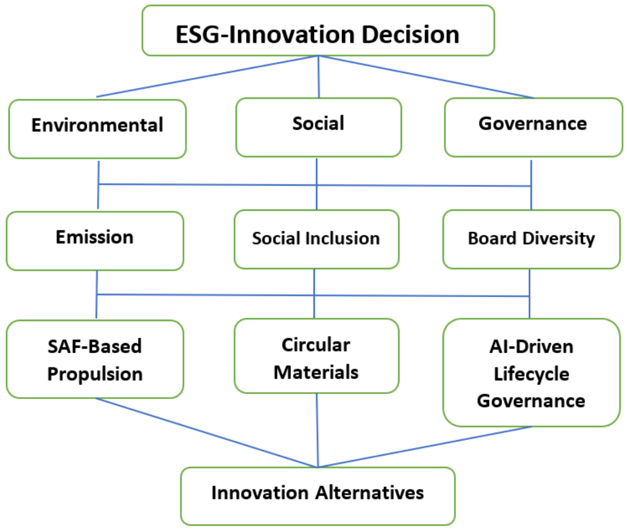

Figure 2. Analytic Hierarchy Process structure

Source: Authors' own research.

Interweaving ESG with strategic innovation decisions - from initial planning to deployment and lifecycle monitoring - the model addresses the specific problems and change mechanisms associated with EU aerospace companies that are on the journey to climate-neutral, socially responsible and ethically governed operations.

Strategic Innovation Management and Sustainability Transition Literature

Recent scholarship in strategic innovation management underscores the significance of incorporating sustainability goals in portfolio governance arrangements, particularly in key high-reliability and capital-intensive sectors. There is a critical need for decision support systems that combine environmental performance metrics with risk governance and long-term resilience considerations in strategic policy implementation in the case of sustainable portfolio management and industrial sustainability transitions. (Dr. Robert G. Cooper, Dr. Scott J. Edgett, 2001-2008), (Robert G. Cooper, 2001)

From a socio-technical transition literature perspective, sustainability transitions are viewed as systemic transformations demanding alignment between technological innovation, regulatory frameworks and organizational governance (Geels, 2002). In aerospace environments, long development timelines and stringent certification criteria amplify the demand for structured innovation prioritization mechanisms adapted to navigate uncertainty and multidimensional trade-offs.

This study extends sustainability transition theory by embedding ESG factors within an AHP-Fuzzy TOPSIS framework, and thus provides insights into the intersection of operational innovation decision analytics with ESG criteria in industrial workflows.

In addition to transition theory, sustainability-informed innovation scholarship insists that sustainability is effectively realised strategically as such when it is integrated into governance routines and decision criteria for project selection, resource allocation and portfolio control, rather than being treated as ex post disclosure. Thus, supported the adoption of both weighted scorecards and MCDA as decision structures in sustainability-oriented innovative portfolios for high-reliability industries. (Adams, 2016) (Bansal, 2017)

According to sustainability-oriented innovation research, sustainability is strategically effective only when articulated in the form of decision rules for organization and investment vehicles, namely the portfolio, rather than as post-hoc reporting. Complementary research on sustainable business models also focuses on structured archetypes and measurable mechanisms (e.g., efficiency, value from waste, renewables substitution) that can be used as criteria in portfolio composition (Bocken, NMP; Short, SW; Rana, P; Evans, S, 2014)

In contrast to traditional Stage-Gate portfolio governance models that are based on financial return and technical feasibility, the proposed ESG-integrated framework embeds sustainability criteria directly in the weighting architecture. Such integration is consistent with portfolio governance theory, whereby strategic buckets and weighted scorecards guide capital allocation decisions (Dr. Robert G. Cooper, Dr. Scott J. Edgett, 2001-2008). When ESG criteria are integrated into the hierarchical structure of the portfolio, sustainability is treated much as an ex-ante decision rule rather than an eventual report on reporting.

