MASTER THESIS

Preserving Eco-design and Circular Economy Principles in Aviation Technology Development

Developing EcoFlight, a TRL-staged decision guide for preserving eco-design and circular economy principles in technology development projects

A case study of cabin components

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Document details

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Preface

This thesis was written as the final deliverable of my Master Strategic Product Design at Delft University of Technology, faculty of Industrial Design Engineering, conducted in collaboration with Airbus Netherlands. The research addresses a problem I encountered early in my time at Airbus: environmental ambitions that are genuine at the start of a development project have a tendency not to survive the decision gates that govern how technologies mature. Understanding why that happens, and what a designer can do about it, became the central question of this work.

This question brought me into the real aviation industry, taking part in conversations with practitioners across the full aviation value chain, from cabin engineers and material specialists to maintenance operators and end-of-life recyclers. Those conversations shaped how I conducted the research: learning and executing at the same time, while being embedded in the ecosystem I was studying.

Coming into this project, I had three personal goals. The first was to understand what working in a large corporate environment feels like from the inside, how decisions are made, where ambitions live, and where they get lost. The second was to deepen my knowledge of the aviation industry, a sector I find fascinating for the tension it holds between technical sophistication and a, in all honesty, slow pace of change. The third, and most important, was to find out whether two apparently contradicting things, aviation and sustainability, could go hand in hand. The answer I found is yes, but only when the right people have the right tools, at the right moment.

One of the things I also wanted to investigate is enabling people to act on ideas they already believe in. The barrier this research kept uncovering was not a lack of ambition but a lack of guidance: practitioners who want to do the right thing but do not know how to make it survive the systems they work for. EcoFlight is my attempt to change that, even if only in a small way, and even if the full effect of that change will take longer to see than this thesis allows.

The output of this thesis is twofold: a written analysis of the barriers and conditions that prevent eco-design and circular economy principles from surviving technology development projects, and EcoFlight, a digital interactive decision guide developed to equip practitioners with the framing and methods needed to defend those principles at the moments that matter most.

I would like to thank my supervisors at TU Delft, Shahrokh Nikou and Jelle Joustra, for their guidance, critical feedback, and continued support throughout this process. Their ability to challenge my thinking while trusting my direction made this research significantly stronger. My gratitude also goes to my Airbus supervisor Mrinal Chaudhury, whose practical grounding, industry access, and genuine investment in this project made the collaboration feel like a real partnership. Also, this research would not have been possible without the practitioners who agreed to be interviewed, and helped me during the development of EcoFlight, with their honest and valuable feedback. Their willingness to share what works is what gave this research its empirical depth. Finally, I am grateful to the entire team at Airbus, who welcomed me into their work and office as a real colleague.

Boaz van Lith, Leiden, June 2026

Executive Summary

The global aviation industry faces increasing pressure to reduce its environmental footprint across the full lifecycle of its products, not only through fuel efficiency gains, but through the materials consumed and discarded in the development, operation, and disposal of aircraft components. The aircraft cabin sits at the center of this challenge: 47% of cabin material by weight is currently sent to landfill or incinerated, and the design decisions that determine how much can be recovered are locked in long before a component enters service. Eco-design and circular economy (CE) principles offer a structured way to address this at the source. The problem is that they rarely survive the decision logic that governs aviation technology development projects.

This research investigates why that happens and what practitioners can do about it. The empirical context is the CIRCADIS consortium, a cross-industry collaboration developing a circular thermoplastic overhead stowage compartment door across technology readiness level (TRL) 2 to 5. The main research question is: *how can eco-design and circular economy principles be preserved in TRL-based aviation technology development?* A structured literature review, market analysis, and 17 semi-structured expert interviews across the cabin component value chain established that 20 barriers and conditions, categorized in informational, organizational, regulatory, and commercial domains, challenge environmental criteria as technologies mature.

That finding shaped the design phase. The resulting output, EcoFlight, is a publicly accessible browser-based decision guide structured around three phases: Awareness, which presents the revised barrier and condition typology with an AI-assisted module generating a personalized shortlist; Operationalize, which maps thirteen methods and tools to barrier types and TRL stages; and Justify, which presents conditions under which environmental criteria have survived gate decisions in real aviation development projects, each with practitioner framing notes. These three phases address what existing eco-design and CE tools only partially resolve: most were developed for general contexts, assume data availability that does not exist at early TRL stages, and offer limited guidance on translating environmental criteria into commercial language.

A validation session with eight CIRCADIS practitioners provided initial evidence that EcoFlight was usable, the barrier typology was recognizable, and the commercial framing was perceived as very relevant in the industry's context. These findings reflect perceived relevance after a short, facilitated session, and do not yet demonstrate effectiveness in a live development project, which will need to be further researched.

The final prototype of EcoFlight is designed to improve how eco-design and CE principles are preserved in TRL-based aviation technology development by equipping practitioners with stage-scaled visibility of defensible criteria, operationalizable methods for identifying viable strategies, and commercial framing that justify environmental ambitions to the stakeholders who govern gate decisions. It does so without requiring practitioners to reform the existing technology development logic itself, working within the informational, organizational, regulatory, and commercial constraints that currently govern aviation, rather than against them.

Glossary

CE	Circular Economy
DPP	Digital Product Passport
EASA	European Union Aviation Safety Agency
ESPR	Ecodesign for Sustainable Products Regulation
EU ETS	European Union Emissions Trading System
FST	Fire, Smoke and Toxicity
ICAO	International Civil Aviation Organization
IP	Intellectual Property
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
MRO	Maintenance, Repair, and Overhaul
OEM	Original Equipment Manufacturer
OHSC	Overhead Stowage Compartment
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals regulation
R&T	Research and Technology
SAF	Sustainable Aviation Fuel
SFE	Seller-Furnished Equipment
TRL	Technology Readiness Level

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CHAPTER ONE

Introduction

The aviation industry's environmental footprint reaches well beyond fuel burn, into the materials and components that make up the cabin, and the design decisions that lock in their fate long before they enter service.

1.1 The aviation industry

The global aviation industry is well-known for its high environmental impact. It contributes to around 2.5% of global CO_2 emissions, and when non-CO_2 effects such as contrails and nitrogen oxides are included, its total contribution is even higher (Lee et al., 2021). Despite this, air traffic volumes have continued to grow, and projections suggest that without structural intervention, industry growth will outpace efficiency gains, making net-zero targets unachievable through operational improvements alone (Gössling & Humpe, 2020; Larsson et al., 2019). Innovations focused on decreasing the environmental impact of the industry, such as sustainable aviation fuel (SAF) and next-generation propulsion technologies remain commercially immature within the timelines set by policymakers. Additionally, the industry's characteristically low profit margins also limit the funds available for such a large-scale transition (Gössling & Humpe, 2024). Meanwhile, discussions initiating that innovative propulsion technologies will resolve aviation's environmental challenges, have shown to discourage more strict regulatory responses (Peeters et al., 2016).

Pressure to address and lower the environmental impact of this industry is nonetheless intensifying from multiple directions. 70% of airlines have committed to cutting CO_2 emissions by 50% by 2050, reflecting the degree to which sustainability has entered strategic planning at the industry level (Airbus, 2020). Socially, the public's view of aviation's environmental footprint has sharpened, with sustainability now being a consideration for 51% of travelers when choosing an airline (WTCE, 2026). And while in-flight operational emissions, directly related to fuel-use, have historically received the most attention, this pressure is beginning to extend to non-operational factors: the resources consumed and waste generated in the creation, maintenance, and disposal of aircraft and their components (EASA, 2023a; ICAO Secretariat, 2019; Papadaki & Maleviti, 2025).

1.2 The aircraft cabin

Consequently, the aircraft cabin has also emerged as a new focus point for sustainability, where domains such as recyclability, end-of-life waste, passenger-facing sustainability and weight reduction allow for significant improvements compared to the current state-of-the-art (Bachmann et al., 2021; EASA, 2023a; WTCE, 2026). In absolute terms, tens of thousands of tonnes of cabin material are consumed and reduced to waste each year, and the design decisions that determine how much of that material can be recovered are made long before a component ever enters service (Aerospace Technology Institute, 2022). Over the past decade, an average of 750 commercial aircraft per year have retired, a figure projected to rise to between 1,000 and 1,500 in the coming years following the post-COVID acceleration of fleet renewal (Aerospace Technology Institute, 2022). Approximately 47% of all cabin products by weight are currently not being recycled, which as an alternative, are being sent to landfill or incinerated (Aerospace Technology Institute, 2022). Unlike structural components such as engines and landing gear, which retain high salvage value and are structurally gathered at end-of-life, cabin components offer limited recovery incentives, meaning their material fate is currently largely decided by compliance-driven actions.

Compared to environmental impact driven by fuel-burn, the cabin's absolute footprint may appear modest. Yet its potential areas of impact are nonetheless significant: the waste volumes, high replacement frequencies, and its distinct positioning as the only part of the aircraft that passengers directly experience (Moreira et al., 2014; WTCE, 2026). In addition, the volume of parts replaced during Maintenance, Repair and Overhaul (MRO) operations and the relatively accessible nature of cabin

components, make it a great fit as a system to innovate and improve, compared to structural or propulsion systems (Bik, 2025; EASA, 2023a; Meng et al., 2020; Rutkowski, 2022; Santos et al., 2016).

To conclude, the decisions embedded in the development projects of future cabin components carry forward potential environmental value. The early design stages cover when and how these decisions are set in place, making it the most influential and consequential moment in the cabin's lifecycle (Aerospace Technology Institute, 2022). Addressing those decisions in a structured way, across the full value chain from materials suppliers to end-of-life specialists, is where eco-design and circular economy principles become directly relevant.

1.3 Defining eco-design and circular economy

These two related, but distinct concepts are used throughout this research. Eco-design is defined by ISO 14006:2020 as the integration of environmental aspects into the earliest stages of product design and development, with the aim of reducing environmental impacts throughout a product's entire life cycle (ISO, 2020). The circular economy (CE) (Figure 1) aims at shifting from a linear take-make-dispose model toward one in which materials and components are kept in use for as long as possible through strategies such as reuse, remanufacturing, and recycling (Ellen MacArthur Foundation, 2015; Konietzko et al., 2020). Although the two concepts operate at different levels, they are connected: because a product's circularity is largely determined by the design decisions made at the start of its lifecycle, applying eco-design principles is the primary means through which CE strategies can be enabled in practice (Ellen MacArthur Foundation, 2015; Joustra, 2022).

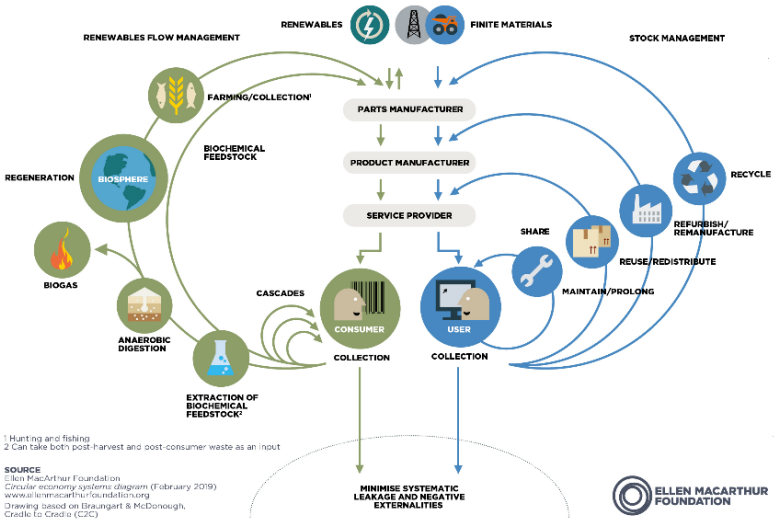

FIGURE 1: *The Circular Economy Butterfly Diagram (Ellen MacArthur Foundation, 2015)*

Within this research, these principles are defined at three levels of specificity. CE principles are the highest-level objectives, such as preserving natural resources, designing out waste, and keeping materials in use (Kirchherr et al., 2017). Strategies are the operational approaches used to execute those principles, including reuse, remanufacturing, and recycling, ordered within a hierarchy by their capacity to retain material value (Joustra, 2022; Saidani, 2019). Design guidelines are product-level rules that translate strategies into concrete design decisions, such as minimizing material complexity or using reversible connections to enable disassembly (Hallstedt, 2017; Joustra, 2022). It is at this level that eco-design operates in practice. Figure 2 illustrates these three levels and their relationship.

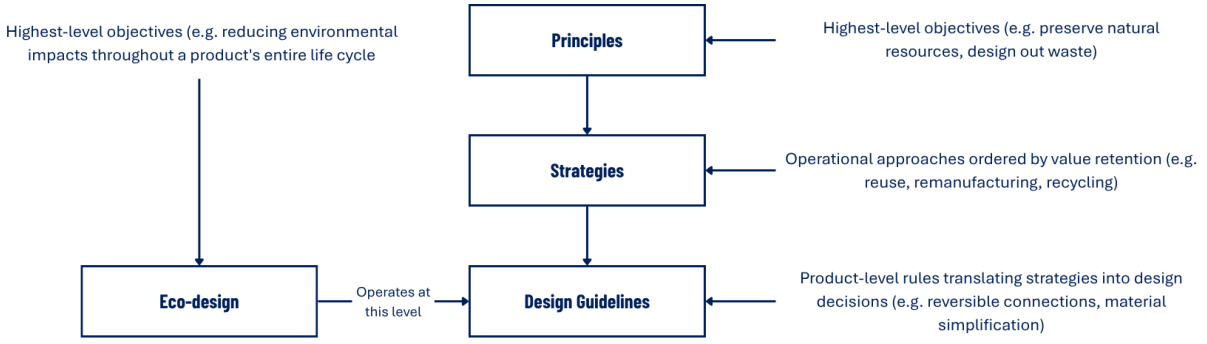

FIGURE 2: *Circular Economy Framework*

However, in commercial aviation and cabin practice, the application of these concepts is significantly narrower than their definition. Because the operational use phase accounts for up to 98% of an aircraft component's total lifecycle emissions, eco-design in aviation is practically reduced to weight reduction (Bachmann et al., 2017; Keiser et al., 2023). CE strategies, if applied at all, concentrate at the lower end of the hierarchy, resulting in recycling and energy recovery, rather than applying high-value strategies such as reuse or remanufacturing (Paletti et al., 2025; Papadaki & Maleviti, 2025). The challenge this research addresses is therefore not one of ambition but of operationalization: ensuring that the full range of eco-design guidelines and CE strategies, beyond weight alone, can survive the gate-based decision logic that governs aviation technology development.

1.4 Aviation technology development

Aviation technology development is structured around stage-gate processes that rely on Technology Readiness Levels (TRLs) to manage technical maturity and associated risks. These levels track the maturity of a technology from early conceptual research at TRL 1 through full operational deployment at TRL 9 (Mankins, 1995), as summarized in Figure 3.

EARLY	TRL 1	Basic principles observed and reported
	TRL 2	Technology concept and/or application formulated
	TRL 3	Analytical and experimental critical function and/or characteristic proof-of-concept
MID	TRL 4	Component and/or breadboard validation in laboratory environment
	TRL 5	Component and/or breadboard validation in relevant environment
	TRL 6	System/subsystem model or prototype demonstration in a relevant environment (ground or space)
LATE	TRL 7	System prototype demonstration in a space environment
	TRL 8	Actual system completed and "flight qualified" through test and demonstration (ground or space)
	TRL 9	Actual system "flight proven" through successful mission operations

FIGURE 3: *Original TRL Summary developed at NASA (Mankins, 1995)*

At each gate, a technology must adhere to defined criteria before advancing to the next development phase. Those criteria were historically built around technical performance, safety, and cost, with environmental value absent from the core assessment logic. Iterations of the TRL framework, while introducing risk matrices and strategic prioritization tools, have not changed this fundamental

structure (Hallstedt & Pigosso, 2017; Mankins, 2009). In practice, a technology is typically validated through a specific product application. The gate criteria governing its maturity are therefore evaluated at the product level, where design decisions determine whether the environmental potential is preserved or lost.