Methodology

This study develops a scientifically grounded, multi-phase methodology to design and validate a decision-making framework for integrating ESG indicators into SIM process of aerospace enterprises in EU member states. The approach combines the most relevant regulatory guidance (EAER 2025, CSRD, RED II, SFDR) industrial best practices and validated multi-criteria decision-making tools (AHP and Fuzzy TOPSIS) to enable ESG- aligned innovation planning. (Alan Francisco Caraveo Gomez Llanos, 2023)

A structured, four-phase methodology was developed:

Phase 1: Identification of EU-Relevant ESG Indicators for Aerospace

In line with this guideline for disclosure of sector ESG applications and sustainability frameworks (like for instance RED II and ReFuelEU) from the EU Taxonomy Regulation and CSRD and SASB, we compiled an aerospace indicator of ESG set based on elements on EASA's EAER (2025) and EU regulatory instruments (CSRD/ESRS, EU Taxonomy, ReFuelEU, RED II) where relevant as the major anchors; non-academic sources were involved for contextual triangulation. The portfolio logic also follows the established SIM and portfolio governance literature (Dr. Robert G. Cooper, Dr. Scott J. Edgett, 2001-2008).

Finally, the ESG indicator set has Environmental (E): (Alan Francisco Caraveo Gomez Llanos, 2023), (European Commission, 2023)

- **Scope 1:** Direct emissions from aerospace enterprise operations (e.g., on-site fuel combustion, test rigs, company vehicles);
- **Scope 2:** Indirect emissions from purchased electricity/ heat/ steam/ cooling for manufacturing, R&D, and test facilities;
- **Scope 3:** Upstream and downstream value-chain emissions (materials, logistics, supplier processes, use-phase where applicable, end-of-life);
- **GHG Lifecycle Reduction:** Potential of SAF technologies (typically exceeding 50-70% compared to fossil baseline, according to RED II);
- **SAF Mandate Compliance:** Minimum 2% in 2025 → 70% by 2050 (ReFuelEU Aviation);
- **Land Use and Biodiversity:** Restrictions on sourcing from high-carbon/biodiverse zones;
- **Renewable Energy Use:** Certification for electricity in SAF production (RFNBO)

Social (S): (Alan Francisco Caraveo Gomez Llanos, 2023), (CDSB, 2021), (EUR-Lex, 2022)

- **Inclusion & Diversity Metrics:** Workforce gender diversity, skills transition, equitable hiring (implicit in EU sustainability policy);
- **Job Preservation through Innovation:** Horizon Europe-linked programs for training and transition;
- **Community Impact:** local impacts around facilities (noise, air quality, land use), stakeholder engagement and grievance mechanisms.

Governance (G): (Alan Francisco Caraveo Gomez Llanos, 2023)**,** (CDSB, 2021)

- **Regulatory Compliance:** Alignment with CSRD, SFDR, EU Taxonomy for aviation;
- **Transparency:** Audit transparency, environmental disclosure under ACA and carbon offset tracking;
- **Accountability:** Stakeholder partnership plans, board diversity and governance structure.

These indicators were weighted using expert-validated hierarchies, based on the model in (Alan Francisco Caraveo Gomez Llanos, 2023), which used AHP for ESG prioritization in aviation.

Phase 2: Mapping Innovation Decision Stage in Aerospace Lifecycle

The aerospace innovation process was decomposed into decision stages to ensure integration of ESG from planning to implementation. These ESG integration points for each stage are summarized in Table 2, in alignment with current aerospace development cycles and EU transition agendas:

Table 2. Relevant ESG Integration Points for every innovation stage

Nr. crt.	Innovation Stage	Relevant ESG Integration Points
1.	Strategic R&D Planning	Alignment with EU Green Deal, carbon neutrality roadmaps
2.	Conceptual Design	Lifecycle analysis, SAF integration potential
3.	Prototype & Testing	Emissions testing, noise compliance, material recyclability
4.	Certification & Validation	Regulatory ESG auditability, risk mitigation planning
5.	Deployment & Scale-Up	Scope 3 data tracking, community impact, governance traceability
6.	Post-Market Monitoring	ESG impact auditing, sustainability KPIs in after-service lifecycle

Source: Authors' own synthesis based on EU sustainability policy instruments (CSRD/ESRS, EU Taxonomy, ReFuelEU) and aerospace lifecycle governance practices.

This mapping was validated against industrial TRLs and EASA innovation procedures.

Phase 3: Application of AHP for ESG Weighting

To ensure quantitative traceability of ESG impact, AHP was applied (the results are presented in Table 3):

- A hierarchy was constructed with ESG Dimensions at Level 1, Sub-criteria at Level 2 and KPIs at Level 3.
- An analysis was realized based on "Rating ESG key performance indicators in the airlines industry" by A. F. Caraveo Gomez Llanos et. al. pairwise comparisons by domain experts (n=7, range 5-15 years exp., EU-based).
- Pairwise comparisons were aggregated using the geometric mean.
- Consistency Ratio was calculated (CR<0.10 required for acceptability).
- Final normalized weights were calculated using eigenvalue decomposition.

- The aggregated AHP pairwise comparison matrix is reported in Appendix 4 for full methodological transparency.
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Table 3. The weight of each criterion- Criteria definitions

Nr. crt	Criteria	Definition	Boundary	Weight
C.1.	Critical Risk Management	Airworthiness/ safety-critical risks, certification blockers, severe consequence nonconformities, safety assurance failures	Broader business continuity and supply-chain resilience	26.3%
C.2.	GHG Emissions	Direct and value-chain GHG impact attributable to the innovation pathway (Scope 1-3 relevance)	Non-GHG environmental benefits (materials circulatory, noise)	22.9%
C.3.	Systemic Risk Management	Enterprise resilience: supply-chain disruption, regulatory shocks, continuity planning, reputational/ system risks	Product safety/ airworthiness hazards handled under Critical Risk	16.5%
C.4.	Environmental Opportunities	Circulatory, resource efficiency, eco-design, noise footprint reduction, renewable inputs enabling new sustainable value	GHG metrics already accounted under GHG Emissions	15.0%
C.5.	Diversity & Inclusion	Workforce inclusion, skills transition, equitable participation in innovation processes	Governance, audit readiness, disclosure infrastructure	11.3%
C.6.	Governance/Transparency	Auditability, traceability, disclosure readiness (CSRD/ESRS), data lineage and oversight	Environmental and social outcome performance itself	8.0%

Source**:** (EASA, 2025)**,** (ICAO, 2016)**.**

The criteria are defined to be mutually exclusive by scope and collectively sufficient to capture ESG-relevant decision needs in long-cycle aerospace innovation governance.

The AHP weighting procedure was based on expert elicitation involving seven industry professionals selected according to the following criteria:

- Minimum five years of experience in aerospace engineering, sustainability, quality, certification or innovation management;
- Active involvement in EU-based aerospace organizations (OEMs, Tier suppliers, MRO or regulatory interface roles);
- Familiarity with ESG reporting or innovation portfolio decisions processes.

Detailed expert profile characteristics, including organizational type, functional role and regional distribution, are provided in Appendix 1 to ensure transparency and reproducibility of the elicitation process.

The distribution across OEM, Tier suppliers, MRO and regulatory-interface roles ensures coverage of design, production, certification and ESG reporting perspectives, mitigating functional bias in pairwise judgments.

To ensure diversity and mitigate bias, experts represented different functional domains and organizational positions. Judgments were collected independently through structured pairwise comparison questionnaires using Saaty's 1-9 scale. Responses were anonymized and aggregated using the geometric mean. CR values were computed for each matrix, with all values below the accepted threshold of 0.10.

To reduce potential conflicts of interest, experts were instructed to assess criteria and alternatives independently and to disclose any direct involvement in the evaluated innovation initiatives; no joint calibration discussion was conducted prior to scoring.