The consequence for preserving eco-design and CE principles throughout a TRL-based trajectory is that these must compete against well-established technical and regulatory benchmarks for which the evidence base is far more developed. That tension, between when environmental criteria could most usefully influence design, and when the evidence to justify them exists, is one of the central themes throughout this research.

1.5 Introduction to Airbus and CIRCADIS

Multiple companies, including Airbus, use TRLs as a standard internal framework to assess the maturity of their technologies. Airbus is one of the world's leading commercial aircraft manufacturers, responsible for approximately half of all civil airliners delivered globally (Airbus, 2025). At a strategic level, Airbus has established formal sustainability commitments, including dedicated initiatives, greenhouse gas reduction targets, and an ambition to bring the world's first zero-emission commercial aircraft (during operations) to market by 2035 through its ZEROe program (Airbus, 2025). In current operational practice however, sustainability efforts have concentrated on lightweighting and aerodynamic efficiency, with one of the latest aircraft generations (Airbus A320neo, A330neo) achieving 20-25% CO_2 reductions per seat primarily through advanced lightweight materials, such as carbon composites (EASA, 2023a). Despite these achievements, translating the strategic sustainability ambitions into criteria and tools that govern day-to-day technology development remains an active challenge: eco-design and CE principles must be operationalized within an ecosystem that is historically built around technical performance, cost, and safety, and where the evidence base for environmental criteria is significantly less developed.

The Circular Cabin Disruptive (CIRCADIS) project operates directly within this ecosystem. CIRCADIS is a cross-industry consortium in which Airbus is a leading partner, bringing together material suppliers, component manufacturers, airlines, and knowledge institutions to develop a circular, lightweight overhead stowage compartment (OHSC) door based on thermoplastic composites. Operating between TRL 2 and TRL 5, the project spans the early- to mid-stages of technology development, where design freedom is highest and fundamental material and configuration choices are still open. The project targets measurable reductions in weight, fuel consumption, and operational maintenance costs, with the expectation that if thermoplastic composites and circular design strategies prove viable within aviation certification requirements, the resulting strategies and solutions could be scaled to other cabin components, contributing to a broader transition toward more sustainable cabin interiors.

The CIRCADIS consortium also serves as empirical context for this research. Its cross-industry structure places a wide range of practitioners within direct reach, providing the necessary sparring partners and domain expertise. In that sense, CIRCADIS functions as a living laboratory: a real, active TRL-based development project embedded in the commercial aviation ecosystem. It should be noted, however, that CIRCADIS represents a more collaborative and sustainability-conscious development environment than is standard across the industry. That distinction is valuable because as the consortium creates conditions more favorable to eco-design and CE principles than a typical program

would, it surfaces best practices, enabling conditions, and transferable examples that could benefit future projects with similar ambitions, operating under less favorable circumstances.

1.6 Research and design gap

As aviation's environmental footprint is significant and growing, the industry faces increasing pressure to reduce this across the full lifecycle of its products, not only through operational efficiency gains. Eco-design and CE principles offer a structured way of addressing the environmental footprint at the source, by enabling or facilitating these into the early stages of design. Despite this potential, and growing attention to these principles in both literature and industry practice, a structured approach to preserving them through TRL-based projects does not yet exist for cabin technology development.

Existing methods and tools, including lifecycle assessment (LCA) methodologies and sustainability screening tools, were largely developed for general manufacturing contexts and assume levels of data availability that do not exist at early TRL stages (Bovea & Pérez-Belis, 2012; Chebaeva et al., 2021). In aviation's TRL-based development context, this insufficiency is compounded by certification requirements and gate logic built around technical performance and weight (Hallstedt & Pigosso, 2017; Mankins, 1995). Teams working on technologies applied to cabin components therefore lack a decision guide that is operationalizable within these constraints, validated against the realities of aviation technology development, and capable of translating eco-design and CE principles into terms that survive the current structure of TRL gate reviews.

This research addresses that gap along two lines. The first is analytical: diagnosing the specific barriers and conditions present, that cause eco-design and CE principles to be deprioritized across TRL stages in aviation technology development applied to cabin products. The second is more practical and addressed by designing a solution: developing a decision guide that equips practitioners to preserve those principles at the moments that matter most, without requiring adaptations to the TRL framework that is currently in place. The CIRCADIS project provides the development context in which both lines of inquiry are grounded.

1.7 Research objectives and questions

The challenge this research addresses is not one of ambition but of operationalization: ambitions that do exist are challenged by the decision logic that governs how aviation technologies mature. Addressing this requires both a diagnostic and a design response. The first, analytical objective is to diagnose the specific barriers and conditions that cause eco-design and CE principles to be deprioritized across TRL stages in aviation technology development, with a specific focus on cabin components. The second, design objective is to translate those findings into a practical, interactive decision guide for practitioners that builds awareness of the barriers and conditions they are likely to encounter, provides operationalizable methods to navigate them, and equips them with the framing needed to make environmental criteria legible to the stakeholders who govern gate decisions.

Based on the context, gap, and objectives described above, the following main research question (MRQ) guides this research:

> **How can eco-design and circular economy principles be preserved in TRL-based aviation technology development?**

Together, the four subquestions below address the analytical and practical dimensions of the main research question.

SUBQUESTION 1 What eco-design and CE principles are relevant to cabin components?
This question investigates the current state of the art in eco-design and circular economy principles, within the context of the aviation industry and cabin interiors.

SUBQUESTION 2 What criteria currently drive decision-making at TRL gates in aviation technology development?
This question investigates the criteria and priorities that currently govern TRL-based decision-making, building a clear understanding of the existing gate logic against which eco-design and CE principles must compete.

SUBQUESTION 3 What barriers and conditions cause eco-design and circular economy principles to be deprioritized during aviation technology development?
This question examines the barriers and conditions that prevent eco-design and CE principles from surviving gate decisions, and explains why this gap persists despite growing sustainability ambitions.

SUBQUESTION 4 What characteristics must a decision guide possess to effectively support practitioners in preserving eco-design and circular economy principles throughout TRL-based development projects?
This question derives the characteristics of existing methods and tools from both the literature and interview findings, ensuring that the resulting design is operationalizable within the constraints of commercial aviation technology development.

1.8 Approach

This research was conducted in three phases, each building on the output of the previous (Figure 4). The explorative phase establishes the theoretical and contextual foundation through a structured literature review and market analysis, presented in chapters 2 and 3. The qualitative phase extends and validates those foundations through 17 semi-structured expert interviews across the cabin component value chain, with the methodology in chapter 4 and findings in chapter 5. The design phase synthesizes both into a practical decision guide, documented in chapter 6.

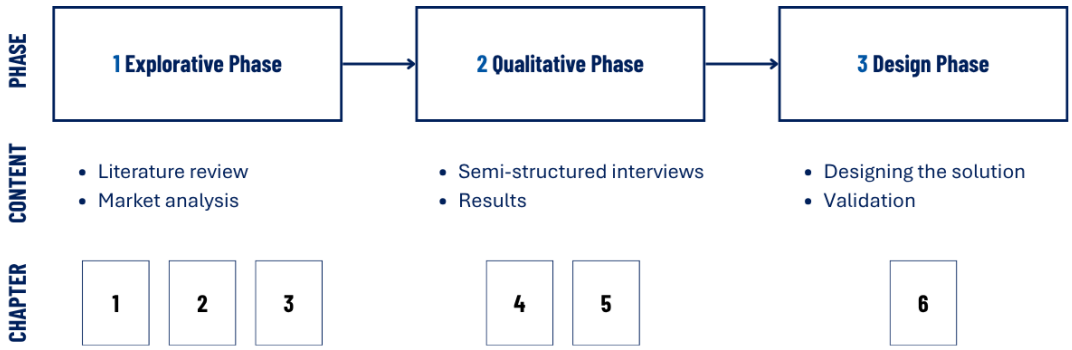

FIGURE 4: *Three-phase approach*

The thesis closes with a discussion of the findings and their implications in chapter 7, followed by the conclusion in chapter 8 and a reflection in chapter 9.

02

CHAPTER TWO

Literature Review

What existing research reveals about the eco-design and circular economy principles, the gate logic that governs aviation technology development, and why environmental criteria struggle to survive it.

2.1 Approach

The following sections present the findings of the literature review, organized around the four subquestions. The first three subquestions establish the foundation for the theoretical framework presented in section 2.5. The fourth subquestion derives the initial characteristics from existing literature, that informs the design of the decision guide developed in chapter 6.

A structured search was conducted using Web of Science (WoS), with seven queries covering the themes relevant to the research questions. The full query strings and exclusion keywords are listed in appendix A. Following the approach used by Hallstedt et al. (2023), four guiding themes were derived directly from the research questions to structure both the selection and analysis of papers: the eco-design and CE principles relevant to cabin components; the source's engagement with TRL-based or stage-gate development logic; the barriers and conditions relevant to preserving eco-design and CE principles; and the characteristics of existing methods and tools. This structure directly informed the organization of the sections in this chapter.

After filtering, the combined results were reduced to 88 papers, from which 15 were selected for detailed review based on title and abstract screening (see Figure 5). Selection was guided by the degree to which each paper engaged with at least one of the four themes; papers addressing contexts too distant from the aviation ecosystem, or too specific to mechanical properties such as engine parts, were excluded. These were supplemented with an additional 29 articles through backward and forward snowballing, capturing foundational literature on eco-design, CE, TRLs, and aviation technology development, as well as practitioner-oriented and grey literature sources suggested by experts.

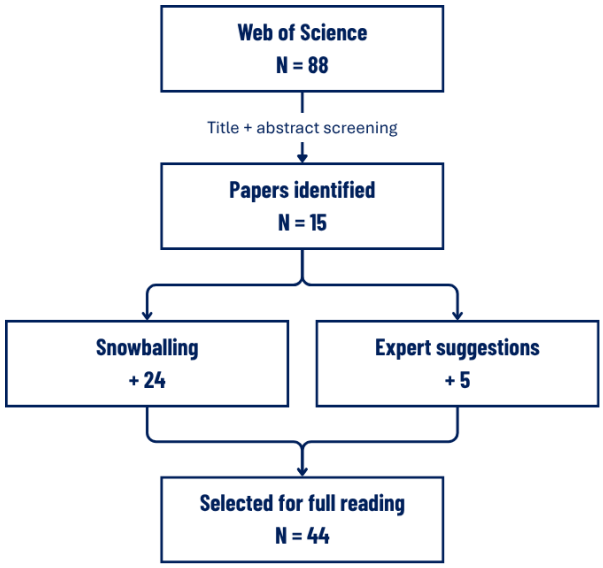

FIGURE 5: *Selection of Literature*

2.2 Eco-design and CE principles

As established in section 1.3, CE principles operate as systemic objectives for managing material value across a product's full lifecycle, and eco-design provides both the method through which those principles are embedded into product development, and the overarching goal of lowering products or technologies environmental impact. This section therefore examines the specific CE principles,

strategies and (eco-)design guidelines that the literature identifies as relevant to cabin components, closing with an assessment of how their application in aviation diverges from standard definition.

The CE strategies that operationalize the CE principles are structured around the goal of keeping materials in closed loops for as long as possible, ordered by their capacity to retain material value. The R-strategy hierarchy orders these from highest to lowest value retention: slowing-loop strategies such as reuse and remanufacturing preserve the most value, while closing-loop strategies such as recycling and energy recovery represent a last resort (Kirchherr et al., 2017; Konietzko et al., 2020; Mügge et al., 2023). Paletti et al. (2025) map this hierarchy onto aviation practices through the operationalization of the ISO 59004:2024 CE standard, ranging from minimizing newly extracted materials and rethinking component design down to recycling as a final intervention. Joustra (2022) adds structural reuse as a strategy specific to composites, retaining components at full structural value rather than shredding them, enabled by design aspects such as embedded markers and design for segmentation. The CE strategies referenced throughout this section are mapped to the full R-strategy hierarchy in Appendix B.

Translating CE strategies into product-level decisions requires a set of design guidelines, and it is at this level that eco-design operates in practice. For cabin interiors, the literature identifies several recurring categories. Design for disassembly is a precondition for any reuse or remanufacturing strategy, requiring reversible connections and the avoidance of permanently bonded assemblies to enable non-destructive component removal (Joustra, 2022; Papadaki & Maleviti, 2025). Material selection guidelines emphasize limiting material complexity within an assembly and substituting thermoset matrices with recyclable thermoplastic alternatives, directly improving end-of-life recoverability (Bachmann et al., 2017; Carvalho et al., 2025). Modularity and accessibility, grouping components into sub-assemblies that align with maintenance intervals, also support repairability and component-level reuse (Papadaki & Maleviti, 2025). Material traceability through digital twins or digital product passports enables the entire supply chain to identify material composition and make informed end-of-life decisions (Mügge et al., 2023; Preut et al., 2021; Wiesner et al., 2025). A full overview of the design guidelines identified in the literature, including their associated design aspects, enabled CE strategies, and supporting sources, is provided in Appendix C.

In practice, the aviation sector's application of these strategies is concentrated around the lower end of the hierarchy. For cabin interiors and composite components specifically, applying CE strategies largely results in downcycling into other industries or energy recovery, while higher-value strategies such as reuse and remanufacturing remain underexplored (Bachmann et al., 2021; EASA, 2023a; Paletti et al., 2025; Vogiantzi & Tserpes, 2023). In line with its strategic sustainability goals, Airbus has begun researching the repurposing of end-of-life aircraft materials, with one example being the reuse of an A380 panel in an A320neo (Airbus, 2026), but these efforts remain isolated, with recertification representing a key unresolved barrier for actual industrialization.

These principles, strategies and design guidelines show that a comprehensive basis for eco-design and CE exists in literature. Their application, however, collapses towards a single metric: weight. With the significant impact of the use-phase shown in LCA studies, up to 98% of an aircraft's total environmental impact, lightweighting becomes the dominant, measurable, eco-design criterion (Bachmann et al., 2017; Keiser et al., 2023; Vidal et al., 2018). But should lower-emission propulsion technologies become commercially viable, the use-phase would no longer dominate the lifecycle impact profile, shifting attention toward manufacturing and end-of-life decisions (Lohawala & Wen, 2024). The full range of eco-design and CE applications identified therefore also carries importance

for the longer term, next to the smaller, but in absolute terms still significant, impact it could already have on the current ecosystem. Why that gap persists, and how the development processes that govern aviation technology projects shape the prioritization of these principles, is the question that section 2.2 begins to address.

2.3 TRL-based decision logic

The TRL framework structures technology development from conceptual research at TRL 1 through full operational deployment at TRL 9, with gate criteria historically built around technical performance, safety, and cost (Mankins, 1995). In practice, the nine levels can be clustered into three phases: early stages (TRL 1-3), where design freedom is highest but available data is most limited; mid stages (TRL 4-6), where key design decisions are progressively locked in through component and system-level testing; and late stages (TRL 7-9), covering full-scale demonstration and deployment (Chebaeva et al., 2021; Mankins, 2009). The transition from TRL 6 to TRL 7 represents a critical threshold: Mankins (1995) describes this shift as moving away from pure technology research, toward assuring system engineering and management confidence. This threshold coincides with a potential transfer of decision authority: as this transition moves from technological exploration toward industrialization, decisions also shift towards more senior management whose mandate is defined by financial risk, schedule, and market viability (Bansal & Grewatsch, 2020; Hallstedt & Pigosso, 2017). The implications of this project handover for eco-design and CE integration are further validated with industry practitioners in chapter 5.