Phase 4: ESG-Based Innovation Project Evaluation Using Fuzzy TOPSIS

This phase ranks the innovation alternatives using Fuzzy TOPSIS by combining the AHP-derived normalized criteria weight (Table 3) and expert evaluations expressed as linguistic terms mapped to triangular fuzzy numbers (e.g., Low/ Medium/ High). The linguistic scale and corresponding triangular fuzzy number (TFN) mapping are detailed in Appendix 2. (Chen, 2000)

- Construct the triangular fuzzy decision matrix (see Eq.1) and define the criteria weights.

$$\tilde{X} = \left[\tilde{X}_{ij}\right]_{mn}, \tilde{X}_{ij} = (l_{ij}, m_{ij}, u_{ij})$$
$$w_j = AHP - derived\ weight \qquad Eq.\ (1)$$

The complete linguistic decision matrix is presented in Appendix 3, while the numerical TFN – expanded matrix used in the TOPSIS calculations is provided in Appendix 3b.

- Normalize the fuzzy matrix into $\tilde{R}$ (see Eq.2.) and compute the weighted matrix (see Eq.3.).

$$\tilde{r}_{ij} = \left(\frac{l_{ij}}{u_j^{max}}, \frac{m_{ij}}{u_j^{max}}, \frac{u_{ij}}{u_j^{max}}\right), u_j^{max} = \frac{max}{i}(u_{ij})$$
$$\tilde{r}_{ij} = \left(\frac{l_j^{min}}{u_{ij}}, \frac{I_j^{min}}{u_{ij}}, \frac{I_j^{min}}{u_{ij}}\right), I_j^{min} = \frac{min}{i}(l_{ij}) \qquad Eq.\ (2)$$
$$\tilde{V}_{ij} = \tilde{r}_{ij} \times w_J, \tilde{V} = \left[\tilde{V}_{ij}\right] \qquad Eq.\ (3)$$

- Determine the fuzzy positive ideal solution A^+ and fuzzy negative ideal solution A^- from $\tilde{V}$ (see Eq. 4). Compute distances using the vertex method (Eq. 5-6) and derive closeness coefficient CC_i (Eq7).

$$A^+ = \left\{\tilde{V}_j^+\right\}_{j=1}^n, \tilde{V}_j^+ = \frac{max}{i}\left(\tilde{V}_{ij}\right);\ A^- = \left\{\tilde{V}_j^-\right\}_{j=1}^n, \tilde{V}_j^- = \frac{min}{i}\left(\tilde{V}_{ij}\right) \qquad Eq.\ (4)$$

$$d(\tilde{a}, \tilde{b}) = \sqrt{\frac{1}{3}[(I_a - I_b)^2 + (m_a - m_b)^2 + (u_a - u_b)^2]} \qquad Eq.\ (5)$$

$$D_i^+ = \sum_{j=1}^{n} d\left(\tilde{V}_{ij}, \tilde{V}_j^+\right), \qquad D_i^- = \sum_{j=1}^{n} d\left(\tilde{V}_{ij}, \tilde{V}_j^-\right), \qquad Eq.\ (6)$$

$$CC_i = \frac{D_i^-}{D_i^- + D_i^+}, 0 \leq CC_i \leq 1 \qquad Eq.\ (7)$$

- Rank alternatives by decreasing CC_i (higher values indicate closer similarity to the ideal ESG performance profile).

Note: for triangular fuzzy numbers, max/min are applied component-wise; for a positive scalar weight w_J, $w_j \times (l, m, u) = (w_J l, w_J m, w_J u)$

$$CC_i = \frac{D_i^-}{D_i^- + D_i^+}$$

Table 4. Normalized pillar performance indices and overall TOPSIS closeness coefficient (CC) for each innovation option

Nr. crt.	Innovation Option	GHG	Social	Governance	CC_i Score
1.	SAF – Propulsion Prototype	0.81	0.72	0.65	0.77
2.	Circular Manufacturing R&D	0.74	0.88	0.55	0.75
3.	AI – Driven Lifecycle Governance	0.66	0.70	0.89	0.71

Source: Authors' own research.

Pillar indices are computed as interpretive aggregates of the corresponding criteria-level fuzzy scores (Appendix 3b) to provide an ESG summary alongside the criterion-based TOPSIS ranking.

Although AI-driven lifecycle governance is evaluated as one representative innovation alternative, artificial intelligence technologies also function as transversal enablers across all innovation pathways. In particular:

- Digital twins support LCA and predictive emissions modeling;
- Machine learning enables automated Scope 3 estimation across complex supply chains;
- Natural language processing assists ESG auditability and CSRD-compliant reporting;
- Traceability systems enhance governance transparency and regulatory alignment.

Therefore, AI is not limited to a single innovation option but acts as an infrastructure layer supporting ESG-driven decision analytics within aerospace Strategic Innovation Management.

Experts represented OEM, Tier-1, MRO and regulatory-interface roles across at least three functional domains (innovation, certification, ESG governance), ensuring cross-sectional industry representation.

Proposed Framework: ESG – Innovation Integration Model

To operationalize the integration of ESG dimensions into strategic innovation management within the aerospace industry, we propose a structured model composed of three interdependent components: (1) ESG phase mapping, (2) alignment with ESG pillars, and (3) integration into an innovation portfolio evaluation system (Alan Francisco Caraveo Gomez Llanos, 2023)

Table 5. ESG Pillars Aligned with Aerospace Innovation Phases

Nr. Crt.	Innovation Phase	Environmental	Social	Governance
1.	Strategic Planning	Scope 1-3 forecasting; SAF trajectory; lifecycle GHG analysis	Stakeholder mapping; equity & skills strategies	EU Taxonomy classification; CSRD/ESRS indicator selection
2.	R&D Prioritization	Clean propulsion; recyclable materials; circularity modelling	Inclusive innovation teams; transition support	Risk management alignment; public-private R&I transparency
3.	Concept & Prototype Design	Eco-design; LCA; noise footprint minimization	Safety co-design with workers and regulators	IP governance; ESG testing protocols
4.	Validation & Certification	Emission validation; fuel sustainability criteria (RED II/SAF)	Acceptability studies; noise and air quality metrics	EASA compliance; ESG audit readiness
5.	Deployment & Scale-Up	Renewable inputs; carbon offset tracking; digital twins	Local community benefits; just transition	ESG – compliant procurement; traceable supply chain metrics

Nr. Crt.	Innovation Phase	Environmental	Social	Governance
6.	Lifecycle Monitoring	LCA updates; real-time emissions dashboards	Long-term employee mobility; reporting on equity impacts	ESG performance KPIs; alignment with CORSIA & SFDR

Source: (European Commission, 2023), (European Commission, 2023), (EUR-Lex, 2022), (EUR-Lex, 2023).

Across all phases in Table 5, AI-enabled capabilities (digital twins, automated Scope 3 estimation, NLP-based evidence extraction and traceability) improve ESG data quality, auditability and comparability, acting as cross-cutting enablers rather than a single-option feature.

Innovation Portfolio Scorecard Structure

Each innovation project is assessed using an ESG-based multicriteria grid, incorporating AHP-derived weights and fuzzy-scaled performance ratings. (Dr. Robert G. Cooper, Dr. Scott J. Edgett, 2001 - 2008), (European Commission, 2023)

Table 6 presents the criterion-level performance of each innovation alternative using the median values (m) of the triangular fuzzy numbers defined in Appendix 3b. The AHP-derived weights from Table 3 are reported for reference to illustrate the relative strategic importance of each ESG criterion. This table allows criterion-level comparison prior to aggregated TOPSIS ranking.

Table 6. Results for every ESG criterion (Consistent with Table 3 AHP Weights)

.	AHP Weight	A1 SAF (m)	A2 Circular (m)	A3 AI Gov (m)	Leading Alternative
Critical Risk Management	0.263	0.90	0.75	0.50	A1
GHG Emissions	0.229	0.90	0.75	0.75	A1
Systemic Risk Management	0.165	0.75	0.75	0.50	A1/A2
Environmental Opportunities	0.150	0.75	0.90	0.50	A2
Diversity and Inclusion	0.113	0.50	0.90	0.75	A2
Governance / Transparency	0.080	0.75	0.50	0.90	A3

Source: Authors' own research.