The criteria evaluated at TRL gates are well-established, and existing literature highlights that environmental performance is largely absent from them. At early stages, gate decisions focus on technical feasibility, proof of concept, material screening, and risk assessment, managing high uncertainty through qualitative criteria rather than detailed assessments (Chebaeva et al., 2021; Hallstedt & Pigosso, 2017; Mankins, 1995). As technologies mature into mid stages, the focus shifts toward system integration, structural performance, cost projections, and manufacturability, reflecting the transition from concept validation toward engineering reality (Chebaeva et al., 2021; Mankins, 1995; Santos et al., 2016). At late stages, the dominant criteria become operational qualification and regulatory certification, where airworthiness, FST compliance, and fatigue standards must be satisfied before deployment (Carvalho et al., 2025; Mankins, 1995). Where environmental considerations do appear at gate reviews, they follow a similar progression: qualitative sustainability targets and hazardous substance checklists at early stages give way to some environmental performance indicators at mid stages, often dominated by weight targets, and only at late stages full lifecycle assessments become possible, precisely when often, structural changes are no longer viable (Chebaeva et al., 2021; Hallstedt & Pigosso, 2017). Environmental criteria therefore appear at decision gates in a form that is consistently behind the design decisions they would need to inform.

This pattern has a theoretical explanation: the eco-design paradox. The eco-design paradox (Figure 6) describes the tension between design freedom and data availability in technology development processes: the greatest opportunity to embed environmental criteria, occurs at the earliest TRL stages, precisely when data availability is lowest and uncertainty is highest (Chebaeva et al., 2021; Poudelet et al., 2012).

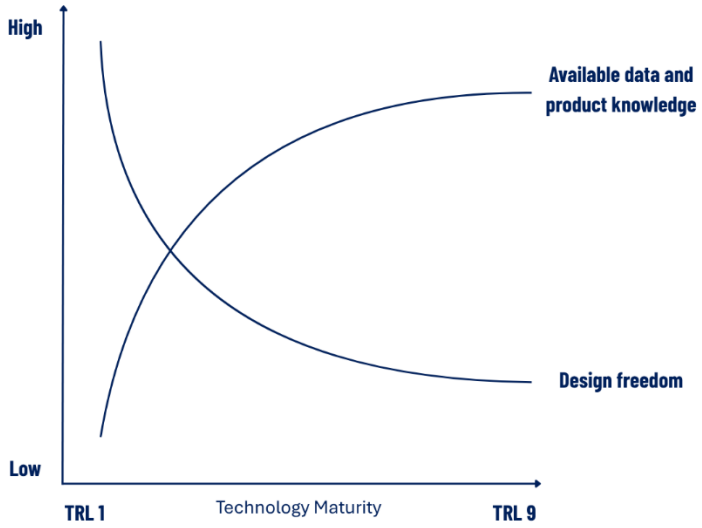

FIGURE 6: *Eco-design paradox in technology development, derived from Poudelet et al., 2012*

The information that determines whether CE strategies are achievable, including lifecycle impacts of new materials, end-of-life recovery rates for novel composite formulations, and disassembly performance of untested connection types, remains unavailable at precisely the stages when design decisions are still open (Chebaeva et al., 2021; Hallstedt & Pigosso, 2017). Structural and performance data from previous technology generations may offer partial guidance, but environmentally relevant data for new materials and configurations matures much later. The result is a persistent knowledge gap at the stages where it matters most.

Taken together, the findings of this section provide a preliminary answer to subquestion 2. TRL gate decisions in aviation technology development are governed by technical performance, weight, cost, and certification criteria, with environmental performance appearing at gates in a form that consistently lags behind the design decisions it would need to inform. The barriers conditions that prevent eco-design and CE principles from competing with these existing criteria as technology matures, are examined in section 2.3.

2.4 Barriers and conditions

Three compounding barrier and condition categories were derived from literature, which explain why eco-design and CE principles are not preserved as technologies mature. Each category operates at a different level: informational barriers and conditions at the data level, organizational ones at the level of the development process and value chain, and regulatory ones at the level of the certification and compliance environment. A full overview of the barrier typology with their supporting sources for each specific barrier is provided in Appendix D.

At the data level, the informational barrier is a structural deficit that makes it hard to defend environmental criteria at gate reviews, where factual standards are high. The eco-design paradox, as established in section 2.2, ensures that the stages where design decisions are still open are precisely the stages where lifecycle impact data for new materials, end-of-life recovery rates for composite formulations, and disassembly performance of untested connection types remain unavailable (Bachmann et al., 2017; Chebaeva et al., 2021). By the time such data exists, the design is effectively frozen. The problem compounds further along the value chain: as components move between stakeholders, material composition data, lifecycle history, and recycled content information are

routinely lost, the result of fragmented databases, manual data exchange practices, and incompatible IT systems across the supply chain (Mügge et al., 2023; Wiesner et al., 2025). Without reliable traceability, operators and dismantlers cannot assess the quality or compositions of components at end-of-life, making closed-loop strategies such as recycling practically impossible, regardless of what early-stage design intentions had specified.

That data fragmentation does not exist in isolation; it is both produced and reinforced by the organizational structures surrounding it. Enabling CE strategies requires coordinated action across stakeholders with different incentives, including OEMs, airlines, MRO operators, and end-of-life specialists, yet the development process concentrates decision-making within design teams at precisely the stages where end-of-life and maintenance actors would need to have input (Konietzko et al., 2020; Wiesner et al., 2025). OEMs focus almost entirely on the early lifecycle and operational phases, while end-of-life actors are excluded from early design, meaning that dismantling and recyclability insights are never fed back into the decisions that determine whether those strategies are achievable (EASA, 2023a; Wiesner et al., 2025). These organizational silos are deepened by IP concerns and a lack of data-sharing culture, with companies unwilling to share material formulations with supply chain partners, and lower-tier or smaller suppliers being simply not used to tracking or providing environmental data (Dekoninck et al., 2016; Fischer et al., 2024). Within the development process itself, these structures are reinforced by organizational cost efficiency: gate criteria reward incremental, low-risk projects instead of circular strategies that carry higher upfront costs and longer development timelines (EASA, 2023a; Santos et al., 2016).

Even where data exists and organizational will is present, certification requirements frequently act as a barrier. The aviation regulatory framework, designed around safety rather than resource recovery, makes certification of recycled or bio-based materials difficult: bio-composites often fail to meet fire-safety standards, and recycled composite formulations frequently degrade mechanical properties to the point where airworthiness requirements cannot be satisfied (Bachmann et al., 2017; Carvalho et al., 2025). Component reuse faces a distinct but related barrier, as recertification demands are administratively and financially difficult enough to make recovery of existing parts unviable compared to replacement with virgin materials (EASA, 2023a; Papadaki & Maleviti, 2025). Unlike the automotive sector, aviation currently lacks binding end-of-life regulations or extended producer responsibility mandates that would counterbalance these costs (EASA, 2023a). That regulatory absence interacts directly with organizational decision-making: without a legal mandate to justify investments in CE strategies, decision-makers have a defensible and financially grounded reason to reject sustainable options, regardless of what the design team had originally intended (Bansal & Grewatsch, 2020; Papadaki & Maleviti, 2025).

These three categories form a compounding structure that makes it difficult to preserve eco-design and CE principles in technology development. Missing lifecycle data makes it impossible to build the evidence base that organizational gatekeepers would need to defend environmental criteria; organizational silos ensure that the data that does exist never reaches the actors who could act on it; and certification requirements eliminate options that managed to survive both.

2.5 Characteristics of existing methods and tools

The identified barriers and conditions result in a challenging environment, that existing tools and methods have not yet resolved. Those that were developed to support sustainable product or technology development, share a structural limitation: most were designed for general manufacturing

contexts and assume levels of data availability that do not exist at early TRL stages, making them unavailable where design freedom is highest (Bovea & Pérez-Belis, 2012; Chebaeva et al., 2021; Poudelet et al., 2012). Byggeth and Hochschorner (2006) identify a related weakness in trade-off handling: most tools can identify environmental priorities but provide no structured mechanism for negotiating them against technical or commercial constraints at decision points.

Researchers have proposed several frameworks to address this gap. Hallstedt and Pigosso (2017) map sustainability criteria onto Technology Readiness Assessments, guiding teams from qualitative targets and material criticality assessments at early stages toward quantitative environmental performance indicators at mid stages and full lifecycle assessments at TRL 7-9. Chebaeva et al. (2021) formalize a parallel set of Sustainability Assessment Levels, scaling the depth of environmental assessment to data availability at each TRL stage. Cooper (2025) takes a different approach through the Eco-Stage-Gate model, embedding environmental screening directly into gate criteria rather than running sustainability as a parallel process. While these frameworks represent progress, Chebaeva et al. (2021) acknowledge that sustainability assessments at early TRL stages remain difficult to apply in practice, as the outputs cannot meet the quality expected by decision-makers.

What is difficult to determine from literature is whether a tool combining these characteristics would be adopted in practice. Adoption depends on conditions that go beyond methodology: organizational hierarchies, workflow integration, and employee awareness. Identifying those conditions requires engagement with practitioners, which is the purpose of the empirical phase described in chapter 4. The characteristics that emerge from that phase, described in section 5.3, combined with the literature findings above, inform the design of the decision guide developed in chapter 6.

2.6 Theoretical framework

Aviation technology development is caught between growing environmental ambitions and a development process that prioritizes technical performance, cost, and certification, creating conditions in which eco-design and CE principles are difficult to preserve. While these principles must be embedded during the early stages of technology development, when changes are still possible, this is precisely the window in which informational, organizational, and regulatory barriers are most active, and in which the data required to defend sustainability criteria at gate reviews does not yet exist.

Figure 7 maps this structure visually. Using the TRL-based development process as its backbone, containing the criteria this process currently prioritizes, it layers the three barrier categories identified in section 2.3 onto that process.

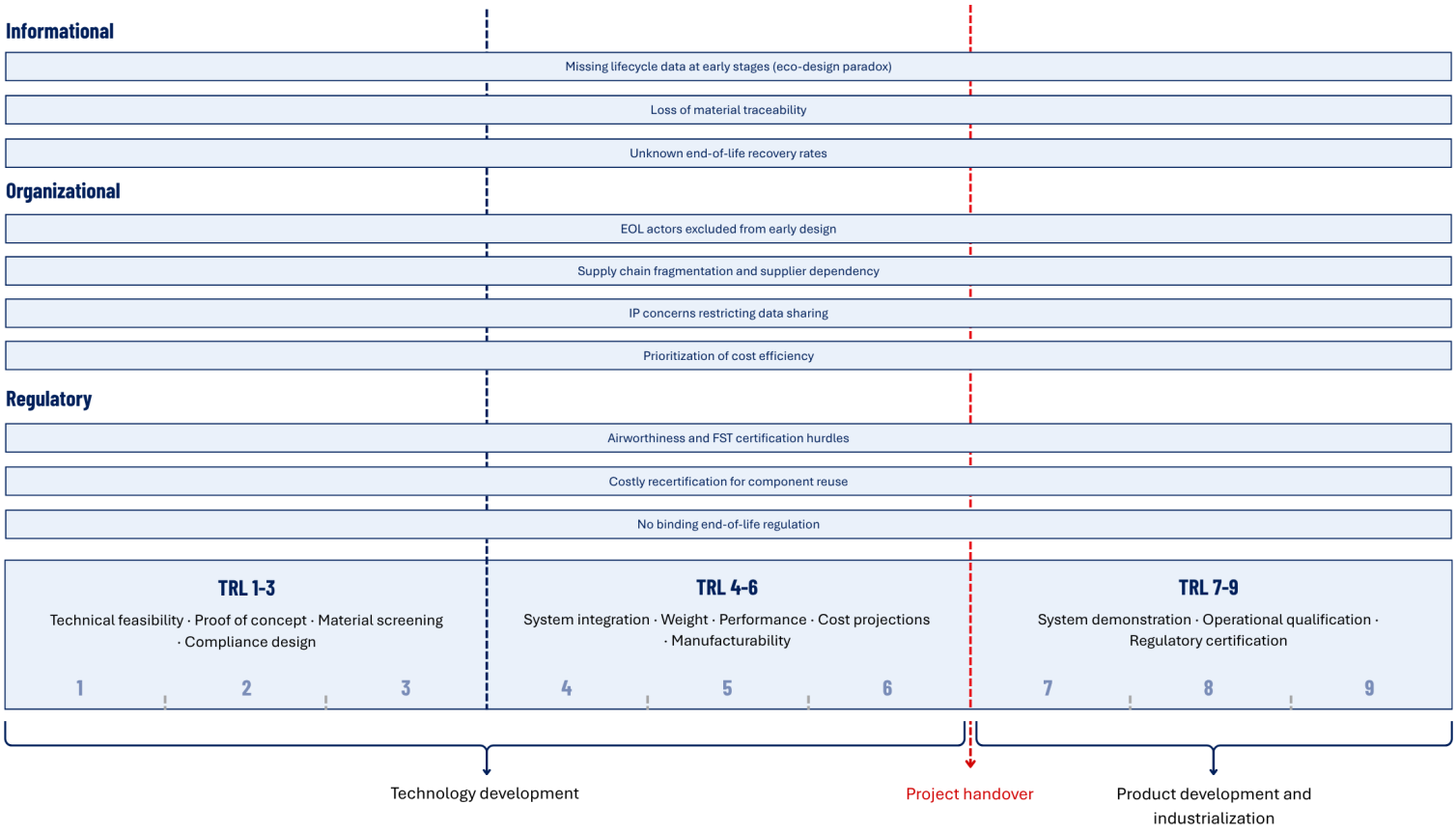

FIGURE 7: *Theoretical framework: barriers across TRL-based aviation technology development*

The framework is preliminary in that it reflects the literature rather than validated industry practice. The barrier categories are mapped at a generic level across the full TRL range, rather than distributed across specific stages where their intensity can vary. It served two functions in the empirical phase: structuring the interview topics to ensure coverage of the relevant themes, and providing a model to be iteratively tested and revised against the experience of practitioners across the aviation value chain.

03

CHAPTER THREE

Market analysis

The regulatory, commercial, and value-chain environment within which any decision guide for preserving eco-design and circular economy principles must operate.

The literature review established the theoretical conditions that complicate the preservation of eco-design and CE principles in aviation technology development. Before moving to the empirical and design phases, it is useful to map the external environment within which the resulting decision guide must operate. This chapter provides that context across three dimensions: the regulatory landscape shaping environmental obligations for aviation organizations, the stakeholder structure and value chain that exist in the cabin component ecosystem, and the commercial dynamics within this. Together, these contextualize the expert interviews that follow and inform the design of the decision guide in chapter 6.

3.1 Regulatory landscape

Aviation organizations currently operate within a regulatory environment that pulls in two directions: environmental obligations are expanding in scope and ambition, while safety and certification requirements constrain the space within which those obligations can be met. On the environmental impact side, four instruments are relevant to the context of this research: the Corporate Sustainability Reporting Directive (CSRD), the Ecodesign for Sustainable Products Regulation (ESPR), the EU Emissions Trading System (EU ETS), and the Registration, Evaluation, Authorization and Restriction of Chemicals regulation (REACH).

The CSRD requires large companies to report on environmental risks, impacts, and value chain dependencies according to the European Sustainability Reporting Standards (European Commission, 2025a). The directive applies to large enterprises regardless of sector, meaning major aviation OEMs and airlines fall within its scope. It can be noted that its presence across the aviation sector reflects a broader shift toward structured environmental accountability, and the demand for related data it creates.

The EU ETS caps total aviation emissions and requires operators to purchase allowances for intra-European flights, with free allowances fully phased out by 2026 (European Commission, 2025b; ICCT, 2024; Lohawala & Wen, 2024). By placing a direct financial cost on operational emissions, the system creates incentives for airlines to reduce their carbon footprint, which in turn generates downstream demand for more fuel-efficient aircraft and cabin components, which in practice translates to lightweighting.