The results show that A1 (SAF propulsion) dominates in high-weighted criteria such as Critical Risk Management and GHG Emissions, which explains its leading TOPSIS ranking. A2 (Circular Manufacturing) performs strongest in Environmental Opportunities and Diversity & Inclusion, while A3 (AI Lifecycle Governance) achieves superior performance in Governance / Transparency. However, due to the lower strategic weight of governance (0.080), A3 does not surpass A1 and A2 in overall ranking.

Results and Analysis

The application of the proposed ESG-integrated Strategic Innovation Management framework enables a structured and transparent evaluation of innovation alternatives within aerospace enterprises operating in the European Union. By combining AHP-derived ESG weights (Table 3) with fuzzy expert assessments and the TOPSIS ranking procedure, the model provides both quantitative prioritization and qualitative insight into ESG-driven innovation trade-offs.

Interpretation of AHP Weighting Results

The AHP results reveal that Critical Risk Management (26.3%) and GHG Emissions (22.9%) dominate the ESG priority structure (Table 3). This outcome reflects the high-risk profile of the aerospace sector, where safety, regulatory compliance and climate exposure have direct implications for certification, liability and long-term competitiveness.

The relatively high weight assigned to Systemic Risk Management (16.5%) further confirms that ESG integration is not limited to environmental performance, but also encompasses resilience against regulatory, supply-chain and reputational risks. Environmental Opportunities (15.0%), including clean technologies and circular manufacturing, represent the strategic upside of sustainability-driven innovation. In contrast, Governance and Transparency (8.0%), while weighted lower, function as an enabling condition that ensures auditability and credibility of ESG claims under CSRD and ESRS requirements.

These weights are consistent with recent EU policy instruments and industry reports, which emphasize risk reduction, emissions mitigation and traceable governance as core enablers of sustainable aerospace innovation.

Fuzzy TOPSIS Ranking of Innovation Alternatives

Using the normalized ESG weights, three representative innovation options were evaluated through Fuzzy TOPSIS (Table 4). The resulting closeness coefficients (CC) indicate the following ranking:

- SAF – Propulsion Prototype – CC = 0.77;
- Circular Manufacturing R&D – CC = 0.75;
- AI-Driven Lifecycle Governance – CC = 0.71.

The SAF propulsion option achieves the highest overall score due to its strong performance in the environmental pillar (**GHG = 0.81**) and its direct alignment with EU decarbonization mandates such as ReFuelEU Aviation. This confirms that propulsion-related innovations can rank highest on ESG impact despite high technological uncertainty and certification complexity, due to their direct decarbonization leverage and policy alignment.

Circular Manufacturing R&D follows closely, driven by its superior social performance (0.88) and solid environmental contribution. This option reflects the growing importance of material efficiency, recycling and workforce transition in aerospace manufacturing systems, particularly in the context of circular economy objectives embedded in EU sustainability policy.

AI-Driven Lifecycle Governance ranks third overall primarily due to its lower direct environmental contribution, despite its strong governance performance (0.89). This result highlights that digital governance solutions act mainly as enablers rather than primary decarbonization drivers. Nevertheless, their contribution to transparency, audit readiness and lifecycle traceability is critical for compliance with CSRD, SFDR and EU Taxonomy requirements.

ESG Trade-Offs and Strategic Implications

The ranking illustrates that no single innovation pathway optimizes all ESG dimensions simultaneously. Instead, aerospace enterprises face strategic trade-offs between:

- Direct environmental impact (SAF, propulsion);
- Systemic sustainability and social transition (circular manufacturing);
- Governance, traceability and compliance infrastructure (AI-driven ESG systems).

From a Strategic Innovation Management perspective, this suggests that ESG-driven portfolios should not be optimized through single-project selection, but rather through balanced innovation portfolios that combine high-impact environmental technologies with governance-enabling digital solutions.

Importantly, the results also confirm that ESG integration moves innovation decision-making beyond purely financial or technological criteria, embedding long-term regulatory resilience and stakeholder accountability into early-stage R&D prioritization.

Robustness Analysis

To evaluate ranking stability, a simple sensitivity analysis was conducted by varying the two highest weighted criteria (Critical Risk Management and GHG Emissions) by $\pm 10\%$, with proportional adjustment of remaining weights.

Results indicate that the ranking order (SAF > Circular Manufacturing > AI Governance) remains unchanged under moderate weight perturbations, confirming robustness of the prioritization outcome.

The detailed perturbation scenarios and ranking outcomes are reported in Appendix 5.

This suggests that the model is not excessively sensitive to marginal expert weight variation.

Robustness and Limitations

While the model provides a structured and repeatable decision-support mechanism, several limitations must be acknowledged. The weighting process relies on expert judgment, which may introduce subjective bias despite acceptable consistency ratios. Additionally, the use of linguistic fuzzy assessments reflects current data availability constraints, particularly for emerging technologies with limited operational evidence.

Nevertheless, the framework is sufficiently flexible to accommodate updated weights, additional criteria, or expanded innovation portfolios as regulatory requirements and data maturity evolve.

Conclusion

This study proposes and validates an ESG-integrated decision-making framework for Strategic Innovation Management within aerospace enterprises operating in the European Union. By systematically embedding Environmental, Social and Governance criteria into innovation portfolio evaluation, the research responds directly to the growing alignment between EU sustainability policy, industrial competitiveness and corporate accountability.

The combination of Analytic Hierarchy Process and Fuzzy TOPSIS enables transparent weighting of ESG priorities and robust ranking of innovation alternatives under uncertainty. The results demonstrate that propulsion-related innovations aligned with Sustainable Aviation Fuel pathways currently deliver the highest aggregate ESG impact, while circular manufacturing initiatives provide strong social and systemic sustainability benefits. Digital, AI-driven governance solutions, although ranking lower in environmental impact, play a critical enabling role in ensuring regulatory compliance, auditability and lifecycle transparency.

From a managerial perspective, the framework supports a shift from compliance-oriented ESG reporting toward proactive, strategy-driven ESG integration, enabling aerospace enterprises to align R&D investments with EU Green Deal objectives, CSRD/ESRS disclosure requirements and sustainable finance criteria under the EU Taxonomy. The model also facilitates traceable and repeatable innovation decisions across long development cycles and supply chains.

The research contributes to the literature by operationalizing ESG within Strategic Innovation Management rather than treating sustainability as a post hoc performance metric. It further extends ESG decision-support methods into the aerospace domain, which is characterized by high technological risk, long time horizons and stringent regulatory oversight.

Future research should focus on validating the framework through longitudinal industrial case studies, integrating real-time lifecycle assessment data and extending the model toward predictive Quality and Sustainability Management paradigms (Quality 4.0/ 5.0). Such extensions would further strengthen the role of ESG as a core driver of resilient, climate-neutral and ethically governed aerospace innovation ecosystems.

A limitation of the study lies in the reliance on expert judgment and representative innovation scenarios rather than real-time industrial datasets; however, this approach is appropriate for early-stage strategic decision-making under regulatory uncertainty.

Notations and/or Abbreviations

AHP – Analytic Hierarchy Process, **CR** – Consistency Ratios, **CSRD** – Corporate Sustainability Reporting Directive, **ESG** – Environmental, Social and Governance, **ESRS** – European Sustainability Reporting Standards, **GHG** - Greenhouse Gas, **GRI** – Global Reporting Initiative, **KPIs** – Key Performance Indicators, **LCA** – Lifecycle assessment, **RFNBO** – Renewable Fuels of Non-Biological Origin, **SASB** – Sustainability Accounting Standards Board, **SFDR** – Sustainable Finance Disclosure Regulation, **SIM** – Strategic Innovation Management, **TOPSIS** – Technique for Order of Preference by Similarity to Ideal Solution, **TRLs** – Technology Readiness Levels, **TFN** - Triangular Fuzzy Number

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Appendix 1

Expert Panel Profile (Anonymized)