ESPR adopts a more direct product-level approach, establishing eco-design requirements covering durability, reusability, repairability, and recyclability, and mandating a Digital Product Passport (DPP) to improve material traceability across supply chains (Circularise, 2025; European Union, 2024). The DPP has direct relevance to the informational barriers identified in section 2.3, as it creates infrastructure for tracking material composition and lifecycle history across stakeholder handoffs. It should be noted that the ESPR's first working plan for 2025 to 2030 prioritizes material categories in specific industries, such as steel, aluminum, and textiles, and does not yet include any aviation cabin components (European Union, 2024). The precise scope of ESPR obligations for the aviation industry therefore remains unclear.

REACH regulates the use of hazardous substances in materials and manufacturing processes across the European Union, requiring companies to register, evaluate, and where necessary restrict chemicals that pose risks to human health or the environment (European Commission, 2025c). For aviation cabin components, REACH creates a dual constraint. At the design stage, it requires teams to anticipate which chemical substances may be restricted or banned over a component's operational lifetime, since materials incorporating substances such as chromates for corrosion protection have historically required costly redesigns when those substances were later prohibited. At end-of-life, REACH compounds the circularity challenge: the flame retardants and chemical additives required to meet FST certification standards directly constrain which materials can be safely repurposed or recycled, as cabin

plastics containing heavy chemical treatments cannot be cascaded into other industries without presenting toxicological risks.

These environmental regulations operate within a certification baseline set by the European Union Aviation Safety Agency (EASA), which governs the airworthiness requirements that any aircraft component must adhere to before it can enter service. For cabin interiors, this means compliance with fire, smoke, and toxicity (FST) standards, structural fatigue requirements, and material qualification processes administered under EASA's Part 21 and Continuing Airworthiness frameworks (EASA, 2023b). These requirements were designed around safety and operational reliability, not resource recovery, and they fall under the barriers explained in section 2.3: conventional, well-characterized materials carry established certification pathways, while novel alternatives, including recycled composite formulations and bio-based materials, must complete qualification processes that are administratively intensive and carry technical risk (Bachmann et al., 2017; Carvalho et al., 2025).

Together, these regulatory developments create a mixed environment for practitioners with environmental ambitions. CSRD, ESPR, and REACH each generate pressure to engage with material traceability, lifecycle impact, and chemical risk at early development stages, which a designed solution would target. The gaps they leave, however, are equally structural. ESPR does not yet cover aviation cabin components, meaning there is no binding mandate for the sector, and the certification baseline set by EASA remains organized around safety and operational reliability, not environmental recovery. These are constraints a decision guide must work within, rather than around.

3.2 Stakeholder structure and value chain

Technology development does not always take place within a single organization, but across a network of actors with different roles, incentives, and points of engagement with the value chain. Figure 8 maps this network using the CIRCADIS consortium as the primary reference case, organizing actors according to their proximity to the design and development process. The OEM sits at the center as the primary development authority, surrounded by its closest collaborators: material suppliers, component manufacturers, and knowledge institutions, all of whom are active partners within the CIRCADIS consortium. Moving outward, the middle ring captures the operational layer: airlines as the direct customer of the OEM, and MRO operators responsible for in-service maintenance. Passengers sit within this layer as the end consumers whose preferences reach the chain through airlines, as further explained in section 3.3. The outer ring represents end-of-life actors, such as aircraft dismantlers and composite recyclers, whose distance from the center reflects their exclusion from early decisions. Regulatory bodies sit outside the consortium boundary as an influence spanning the full network. It should be noted that logistical operators are not represented as an actor on this map. Their environmental relevance, however, can be important: transport choices such as planes, trucks or ships, carry differences in carbon footprint and thereby influence the environmental impact, making these choices a consideration within the domain of sustainability ambitions.

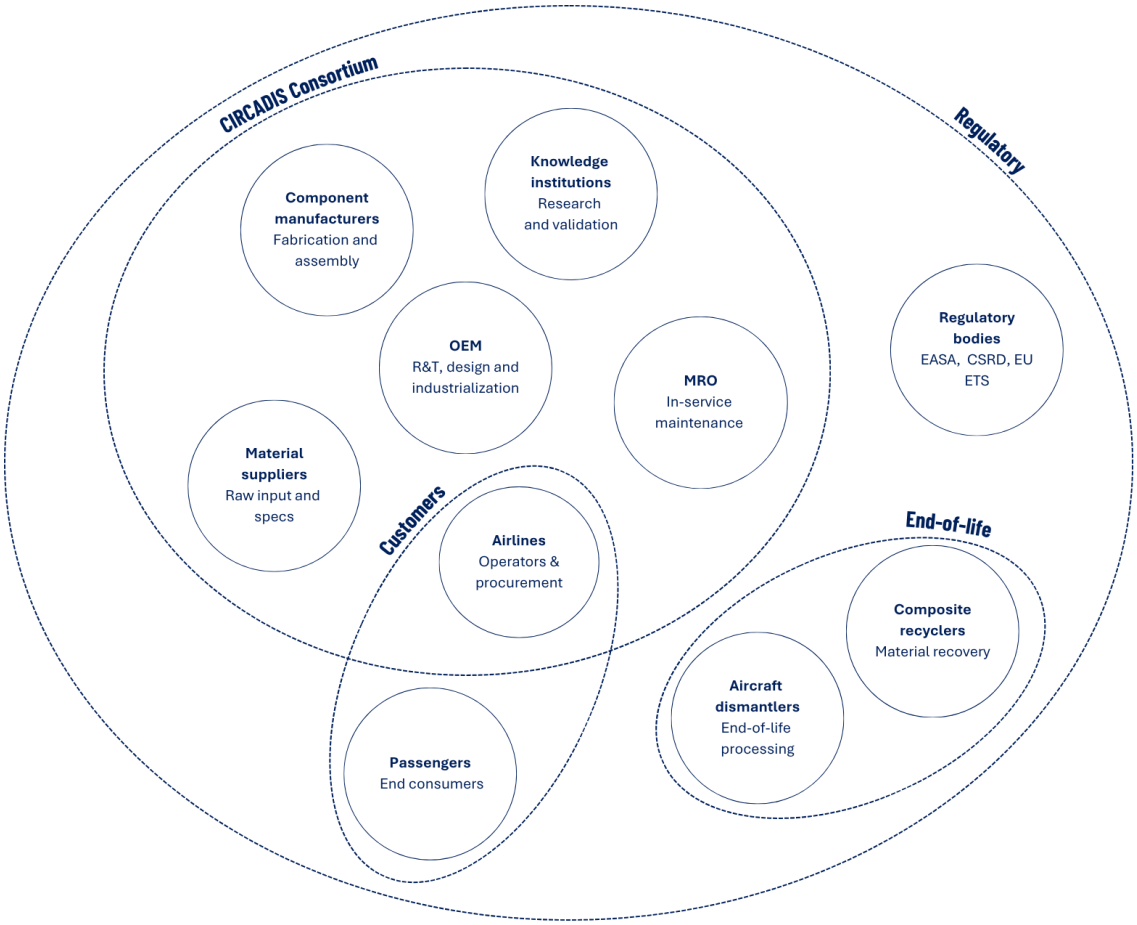

FIGURE 8: *Stakeholder map*

The detailed value chain, provided in Appendix E, extends this picture by mapping the full cabin component value chain in greater detail, tracing the flow of both materials and information from raw material input through component manufacturing, module assembly, and product integration at the OEM, to airline operations, aircraft dismantling at end-of-life specialists such as AELS, and final material recovery. The value chain was developed through a co-creation workshop using value chain mapping as a method, bringing together practitioners from across the chain to identify actor roles, material flows, and information gaps. This method is further elaborated in Appendix K as one of the core tools within the developed decision guide.

The CIRCADIS consortium spans the early stages of this chain, from material suppliers through to the OEM and airlines, but end-of-life processing is not represented within the consortium itself. This reflects a gap common across aviation development initiatives and connects directly to the organizational barriers discussed in section 2.3. For the purposes of this research, that gap is addressed through the semi-structured interviews: end-of-life and recycling specialists were included in the interview sampling described in section 4.2, ensuring that the findings reflect perspectives from across the full chain rather than only from those actors already embedded in the development process.

3.3 Commercial drivers and passenger perspectives

Passenger environmental awareness, as already established in section 1.1, is beginning to translate into actual client pressure: airlines are responding to passenger expectations by requiring suppliers and OEMs to provide sustainability data and develop more environmentally responsible products (Aerospace Technology Institute, 2022; WTCE, 2026). However, the gap between stated passenger preference and

actual booking behavior remains large. Most passengers have never taken environmental credentials into a purchasing decision, and willingness to pay for sustainability-related costs remains far below the actual price differences (Lohawala & Wen, 2024; WTCE, 2026). Passenger-facing sustainability is therefore best understood as a commercial driver that has not yet translated into purchasing decisions in practice (Aerospace Technology Institute, 2022; EASA, 2023a). As an alternative, there are some airline examples that embed environmental value into their products in a different way. Lufthansa Group's Green Fares, now adopted by ITA Airways, bundle carbon offset contributions and SAF investments directly into tickets, rewarding passengers with additional miles for choosing greener options (ITA Airways, 2026). Alaska Airlines has introduced a similar model, allowing passengers to boost loyalty status by contributing to SAF during Earth Month (Simple Flying, 2026). These initiatives reflect an important commercial logic: environmental incentives survive when they are packaged as a full value proposition, rather than a standalone environmental commitment with additional costs.

Examples of environmental ambitions, including eco-design and CE principles applied to cabin technology development, are nonetheless emerging across the value chain. This demonstrates that sustainability-oriented products can reach the market even within current ecosystems' conditions. An example is Testori Textiles' plant-based fibre system, that introduces natural fibres across seat covers, curtains, and wall surfaces without compromising aviation standards (APEX, 2026). Beyond material innovation, also practitioner-facing tools appear. An example of this is the Gen Phoenix's CirculAir Playbook, developed in collaboration with Boeing, which provides some practical guidelines for embedding circular design into textile cabin seat covers (Inflight Online, 2026). And even full organizations such as The Green Cabin Alliance bring together airlines, OEMs, suppliers, and knowledge institutions to advance sustainable cabin practices. They argue that sustainability must be embedded across the full value chain rather than addressed in isolation by individual actors, treating sustainable cabin development as a shared challenge (Green Cabin Alliance, 2024).

The aviation industry nonetheless remains profit-driven, causing sustainable practices to be adopted when they align with existing business drivers, and are resisted where they require absorbing costs without corresponding financial returns. A clear illustration is that sustainable end-of-life practices were discontinued, because the financial cost outweighed the environmental gains (EASA, 2023a). Weight-reducing material substitutions are being adopted not because they reduce emissions, but because they reduce operational costs. Passenger-visible sustainability initiatives are increasingly framed as growth strategies that build brand loyalty and justify premium pricing, rather than environmental commitment from the airline (Aerospace Technology Institute, 2022; WTCE, 2026). It is therefore essential that a decision guide focused on preserving eco-design and CE principles connects to this commercial logic, whether through cost reduction, weight savings, supply chain resilience, or marketable differentiation. That condition directly informs the design, developed in chapter 6.

This market analysis also shaped the empirical phase that follows it. The commercial dynamics identified here informed the inclusion of a dedicated commercial context section in the interview protocol, ensuring commercial framing was explored as a structural condition, and the value chain and stakeholder mapping guided sampling decisions across the full development and end-of-life spectrum. Familiarity with this context, including current regulations, also strengthened the empirical phase more broadly, enabling more informed questioning during interviews and reducing the risk of surface-level responses on complex topics.

04

CHAPTER FOUR

Research Methodology

How the empirical phase was designed: a qualitative, interview-based approach for testing the theoretical framework against practitioner experience from across the value chain.

As stated in section 1.8, this research was conducted in three phases, each building on the output of the previous. This chapter describes the research methodology underpinning the second phase, covering the qualitative research approach and its justification, the sampling strategy, the data collection process, and the method applied to the analyze the interview data.

4.1 Research approach

This research adopts a qualitative approach, grounded in the premise that the barriers and conditions complicating the preservation of eco-design and CE principles in technology development are not fully captured by existing literature alone. The theoretical framework developed in section 2.5 reflects the literature rather than validated industry practice, and semi-structured interviews served as the primary method through which that framework was tested, challenged, and refined against industry experience.

The qualitative orientation is appropriate given the nature of the research question. Preserving eco-design and CE principles at TRL gates involves organizational dynamics, competing priorities, and context-specific constraints that are difficult to quantify. Semi-structured interviews balance theoretical anchoring with open responsiveness, following a thematic structure while remaining flexible enough to allow for reasoning that the literature had not yet captured (Kvale & Brinkmann, 2009). Wiesner et al. (2025) apply this same logic in a related study on CE integration in aviation, justifying the semi-structured format on the grounds that it allows a guiding structure while accommodating follow-ups where participants diverge from pre-defined questions. Key visualizations, including the theoretical framework and the stakeholder map, were introduced during interviews to give participants something concrete to reflect on, helping anchor abstract questions about TRLs and barrier mechanisms to a tangible context (Joustra, 2022).

4.2 Sampling and stakeholders

Key participants were identified based on the stakeholder structure established in section 3.2 and through the CIRCADIS consortium network. Five stakeholder categories were selected to ensure coverage across the full aviation value chain: cabin designers and engineers, eco-design and sustainability specialists, material and component experts, MRO experts, and end-of-life and recycling specialists. Seventeen participants were recruited through the CIRCADIS consortium, direct outreach to Airbus professionals, and referrals from initial contacts, of which a detailed mapping can be found in Appendix G. The stakeholder groups and their relevance to the research are as follows:

N = 4 Cabin designers and engineers

To gain insight into how design decisions are made in practice and how sustainability criteria are weighed against technical and commercial constraints at gate reviews.

N = 3 Eco-design and sustainability specialists

To understand how environmental criteria are currently operationalized within aviation development processes and where they encounter structural resistance.

N = 4 Material and component experts

To gain insight into the constraints and opportunities at the material level, including data availability, certification requirements, and end-of-life considerations built into material selection.

N = 2 MRO experts

To capture the maintenance and operational perspective, including how design decisions made at early TRL stages affect repairability, component lifespan, and material recovery in practice.

N = 4 End-of-life and recycling specialists

To provide insight into what circular strategies are currently achievable at end-of-life and what design conditions would need to be in place to make higher-value recovery viable.

This spread of stakeholder categories was chosen to capture perspectives from across the full value chain, ensuring that the findings reflect all barriers and conditions that determine whether eco-design and CE principles are preserved in practice. Two sampling limitations are worth noting. First, senior program managers are underrepresented: their perspective is present in the sample but not in proportion to their potential influence on decisions, meaning the barriers and conditions identified in chapter 5 may more reflect how gate logic is experienced by practitioners subject to it, rather than how it is exercised by those who hold authority. Second, sampling through the CIRCADIS consortium introduced a sustainability orientation bias, as some participants may hold more developed views on eco-design and CE than the broader practitioner population. Together, these limitations suggest the findings may underestimate the resistance that eco-design and CE principles encounter in less sustainability-oriented contexts. The implications of both are discussed further in section 7.3.

4.3 Data collection

Each interview was conducted in a semi-structured format lasting approximately 45 to 60 minutes. Following the thematic structure applied by Dekoninck et al. (2016) and Wiesner et al. (2025), the protocol moved from open contextual questions toward validation of the theoretical framework, before closing with practitioner-oriented questions on decision guide characteristics and adoption conditions. The question formulation draws on the interview templates developed by Hallstedt et al. (2010), whose structure, moving from introductory questions through detailed process questions to forward-looking control questions, informed the logic of each section. The protocol (Appendix F) consists of 17 guiding questions organized across five thematic sections: role and context, eco-design and CE in practice, barriers and conditions, method and tool characteristics, and commercial context. All interviews were recorded and transcribed, with informed consent obtained in advance. The template of the informed consent form, along with the approved Human Research Ethics Committee (HREC) application required for human participants, can be found in Appendices H and I.

4.4 Data analysis

Interview data was analyzed following the Gioia methodology, a systematic approach to qualitative analysis designed to surface concepts and themes from practitioner accounts while maintaining transparency between raw data and theoretical conclusions (Gioia et al., 2013). Given the volume of interview data, an Airbus internal large language model was used as a coding assistance tool to support the initial organization of first-order codes from transcripts, consistent with emerging practice in qualitative research that positions AI as an analytical aid (Feuston & Brubaker, 2021; Tai et al., 2024). To support interpretive consistency, first-order codes were iteratively checked against the original transcripts throughout the analytical process, ensuring that code labels remained grounded in informants' own language rather than theoretical interpretation. All codes were reviewed, verified, and finalized by the researcher, with the final coding structure and all analytical interpretations remaining the researcher's own.

The analysis proceeded in three ordered steps. In the first-order phase, interviewee statements were coded using the informants' own terms and language, preserving the original language of each account without imposing theoretical interpretation. In the second-order phase, related first-order codes were grouped into categories corresponding to the barrier types and decision guide characteristics established in the literature review. In the third-order phase, patterns in the data were assessed for the degree to which they confirm, extend, or revise the theoretical framework developed in section 2.5. The resulting data structure provides a transparent account of how the analysis progressed from raw interview data to theoretical conclusions.

This approach was appropriate given the dual purpose of the empirical phase: validating an existing theoretical framework while remaining open to findings the literature had not captured. Where interviewees diverged from the framework's assumptions, these were treated as analytical contributions rather than outliers, informing the revisions to the theoretical framework presented in section 5.4.

05

CHAPTER FIVE

Results

What 17 expert interviews across the value chain reveal about how TRL gate logic works in practice, the barrier and condition categories that filter out environmental criteria, and the addition of a commercial dimension.

The findings presented in this chapter are derived from 17 semi-structured expert interviews conducted across the aviation cabin component value chain, analyzed using the Gioia methodology described in chapter 4. The analysis of interview transcripts produced 745 first-order codes, organized into 22 second-order categories and six aggregate dimensions. These dimensions span four categories covering informational, organizational, regulatory, and commercial barriers and conditions, one category examining TRL-logic in practice, and one solution-oriented category capturing practitioner perspectives on the requirements for the decision guide. Figure 9 presents the full Gioia data structure.

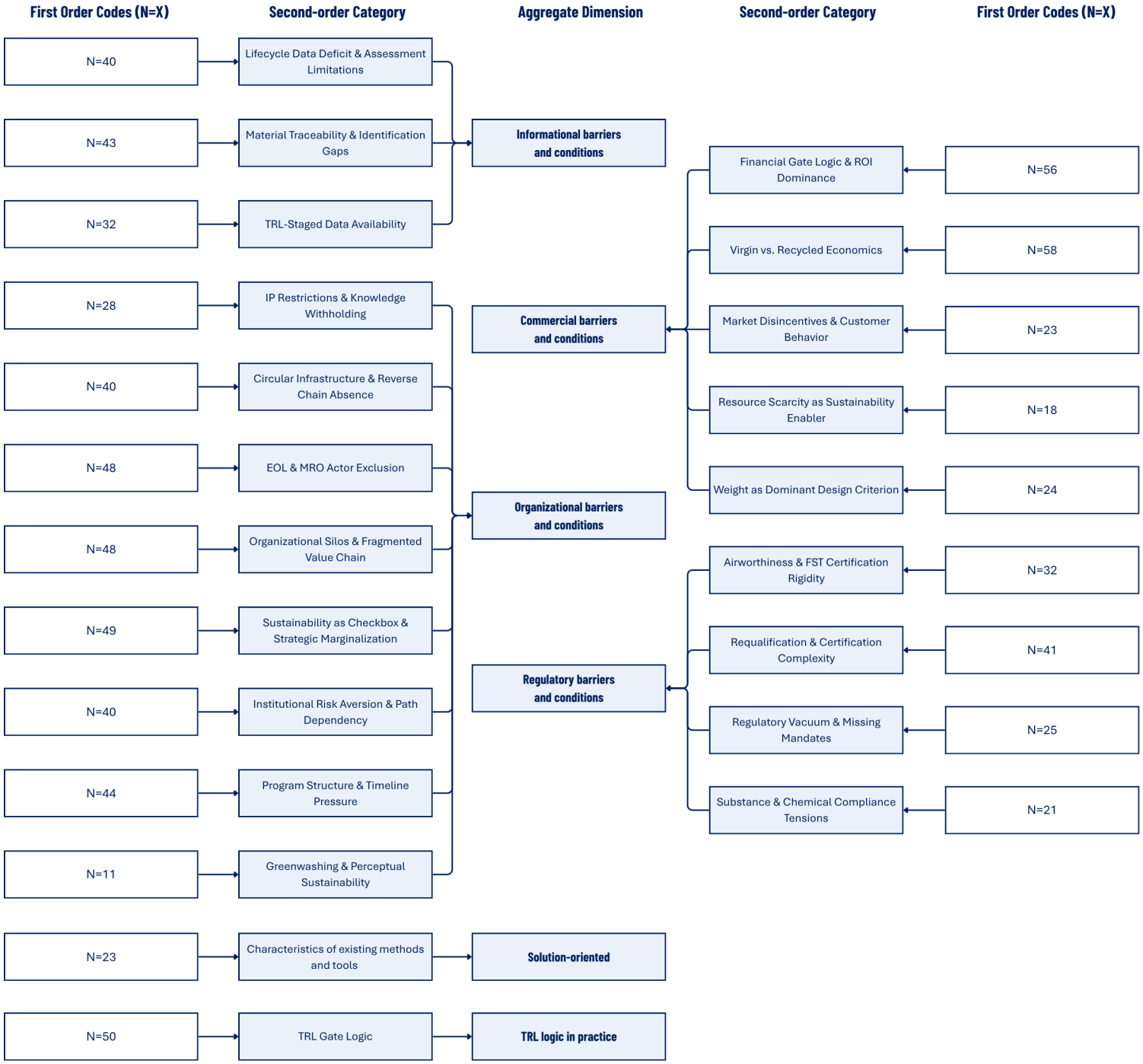

FIGURE 9: *Gioia data structure*

Across the 17 interviews, a consistent empirical storyline emerged. Environmental ambitions are present early in development: practitioners across the value chain described genuine intent to integrate eco-design and CE principles at low TRL stages, where design freedom is highest. As technologies mature, however, that intent becomes increasingly difficult to defend. Rising cost pressure, production ramp-up demands, certification constraints, and the shift in decision authority toward commercially-driven senior management create a compounding filtration effect in which environmental criteria are deprioritized. The sections below trace how each of these pressures operates, and where they tend to be most acute.

These sections are ordered according to the sequence of the subquestions, moving from TRL-logic (2), through the barriers and conditions (3), to the characteristics practitioners identified as necessary for a workable decision guide (4). Section 5.4 synthesizes these practitioners' findings against the theoretical framework developed in chapter 2. All interview participants are anonymized throughout this chapter. Quotes are attributed by interviewee identifier (e.g., INT 3), of which a full overview can be found in Appendix G.

5.1 TRL-logic in practice

As multiple interviewees worked in a TRL-related environment themselves, this emerged as one of the recurring themes across all interviews. In total, 11 interviewees informed the findings in this subsection, which allow for a more detailed assessment of how the TRL-based development projects work specifically in aviation cabin component technology. The **TRL-logic in practice**, extending the literature framing in section 2.2, functions less as a neutral technology maturity assessment and more as a progressive filtration system in which the criteria that survive each gate are determined by commercial and regulatory priorities. Participants described large numbers of technology concepts entering TRL 1 or 2, with only those able to demonstrate cost competitiveness, weight performance, schedule compatibility, and certification feasibility advancing toward industrialization.

The criteria that govern gate decisions are consistent across interview results. Financial viability is found to be the dominant filter: as one eco-design and sustainability specialist put it, *"the most important unit in engineering is the Euro"* (INT 4), meaning that a ten percent cost premium on a sustainable technology is sufficient grounds for rejecting this. Weight functions as a second, connected constraint, as this is directly linked to the costs related to fuel burn during the use phase. Schedule pressure currently compounds both: production ramp-up capacity is described by a material and component expert as "*on top of the list for everybody right now"* (INT 10), and technology that extends development timelines therefore faces immediate resistance. FST certification requirements represent a non-negotiable, non-commercial criterion, which directly influences possible material selections. Consistent with the literature findings, sustainability criteria do appear in gate reviews, but their position is structural rather than substantial: an eco-design specialist confirmed that sustainability is "*literally the last point on the whole mandatory requirements"* (INT 4), assessed after all technical and commercial criteria have been evaluated.

That position explains why sustainability assessments, despite being mandatory at specific moments in the TRL process, function as a compliance exercise rather than outputs that guide design decisions. A cabin designer and engineer described the assessments as "*a tick in a box and not really integrated into the real business decisions"* (INT 2). An organizational condition deepens this: assessments are often conducted by subcontracted departments or companies removed from the project team. These findings together contribute to the eco-design paradox established in section 2.2: where design

freedom is highest and assessments could still inform choices, the data remains too immature. By the time a full LCA becomes technically feasible, the design is no longer open to changes that the assessment would recommend.

The threshold at TRL 6-7 introduced in section 2.2, as the point at which decision authority shifts from research departments toward management and industrialization priorities, is confirmed and extended by practitioner. Multiple interviewees described TRL 6 not as a technology freeze, but more precisely as the threshold at which research teams' hand over their research and applications to program managers, whose mandate is defined more exclusively by cost, schedule, and industrialization possibilities.

5.2 Barriers and conditions

The following four subsections map the barriers and conditions that complicate the preservation of eco-design and CE principles across TRL-based development in commercial aviation. Each subsection corresponds to one of the four aggregate dimensions identified in the Gioia analysis, covering informational, organizational, regulatory, and commercial respectively.

5.2.1 Informational

Three second-order categories underpin the informational barriers and conditions identified in the interview analysis: **lifecycle data deficit and assessment limitations, material traceability and identification gaps,** and **TRL-staged data availability,** drawing on 115 first-order codes across 13 of 17 interviews. Together these provide a more granular practitioner perspective of the informational category established in section 2.3.

The core challenge related to lifecycle data deficit and assessment limitations is not that there are no environmental assessment methodologies available, but that these cannot be meaningfully executed. An end-of-life and recycling specialist noted that at early TRL stages, technologies are often "*two lines on a screen"* (INT 17), with critical choices such as material compositions still open to change. The resulting assessments rest on assumptions that are too rough to be justified, confirming the data deficit established in section 2.3. This dynamic is most acute across TRL 1-6, where decisions are still open but the data underpinning any meaningful environmental assessment does not yet exist.

Material traceability and identification gaps are compounded by commercial behavior in the value chain, confirming and extending the informational barriers in section 2.3. Suppliers withhold material composition and process data because it carries competitive value: specific details can reveal their production or industrialization methods, and companies protect these accordingly. One interviewee also noted that where data is shared, it may have been adjusted before disclosure: "*from my experience you can play a lot with numbers, processes, existing data, and you can somehow make a nice number at the end"* (INT 11). Smaller suppliers face a different version of this barrier: the capacity to generate data at the quality large OEMs require is often a challenge, creating a separate source of data unavailability. Both conditions are most consequential across TRL 4-9, where possible value chain interactions intensify. It should be noted that these conditions accumulate at end-of-life, where dismantling facilities receive cabin components without material labeling of any kind. This forces end-of-life and recycling specialists to resort to workarounds such as X-ray scanning or physical reverse engineering to reconstruct material identities that were not shared.

The third category can be framed as a condition rather than a barrier: TRL-staged data availability, operating across the full TRL range. As a technology matures, the quality and specificity of

environmental data grow alongside technical maturity, but this growth consistently lags behind the decisions it would need to inform. Multiple interviewees described this as understanding environmental impacts too late: by the time data reaches the quality required to make defensible sustainability arguments, the decisions that data would have informed, have already been made. This is consistent with the identified eco-design paradox introduced in section 2.2

5.2.2 Organizational

Eight second-order categories underpin the organizational barriers and conditions identified in the interview analysis: **organizational silos and fragmented value chain, EOL and MRO actor exclusion, IP restrictions and knowledge withholding, circular infrastructure and reverse chain absence, sustainability as checkbox and strategic marginalization, institutional risk aversion and path dependency, program structure and timeline pressure,** and **greenwashing and perceptual sustainability,** drawing on the largest share of first-order codes across the dataset and reaching 15 of 17 interviewees. Where the informational barriers and conditions in section 5.2.1 describe the data gaps that complicate environmental assessments across TRL stages, the organizational ones explain the arrangements that produce and sustain those gaps.

Organizational silos and value chain fragmentation operate across the full TRL range as a foundational condition that coordinated strategies, including CE ones, require. The interview findings reveal how contractual arrangements actively prevent cross-organization collaboration, with each tier in the value chain optimizing its own processes. Consequently, a cabin designer and engineer described the supply chain as a system in which everyone has *"their own piece of cake"* (INT 16).

EOL and MRO actor exclusion extends the fragmentation condition across the full TRL range, with consequences most visible at the earlier stages. A cabin designer and engineer noted that MRO operators, dismantlers and recyclers are structurally excluded because no direct contractual relationships exist between OEMs and end-of-life operators, confirming the organizational barrier identified in section 2.3. The result is a missing feedback loop from service and end-of-life back into new design, meaning new technologies or products tend to be optimized for a single stakeholder, rather than considering the full value chain.

IP restrictions and knowledge withholding add to the fragmentation described above. Beyond silos, companies actively protect material formulations, an issue already flagged in section 5.2.1. An end-of-life and recycling specialist described suppliers holding their cards "*close to their ches*t" (INT 6). A related but distinct IP condition concerns authorities: where a supplier holds the IP on a cabin component, the OEM cannot modify the product without negotiating significant contractual and financial arrangements, regardless of the environmental improvements such changes might enable. The CIRCADIS project represents an exception: because Airbus owns the internal design of the OHSC door, design authority remains with the development team, removing this barrier.

Circular infrastructure and reverse chain absence also operate across the full TRL range as a condition that constrains the actual implementation of circular strategies, even when these are enabled in the design. If recyclability is technically proven, the absence of a reverse supply chain means end-of-life operators have nowhere to route recovered material. An end-of-life and recycling specialist argued that individual waste volumes from aircraft dismantling are too low to make closed-loop recovery cost-effective. This is an organizational with a commercial element: without agreements between OEMs, airlines, and dismantlers that create shared accountability for material flows and financial viability, the infrastructure cannot form regardless of technical feasibility.

Sustainability as checkbox and strategic marginalization is most acute across TRL 3-6, where environmental assessments are often performed, but rarely integrated into decisions. Despite the noteworthy environmental ambitions among interviewed practitioners, it was revealed how organizational structures marginalize environmental criteria: as addressed in section 5.2.1, assessments are routinely delegated to junior staff or subcontracted departments. Interviewees noted that without an explicit mandate from senior management, environmental tools remain a "*nice to have"* (INT 6) or "*paper exercise"* (INT 7) rather than genuine input. Practitioners with genuine ambitions were described as *"lone wolf environmentalists"* (INT 15) requiring a translation to communicate environmental value in terms that resonate with decision-makers.

Institutional risk aversion and path dependency surfaces from TRL 4 onward, as development processes shift from only technological exploration, towards validation and alignment with commercial drivers. A cabin designer and engineer traced what multiple interviewees described as a legacy-mindset, resulting in a culture that resists additional risk into environments where as much as possible is stabilized. A material and component expert illustrated this in the context of the current, thermoset overhead bin door: existing manufacturing infrastructure is already paid for and optimized around conventional thermoset production, meaning adoption of a more circular thermoplastic alternative results in capital and operational costs that no internal stakeholder wants to absorb. This results in the situation where existing technology performs correctly, the organization's question becomes, as an EOL and recycling specialist noted, "*why change it*" (INT 6).