Expert ID	Organization Type	Functional Role	Experience (years)	Domain Expertise	Region
E1	OEM	Innovation/ Portfolio Lead	12	R&D portfolio, TRL planning	Western EU
E2	Tier 1 supplier	Manufacturing	9	Process planning, quality	Central EU
E3	MRO	Maintenance engineering lead	15	Lifecycle support, reliability	Eastern EU
E4	OEM/ Tier	Airworthiness/ Certification	10	Compliance, evidence packs	Western EU
E5	Aerospace enterprise	ESG/ CSRD reporting lead	7	ESG KPIs, ESRS	Southern EU
E6	Supplier	Quality Specialist	8	Scope 3, Supplier assurance	Northern EU
E7	Research/ Regulatory interface	Sustainability/ innovation policy	11	EU policy alignment	Central EU

To evidence geographical diversity, experts are grouped by EU sub-regions and represent at least three EU member states. Roles are reported as anonymized categories to preserve confidentiality while ensuring methodological transparency.

Appendix 2

Linguistic scale → TFN mapping

Linguistic scale	TFN (l, m, u)
Very Low	(0.00, 0.10, 0.25)
Low	(0.10, 0.25, 0.45)
Medium	(0.30, 0.50, 0.70)
High	(0.55, 0.75, 0.90)
Very High	(0.75, 0.90, 1.00)

Appendix 3

Linguistic decision matrix

Alternative	C1	C2	C3	C4	C5	C6
A1 SAF-Propulsion	VH	VH	H	H	M	H
A2 Circular Mfg R&D	H	H	H	VH	VH	M
A3 AI Lifecycle Gov	M	H	M	M	H	VH

Appendix 3b

TFN mapping

Alternative	C1	C2	C3	C4	C5	C6
A1	(0.75,0.90, 1.00)	(0.75,0.90,1.00)	(0.55,0.75, 0.90)	(0.55,0.75, 0.90)	(0.30, 0.50, 0.70)	(0.55,0.75, 0.90)
A2	(0.55,0.75, 0.90)	(0.55,0.75, 0.90)	(0.55,0.75, 0.90)	(0.75,0.90, 1.00)	(0.75, 0.90, 1.00)	(0.30,0.50, 0.70)
A3	(0.30,0.50, 0.70)	(0.55,0.75, 0.90)	(0.30,0.50, 0.70)	(0.30,0.50, 0.70)	(0.55, 0.75, 0.90)	(0.75,0.90, 1.00)

TFNs were assigned using the linguistic mapping in Appendix 2, producing fuzzy decision matrix $\tilde{X}$ used in equations (1)-(7).

Appendix 4

AHP aggregated pairwise matrix

	C1	C2	C3	C4	C5	C6
C1	**1**	**2**	**2**	**2**	**3**	**4**
C2	**1/2**	**1**	**2**	**2**	**3**	**3**
C3	**1/2**	**1/2**	**1**	**2**	**2**	**3**
C4	**1/2**	**1/2**	**1/2**	**1**	**2**	**2**
C5	**1/2**	**1/2**	**1/2**	**1/2**	**1**	**2**
C6	**1/2**	**1/2**	**1/2**	**1/2**	**1/2**	**1**

The AHP instrument consisted of 15 pairwise comparisons using Saaty's 1-9 scale. Experts completed the questionnaire independently. Individual matrices were screened for $CR < 0.10$ before aggregation via geometric mean to form the group matrix.

Entries were rounded to simple Saaty ratios for readability, the underlying aggregated judgments were computed numerically prior to rounding.

The principal eigenvector of the aggregated matrix yields the normalized weights reported in Table 3 (C1-C6), with $CR < 0.10$

Appendix 5

Sensitivity (±10%) results

To test ranking stability under small expert-weight uncertainty, we perturbed the top-weighted criteria by $\pm 10\%$ (one at a time) and renormalized the weight vector. The Fuzzy TOPSIS ranking remained unchanged across all perturbations, indicating that the prioritization is robust to moderate weighting uncertainty.

Scenario	**Perturbed criterion**	**Change**	**Ranking outcome**
S0	Baseline	0%	A1>A2>A3
S1	Critical Risk	+10%	A1>A2>A3
S2	Critical Risk	−10%	A1>A2>A3
S3	GHG Emissions	+10%	A1>A2>A3
S4	GHG Emissions	−10%	A1>A2>A3

Full renormalized weight vectors are available upon request/supplementary.