Program structure and timeline pressure become more acute from TRL 6 onward, as development shifts toward industrialization and procurement feasibility. A standard customer procurement program was described as running approximately 24 months, structured around fixed reviews at which suppliers even face penalties for missed milestones. An eco-design and sustainability specialist described how this forces teams toward existing, proven solutions: the risk of innovation causing a delay is simply too high. A material and component expert confirmed that schedule is frequently the most decisive factor, favoring established technologies. The consequence is that for example circular strategies are not even proposed, as their implementation is considered too risky within the constraints of an active program.

Greenwashing and perceptual sustainability emerge most prominently at TRL 7-9, as technologies approach industrialization and external visibility increases. Multiple interviewees described sustainability initiatives shaped primarily by external positioning rather than internal commitment, supported when they generate favorable visibility and cancelled when they require net costs. An eco-design and sustainability specialist noted that sustainability ambitions risk becoming "*marketing focused*" (INT 4) when organizational structures do not back them with genuine resources or mandates. The commercial logic that underlies this condition is examined further in section 5.2.4.

5.2.3 Regulatory

Four second-order categories underpin the regulatory barriers and conditions identified in the interview analysis: **regulatory vacuum and missing mandates, airworthiness and FST certification rigidity, substance and chemical compliance tensions,** and **requalification and certification complexity,** drawing on 119 first-order codes across 15 of 17 interviewees. Where section 2.3 established that certification requirements act as a barrier to circular materials and that the absence of end-of-life mandates removes the incentive to design for disassembly, the interview findings both confirm and extend them.

The regulatory vacuum and missing mandates operate across the full TRL range as a persistent condition. Currently, due to no binding end-of-life regulations or extended manufacturer responsibilities, accountability of products and materials often ends at aircraft delivery, illustrated by this quote of a cabin designer and engineer: "*currently we are still in a linear thinking, and the thinking stops at the moment I deliver my aircraft"* (INT 16). Several interviewees did note that anticipated regulatory developments are changing this. An example was mentioned of Austria's regulations banning thermoset landfilling, which has already forced suppliers to develop solutions. This illustrates that regulatory signals can accelerate environmental ambitions. Binding mandates therefore could create conditions under which eco-design and CE principles become more defensible through a TRL process.

Airworthiness and FST certification rigidity is most acute at TRL 1-4, where material selection decisions are still open but must already account for the certification pathway ahead. FST requirements have been described as "*written in blood"* (INT 10), reflecting historical aviation accidents. Interviewees indicated that natural and bio-based fibres therefore require such intensive flame-retardant treatment to meet aviation FST standards, that their environmental benefits are largely eliminated in the process: as a material and component expert explained, once treated to pass certification, "*there is not much of the natural fibre left*" (INT 10). It should be noted that safety and airworthiness requirements themselves are not challenged: these represent a non-negotiable baseline that interviewees consistently confirmed.

In addition to the previously mentioned rigidity are the substance and chemical compliance tensions, also operating most acutely at TRL 1-4. Here, regulations such as REACH play a major role in avoiding hazardous substances. Next to the early TRL stages, this reappears at end-of-life: cabin plastics containing heavy flame retardants cannot be safely repurposed into other industries due to their toxicological profile, closing off ways of recycling that would otherwise be technically viable.

Requalification and certification complexity intensifies from TRL 4 onward, as technologies approach the point where formal certification becomes necessary. A material and component expert confirmed that requalifying a material or repurposed component is "*very costly and very cumbersome"* (INT 7). The proof-of-concept described in section 2.1, in which a thermoplastic panel was restamped for reuse in a new generation aircraft, illustrates this precisely: technical feasibility was shown, but implementation remains stalled because no cost-effective regulatory pathway exists to qualify the part. Virgin replacement therefore remains cheaper and legally safer. A cross-cutting finding here is that certification requirements are not always the genuine constraint: an eco-design and sustainability specialist noted that regulatory bodies remain open to some options, provided safety can be demonstrated, and that the genuine barrier is often the financial commitment required to reach that demonstration. Certification, in this framing, becomes the most widely accepted argument against alternatives. That dynamic connects directly to the commercial barriers examined in section 5.2.4.

5.2.4 Commercial

The commercial dimension represents the most significant contribution of this empirical section. Unlike the informational, organizational, and regulatory barriers examined in the preceding sections, commercial logic was not present as a distinct category in the theoretical framework developed in section 2.5, where related dynamics were distributed across other categories. The interview findings surface it as a category in its own right, reaching 16 of 17 interviewees and drawing on 179 first-order codes. Critically, commercial logic does not always operate in parallel with the other barriers: it

functions as a cross-cutting filter that determines which of the other barriers are addressed or left in place. Five second-order categories underpin the commercial barriers and conditions identified in the interview analysis: **financial gate logic and ROI dominance, virgin versus recycled economics, weight as dominant design criterion, market disincentives and customer behavior,** and **resource scarcity as sustainability enabler.**

Financial gate logic and ROI dominance operate across the full TRL range as a foundational filter. The most direct evidence comes from cases where informational, organizational, and regulatory barriers and conditions had been successfully overcome, yet preserving eco-design and CE principles in technologies still failed. An eco-design and sustainability specialist described a benchmark in which LCA data clearly demonstrated the environmental advantage of one component over another, the data was available, the team was aligned, and the technical case was correct, yet the sustainable option was still rejected because cost parameters favored the current design. As a material and component expert stated directly, *"money wins... you can have the best performance, but if it is not at the right price, then that is going to be very difficult for you to succeed"* (INT 7).

Virgin versus recycled economics operates across the full TRL range as a condition that structurally disadvantages circular material alternatives. This condition cannot be attributed to a single organization or stakeholder: even where environmental ambitions are present, current market dynamics mean that virgin materials are almost always cheaper than recycled equivalents. A material and components expert illustrated this directly: *"The recycled variants are more expensive than the virgin ones. We make the experience that the customer chooses the virgin at the end, especially in price-driven applications"* (INT 11). And where implementing recycled material results in a higher cost price for the buyer, the commercial outcome is dominant. For this to shift, interviewees suggested that legislative penalties would need to increase the cost of virgin raw materials, pointing again to the regulatory vacuum identified in section 5.2.3.

Weight as a dominant design criterion intensifies from TRL 4 onward, as material choices transform into direct commercial logic. What makes weight a commercial condition rather than only a technical one, is that it carries a significant financial element. Every gram saved translates directly into fuel burn reduction, and airlines, already operating on thin margins, therefore favor lightweight components over sustainable ones. A cabin designer and engineer captured this precisely: *"weight is cost, and therefore cost reduction; everybody likes it"* (INT 1). Design guidelines that do preserve eco-design and CE principles, such as design for disassembly, material traceability, and modularity, lack an equivalent commercial translation, meaning they are structurally outcompeted because they cannot be expressed in the same financial logic as weight reduction.

Market disincentives and customer behavior becomes most visible at TRL 7-9, as technologies move towards industrialization and commercialization. The findings here connect directly to the virgin versus recycled economics described above: an eco-design and sustainability specialist stated plainly that airlines willing to pay a twenty percent premium for a fully recyclable cabin have simply been not encountered in practice. And despite survey data suggesting broad passenger interest in sustainable aviation, an eco-design and sustainability specialist noted the practical reality: *"we often hear the term 'it shouldn't cost anything on top of today' – if the product is more costly, it won't be accepted"* (INT 2). Sustainability therefore seems to only survive when it is commercially aligned with cost reduction.

The interview data therefore does identify conditions in which commercial logic actively enables environmental incentives, operating across the full TRL range. Resource scarcity and supply chain

disruption are the most consistent here: geopolitical tensions affecting critical supply chains, for example those of titanium, have reframed closed-loop strategies as a supply chain resilience, therefore resulting in commercial logic rather than only environmental incentives. Next to this, incentives such as green finance instruments and cheap second-hand part recovery were mentioned as features under which environmental criteria become defensible within the commercial logic of the industry.

5.3 Characteristics of existing methods and tools

One second-order category addresses the requirements for the decision guide, drawing on 23 first-order codes across 5 of 17 interviewees. Unlike the barrier and condition categories, **characteristics of existing methods and tools** sit outside the barrier typology: it does not explain why eco-design and CE principles are difficult to preserve, but surfaces what practitioners identified as necessary requirements for a solution. The findings are therefore treated here as design requirements that inform the decision guide developed in chapter 6.

The most consistent requirement is that a useful decision guide must be lightweight, self-contained, and consultable without specialist involvement. Existing sustainability tools, particularly full LCAs, are widely described as too expensive and too time-consuming. As established in section 5.2.1, LCA outputs are frequently handed to practitioners as raw environmental metrics with no guidance on how to act on them, making the output operationally useless. The solution must therefore be usable by a wide range of practitioners, not only by sustainability specialists.

A second requirement is that sustainability criteria must be translated into commercial and operational language. A cabin designer and engineer suggested converting environmental impacts into cost equivalents to create direct business value arguments, while multiple interviewees emphasized framing circularity as supply chain de-risking and regulatory risk mitigation rather than environmental commitment. This requirement connects directly to the commercial barrier and condition findings in section 5.2.4: a decision guide that presents environmental criteria in the language of cost, risk, and weight, is structurally more adoptable than one that presents them only in environmental terms.

A third requirement concerns adoption conditions: a decision guide must integrate with existing workflows rather than add to them. An eco-design and sustainability specialist noted that tool adoption requires a formal mandate from senior management to avoid remaining a *"nice to have"* (INT 3), while a cabin designer and engineer observed that engineers will only engage with a tool if it saves time and reduces friction in their daily work. Together, these three requirements, usability without specialist involvement, commercial language translation, and workflow integration, define the design space within which the decision guide, presented in chapter 6, operates.

5.4 Conclusion and revision of the theoretical framework

The findings presented in sections 5.1 through 5.3 confirm the core structure of the theoretical framework developed in section 2.5 while requiring one significant revision. All barriers identified in the original three-category typology are confirmed by the interview data, and each category is extended with practitioner-specific barriers and conditions the literature had not captured.

The revision concerns the barrier typology itself. Commercial barriers and conditions emerge from the interview data as a fourth structural category absent from the original framework. The updated

theoretical framework, presented in Figure 10, incorporates this revision by adding commercial barriers as a fourth barrier band and distributing barrier intensity across TRL phases rather than treating all barriers as continuous and uniform. The implications of this revision are further explained in chapter 7.

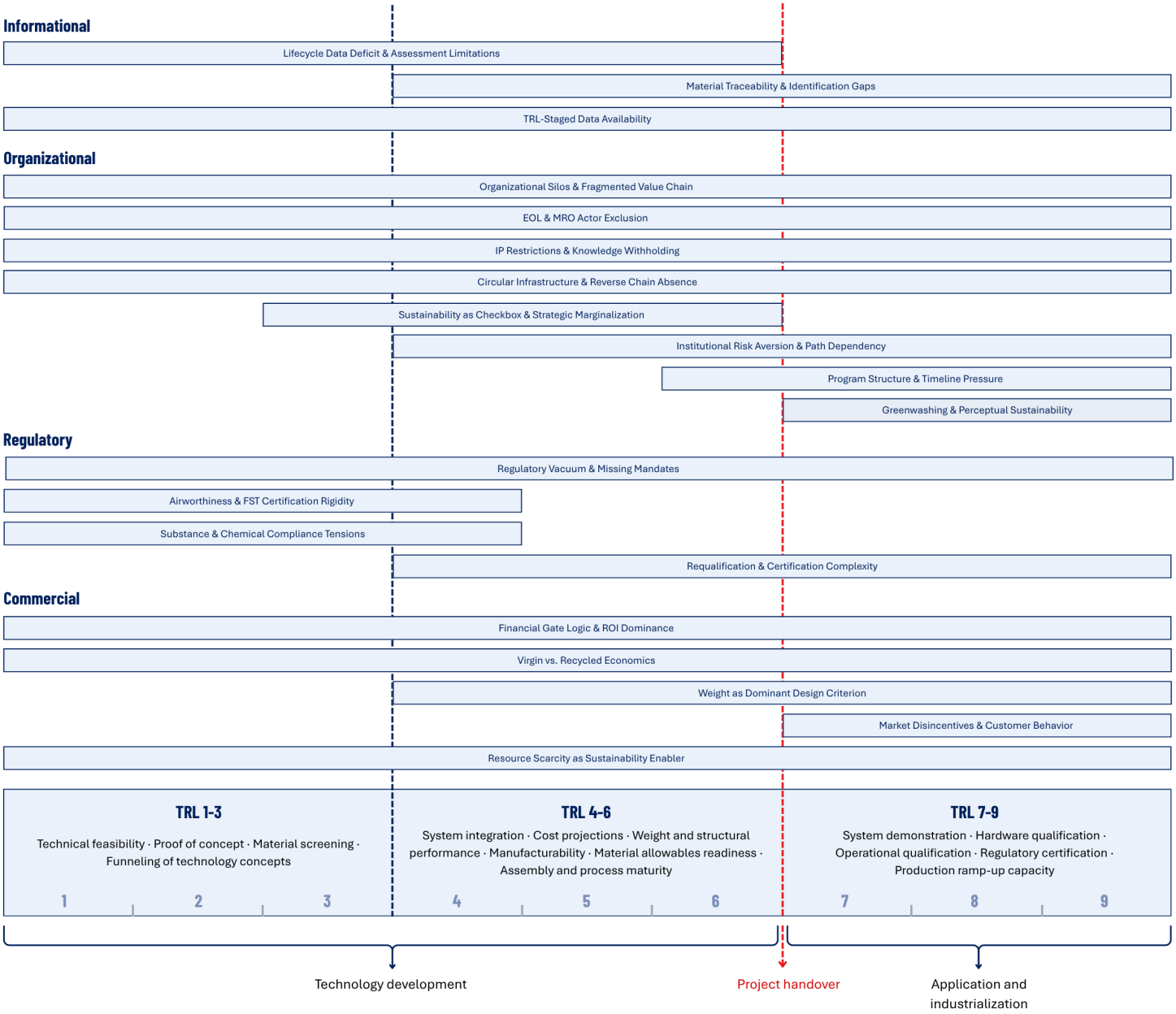

FIGURE 10: *Revised theoretical framework: barriers and conditions across TRL-based aviation technology development*

These findings directly shaped the structure of EcoFlight, developed in chapter 6. The revised four-category barrier and condition typology, including the commercial dimension absent from the original framework, forms the diagnostic content layer of the decision guide, giving practitioners stage-scaled visibility of which barriers and conditions are most active at their current development stage. The distribution of barrier intensity across TRL stages informed the logic through which existing methods and tools are connected to specific moments in the development process. The commercial barrier findings, as the most critical dimension, drove the design of a dedicated component that equips practitioners to justify environmental ambitions into the cost, weight, and risk language that gate decisions respond to. Together, the revised framework provides both the content and the structural logic of EcoFlight's architecture.

06

CHAPTER SIX

Design Phase

How the research converges into EcoFlight: a browser-based decision guide that equips practitioners with the awareness, methods, and commercial framing needed to preserve eco-design and circular economy principles through the gates.

The analytical work of this research, mapping relevant eco-design and CE principles, examining the gate logic that governs aviation technology development, and identifying the barriers and conditions that complicate their preservation, converges on a single design challenge: how to equip practitioners with the awareness, methods, and framing needed to preserve eco-design and CE principles across TRL-based development processes. This chapter outlines how that challenge was addressed through the process, solution, architecture, and choices made in developing **EcoFlight**, a browser-based interactive decision guide for practitioners working in aviation technology development. Appendix J presents an EcoFlight one-pager, that summarizes the solution, its intended audience and how to access it, also serving as an introduction for practitioners encountering the tool.

6.1 Design Approach

The design phase was structured around the double diamond framework, which organizes design processes into four phases: Discover, Define, Develop, and Deliver (Design Council, n.d.), visualized in Figure 11, which provides the structure of this section. Throughout the process, practitioner and ecosystem insights shaped the design as it developed: the barriers and conditions diagnosed in the empirical phase, the requirements they surfaced, and the feedback gathered through co-creation sessions.

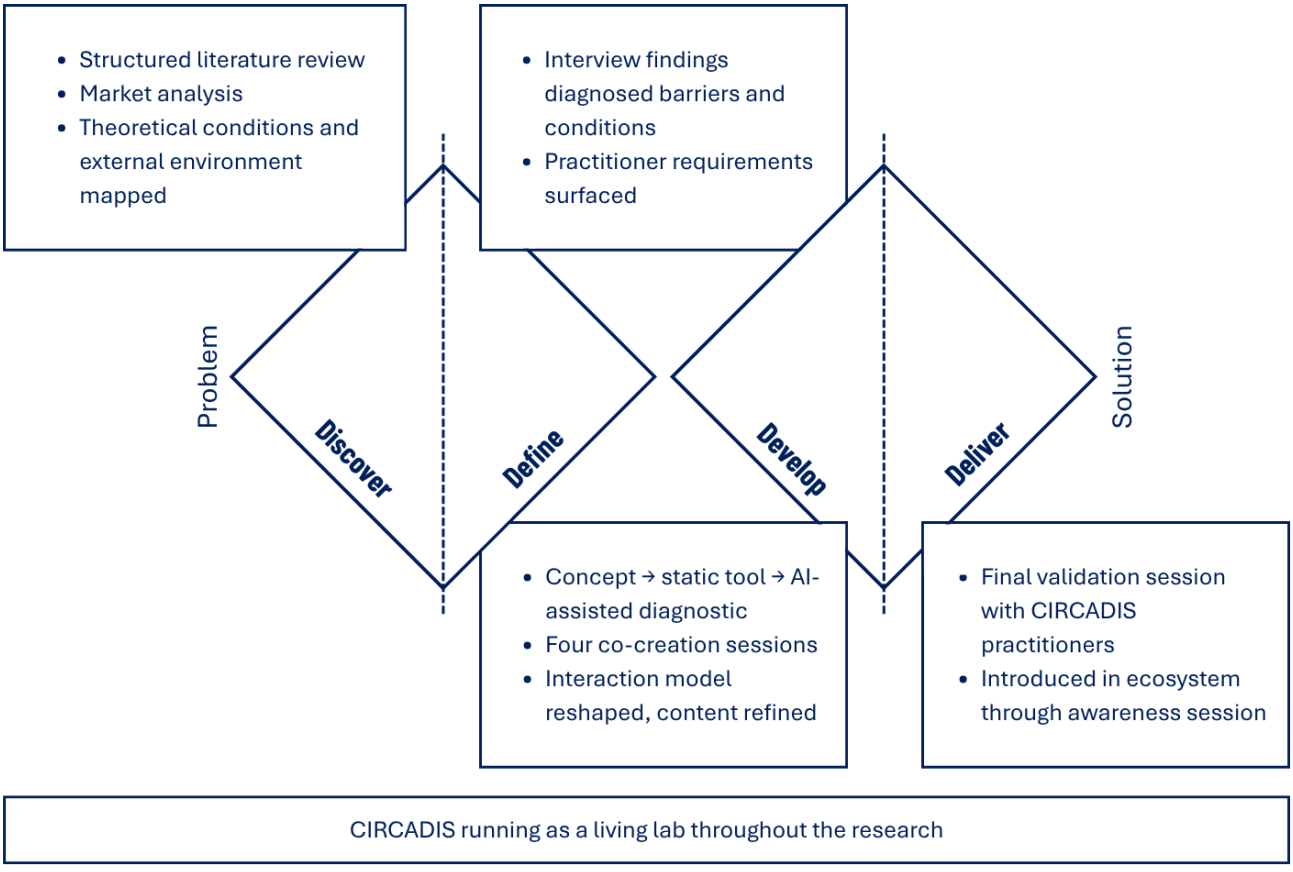

FIGURE 11: *Double diamond framework (Design Council, n.d.)*

Discover and Define

The Discover phase was informed by the structured literature review and market analysis in chapters 2 and 3, establishing the theoretical conditions under which eco-design and CE principles are difficult to preserve and mapping the external environment within which any solution must operate. The Define

phase was shaped by the empirical findings of chapter 5, which diagnosed the barrier and condition structure and surfaced the three practitioner requirements that define the design space: a tool lightweight enough to consult without specialist involvement, capable of translating environmental criteria into commercial language, and able to integrate into existing workflows rather than sit alongside them.

Develop

The Develop phase translated those requirements into a working, interactive decision guide through successive iterations. The CIRCADIS consortium provided direct access to practitioners and an active development context, making it possible to refine the tool against a real project. Methods used within the consortium, including value chain mapping and circular strategy mapping, were performed in workshop settings and adapted into methods within EcoFlight's content. The first response to the practitioner's requirements was not a three-phase decision guide but an editorial concept: a landing page carrying the visual identity and tone of the eventual tool, only consisting of directional content and placeholders. The three-phase structure took shape only as the requirements were mapped onto it, with awareness, operationalization, and commercial framing each becoming a distinct phase. This produced the first functional version of EcoFlight, in which practitioners navigated a static, filter-based barrier and condition library by selecting categories and reading the results.

Four co-creation sessions with practitioners from Airbus, the German Aerospace Center (DLR), the Green Cabin Alliance, and fellow students then tested that version against real use. Consistent findings emerged: the structure resembling a static PDF, dense with barrier categories and labels, created an overload of information rather than orientation, with one participant summarizing the experience as not knowing where to start. The most significant design response was a change to the interaction model and navigation through the three phases. The category-based barrier selector was accompanied with an AI-assisted diagnostic, and the user flow was improved to move naturally between the phases. This moved EcoFlight from a static reference toward a context-sensitive, phased guide. The same sessions drove a series of further refinements, surfacing examples that had been buried, repositioning the foundational concepts of eco-design and CE earlier in the user journey for practitioners without background knowledge, adding a clear statement of audience and purpose to the homepage, and prompting a final content and terminology check aligning all content with the empirical findings of chapter 5.

Deliver

The Deliver phase produced the final version of EcoFlight, which was validated through a concluding round of practitioner feedback within the CIRCADIS consortium, documented in sections 6.4 and 6.5. Delivery also extends beyond the tool itself to its introduction into the aviation ecosystem, through an awareness session open to Airbus practitioners and the broader CIRCADIS consortium, including external stakeholders. The session gives practitioners direct access to EcoFlight and creates the conditions for its adoption beyond the scope of this thesis.

The design decisions made across these iterations produced the final version of EcoFlight, whose three-phase architecture is described in the following section. This is the version used in both the validation session with CIRCADIS practitioners and the final awareness session.

6.2 EcoFlight: the decision guide

EcoFlight is a browser-based decision guide structured around three sequential phases, each making the empirical findings of chapter 5 accessible to practitioners without specialist sustainability knowledge (Figure 12). The tool is currently publicly accessible at **ecoflight.pages.dev**, reflecting the requirement established in section 5.3 that the solution must be consultable without specialist involvement and integrable into existing workflows rather than added alongside them. Both this URL and the GitHub reference can be found on the one-pager in Appendix J.

Each phase addresses a different dimension of the preservation challenge: building awareness of what barriers and conditions exist and when, providing operationalizable methods to identify and address or navigate these in a specific project, and enabling practitioners with the commercial framing needed to justify their environmental ambitions at gate reviews and program handovers.

Before entering Phase 01, practitioners can explore the three foundational concepts that underpin the decision guide: eco-design, CE, and the TRL framework. Each concept is presented on the homepage, providing a definition and its specific relevance to aviation technology development. This entry point ensures that the tool is accessible to practitioners regardless of their familiarity with these concepts.

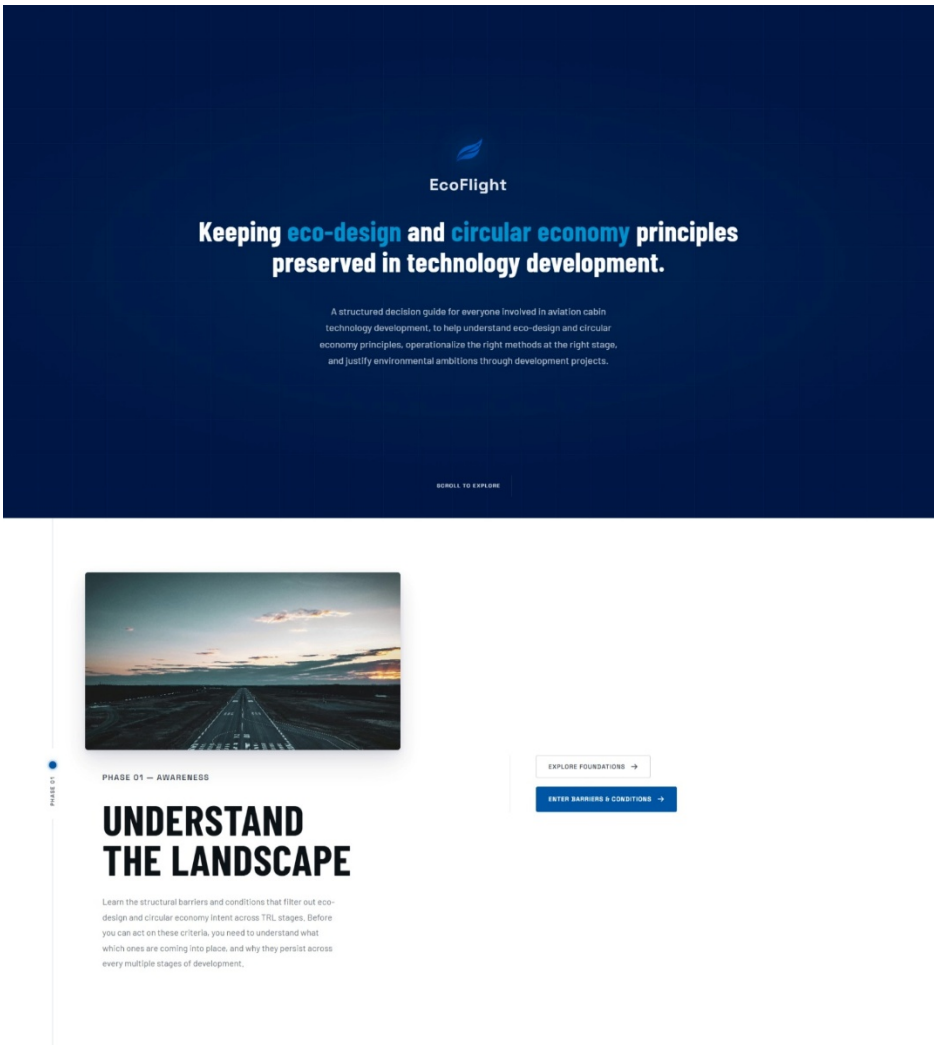

FIGURE 12: *The EcoFlight landing page and first phase entry*

6.2.1 Phase 01 – Awareness

Phase 01 presents the full barrier and condition typology identified in chapter 5, organized by category: informational, organizational, regulatory, and commercial. Practitioners can interact with these barriers and conditions in two ways. The full landscape can be explored in detail, containing all barriers and conditions outlined in the revised theoretical framework, filterable by category and TRL stage. The second interaction is generated through an AI-assisted analysis of the practitioner's input against the full barrier library, with the output consisting of a personalized shortlist of the three to five most active barriers in their specific situation (see Figure 13). Each barrier and condition includes a description and a commercial framing note, translating the barrier directly into language that is more justifiable in the industry. It also connects to methods and tools from Phase 02, and cites possible regulations that could be relevant if the practitioner encounters the selected barriers or conditions.

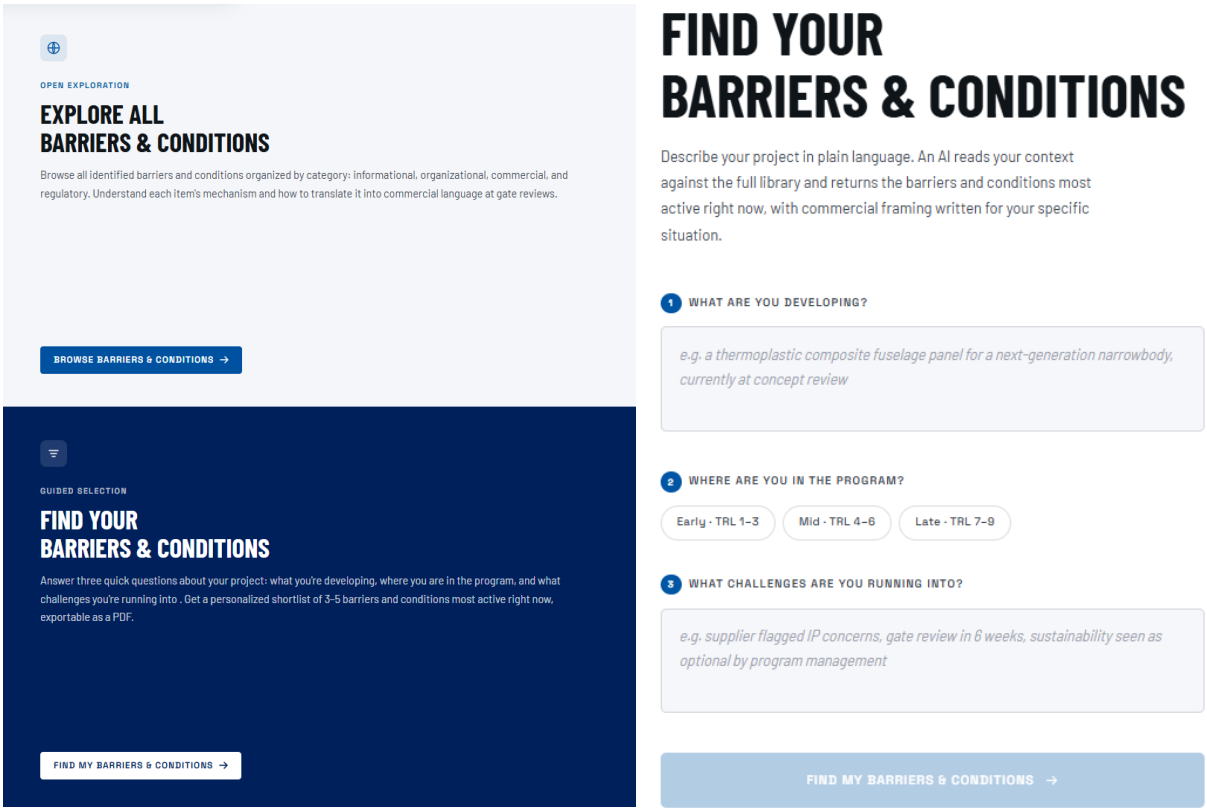

FIGURE 13: *The two options to interact, and the AI-assisted find-your-barrier module*

6.2.2 Phase 02 – Operationalize

Phase 02 presents a set of thirteen methods and tools, each mapped to one or more barrier types and TRL stages (see Figure 14). These methods were selected to identify and navigate the barriers and conditions identified in chapter 5 in specific situation, with the characteristics established in section 5.4 determining how they are presented and filtered. Practitioners filter by barrier type, TRL stage, or both, to find the methods and tools most relevant to their current scenario or project. Each method entry includes a description of what it is, when to use it, how to apply it, and what resources are needed. The filtering logic mirrors the diagnostic sequence a practitioner would follow completing Phase 01: having identified which barriers are active, they can immediately find the methods designed to address them. Methods range from Fast-Track LCA for early TRL informational barriers, to Value Chain and Circular Strategy Mapping for organizational barriers at TRL 1-4, to Business Case

Translation for commercial barriers across TRL 1-6. A full overview of the methods and tools present in Phase 02, can be found in Appendix K.

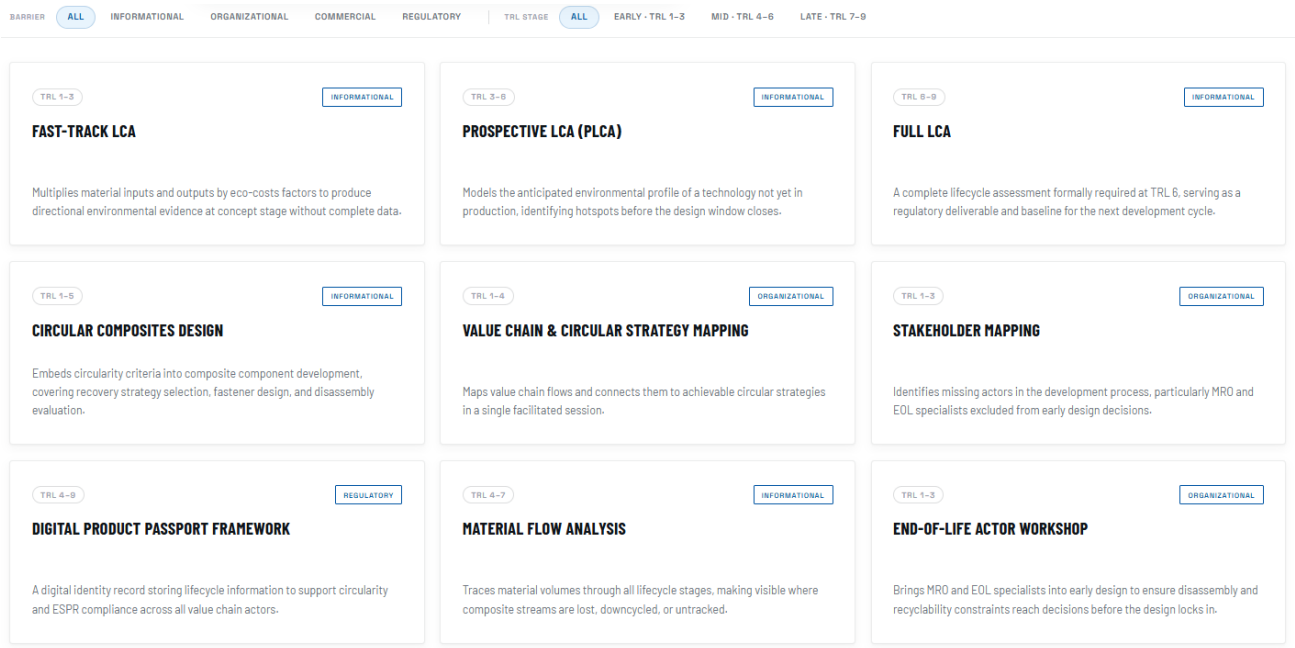

FIGURE 14: *An overview of 9 out of 13 methods and tools present in Phase 02*

6.2.3 Phase 03 – Justify

Phase 03 presents seven conditions under which environmental criteria have survived gate decisions in real aviation development projects. These are not generic recommendations, but examples drawn from the interview findings in chapter 5, each accompanied by a practitioner note explaining how the condition can be replicated or referenced within a different project context. Examples include formal environmental deliverables, resource scarcity reframing circularity as supply chain resilience, and green finance instruments translating environmental ambitions into cost savings. Phase 03 addresses the commercial barrier findings most directly, providing practitioners with the framing language needed to justify environmental ambitions in an ecosystem where commercial logic dominates.

6.3 User flow and information architecture

EcoFlight is designed around a practitioner journey that moves from awareness through operationalization to commercial justification, while remaining flexible enough to be entered at any phase depending on the practitioner's current need. Figure 15 on the next page presents the full user flow.

A practitioner encountering EcoFlight for the first time would typically begin on the homepage, where the three foundational concepts are available as entry points and the three phases are presented as a sequential journey. An AI-enabled navigation assistant on the homepage allows practitioners who already know their situation to describe it in plain language and be routed directly to the most relevant section, bypassing the sequential flow where appropriate.

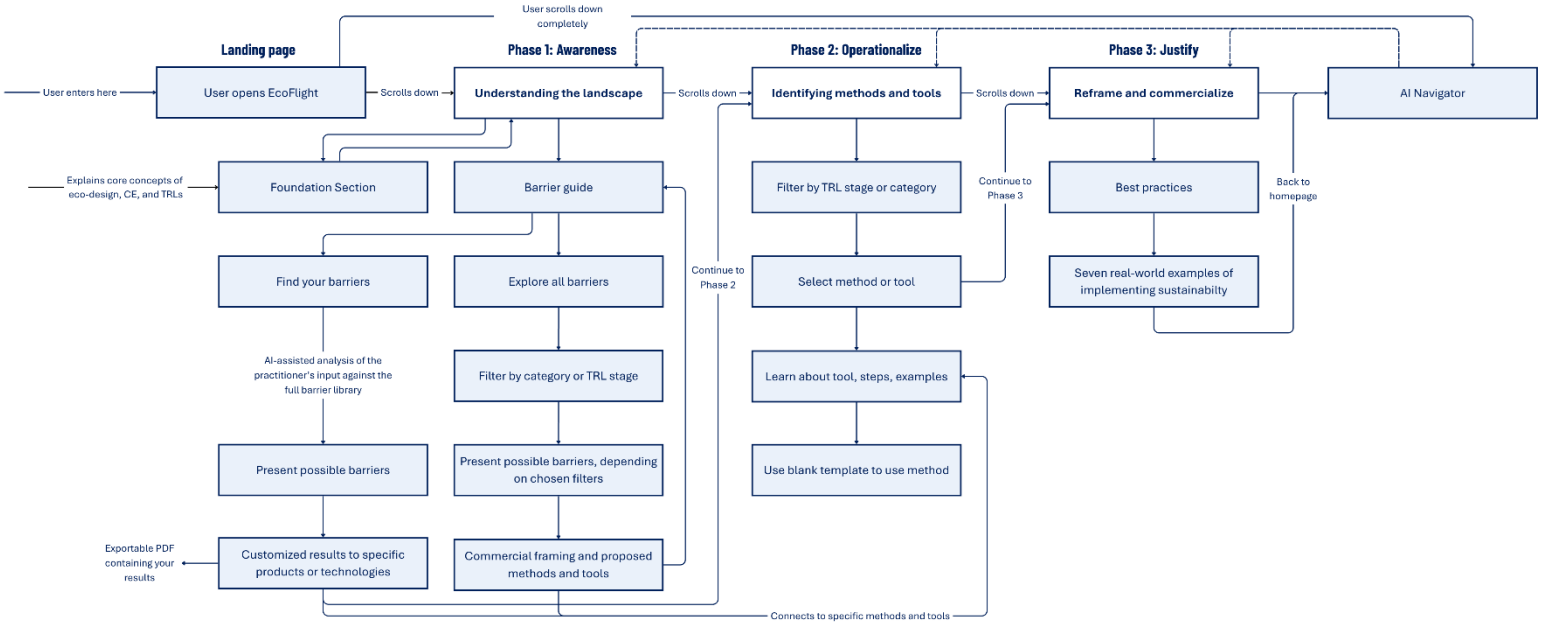

FIGURE 15: *User flow of EcoFlight*

In addition to the user flow, Figure 16 presents an information architecture diagram of EcoFlight. This makes explicit how each layer of the research, the literature review, market analysis, interview findings, and informal Airbus and CIRCADIS discussions, maps onto the tool's structure and content, showing how the empirical findings shaped each of the three phases.

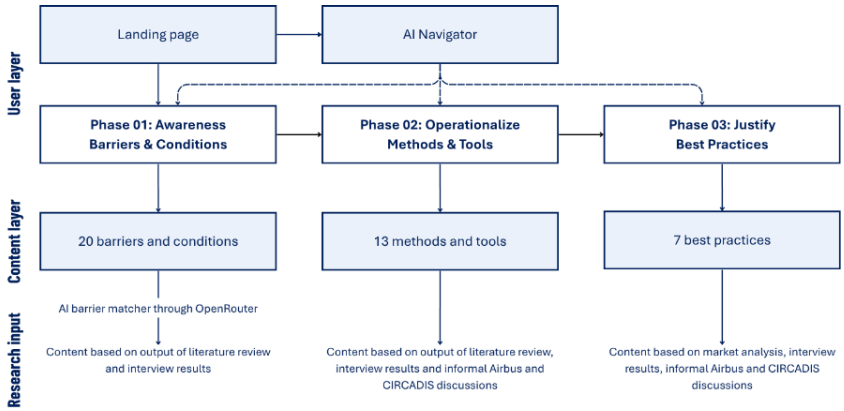

FIGURE 16: *Information architecture of EcoFlight*

A notable element within the information architecture is the AI-assisted barrier and conditions matcher embedded in Phase 01, which deserves specific attention given its role in making the barrier and condition library interactable. This uses a large language model (LLM) accessed via the OpenRouter Application Programming Interface (API) to analyze a practitioner's project context against the full set of 20 barriers and conditions. The practitioner provides three inputs: a text description of what they are developing, a TRL stage selection, and a text description of their current project context. This combination of natural language allows for nuance that predefined categories would flatten, while TRL stage benefits from categorical precision. The model returns a shortlist of three to five barriers, each with a relevance explanation written for the practitioner's specific context and a commercial framing sentence. Output is rendered as category-coded cards and can be exported as a PDF. The feature uses instructions that prevent the LLM from hallucinating or output that is not consistent with the barrier and condition content.

6.4 Validation of EcoFlight

A validation session with partners from the CIRCADIS consortium was designed to assess whether EcoFlight performs as intended, defined here as whether the tool's goal is legible to practitioners, its three-phase procedure is usable, understood and easily navigated, its content is applicable to real project contexts, and its barrier typology and commercial framing are recognizable from practitioner experience. This followed the Framework for Evaluation in Design Science Research (FEDS) proposed by Venable et al. (2016). FEDS structures evaluation through a four-step process: explicating the goals of the evaluation, choosing an evaluation strategy, determining the properties to evaluate, and designing the individual evaluation episode. The properties to evaluate are informed by Method Content Theory (MCT), proposed by Daalhuizen and Cash (2021), which fills the criteria that FEDS leaves open to define. The four-step evaluation process is described in detail below.

Step 1: Explicate the goals of evaluation

The evaluation is primarily summative in purpose: to assess whether EcoFlight, as a final prototype, performs as intended before potential broader deployment within the aviation ecosystem. The goal therefore is to gather qualitative practitioner evidence confirming that EcoFlight's content functions as designed. The evaluation also contains a formative element: Venable et al. (2016) note that "the mechanics of any particular evaluation activity may yield evidence that is useful both formatively and summatively," meaning that where the session surfaces gaps or usability friction, these are reported as directions for future development rather than treated as validation failures.

Step 2: Choose the evaluation strategy

FEDS identifies four evaluation strategies, each suited to different combinations of design risk, resource availability, and evaluation goals. Based on the criteria set by Venable et al. (2016), this evaluation follows a Quick and Simple strategy. Technical risk is low: EcoFlight is a lightweight, stateless browser-based guide requiring no installation, login, or specialist support. Social risk is equally low: the tool does not intervene in or replace existing workflows but supplements them, carries no organizational mandate or dependency, and can be adopted by practitioners without consequence to their organization. Uncertainties regarding content and usability were already reduced through co-creation with practitioners during development, making a single evaluation episode appropriate within the timeframe of the research.

Step 3: Determine the properties to evaluate

FEDS requires the properties of the artifact to be evaluated, adapted to the artifact type and situation. Daalhuizen and Cash (2021) propose five elements, each corresponding to a distinct dimension of how a method functions in context: Method Goal, the described aims and their prioritization; Method Procedure, the structural activities and their chronological and logical ordering; Method Framing, the intended context of use; Method Rationale, the motivations underlying the goals of the method; and Method Mindset, the values, beliefs, and logic informing its use. Together, these five elements provide the evaluation properties against which EcoFlight, functioning as a method to support practitioners in preserving eco-design and CE principles in aviation technology development, is assessed.

Five discussion questions operationalize these elements for the validation session. Each question targets one or more MCT elements as follows.

Q1 Do you think exposure to Phase 01 could help build awareness of barriers and conditions in preserving eco-design and circular economy principles, including people with no prior knowledge? (Method Goal and Method Mindset)

Q2 Does the three-phase structure reflect how you could navigate an environmental challenge throughout a development project? (Method Goal and Method Procedure)

Q3 Does the tool feel scoped to the right context, the right project types, roles, and moments in a development process? (Method Framing)

Q4 Does the framing in Phase 03 resonate with what you need to justify environmental ambitions to other stakeholders? (Method Rationale)

Q5 What would need to be improved for you to reach for this tool in your next project? (All five elements)

Step 4: Design the individual evaluation episode

The evaluation episode was a 30-minute online session conducted with CIRCADIS partners, facilitated by the researcher via shared screen. The eight participants span the cabin component value chain across cabin design, material and component expertise, eco-design and sustainability, MRO, and project management, and are listed with their anonymized roles in Appendix G. The session was recorded with informed consent and transcribed.

The episode was structured in three blocks. The session opened with a statement of purpose, confirmation of informed consent, and an introduction to EcoFlight, in which the researcher outlined the tool, its three-phase structure, and the development scenario participants were asked to hold in mind: a cabin interior component approaching a TRL gate review, where a circular strategy must be justified under cost and schedule pressure (5 minutes). Participants then navigated EcoFlight themselves in breakout rooms, exploring the three phases freely against the scenario and the five discussion questions, which were shared together with the tool link (10 minutes). The session closed with a facilitated discussion in which one participant per breakout room walked through their findings and responded to the questions (15 minutes). This discussion informs the analysis in section 6.5.

The session did not test actual use in a live development project, behavioral outcomes over time, or independent adoption outside a facilitated setting. These boundaries are reflected in the interpretation in section 6.5.

6.5 Analysis of EcoFlight

This section applies the evaluation elements and questions established in section 6.4 to analyze how each of EcoFlight's five method content elements performs, and how practitioners responded to the decision guide in general. It combines the design rationale established in sections 6.1 through 6.3 with the empirical findings of the validation session. Relevant quotes and observations were drawn from the session transcript by reviewing participant responses against the discussion question each MCT element was designed to elicit. Where a finding was expressed by multiple participants it is noted as shared; where it reflects a single participant's view, this is indicated. The eight validation participants referred to throughout this section by their validation IDs.

Additionally, Table 1 maps participant responses to each MCT element, distinguishing supporting from critical views.

MCT Element	Supporting	Critical
Method Goal	VAL 3, VAL 6, VAL 7	VAL 1, VAL 2, VAL 4; blocked by API error
Method Procedure	Val 5, VAL 7	VAL 4: linear structure critiqued; VAL 5: interruption noted
Method Framing	VAL 1, VAL 4, VAL 5, VAL 6	-
Method Rationale	VAL 4, VAL 5, VAL 6, VAL 7	VAL 1, VAL 2, VAL 3: insufficient time to reach Phase 03
Method Mindset	VAL 4, VAL 7	Limited engagement across session

TABLE 1: *Participant responses mapped to MCT elements. Participants not listed for a given element gave no substantive response to the corresponding discussion question.*

Method Goal

Method goal defines what EcoFlight aims to achieve. The goal is specific: to increase the likelihood that eco-design and CE principles are preserved throughout TRL-based development projects in aviation technology development. This contributes to the broader goal of reducing the environmental footprint of the aviation industry. It is not a goal to directly resolve the barriers or conditions identified in chapters 2 and 5, some of which are structural conditions that a practitioner-facing tool cannot remove. The goal becomes clear for the user as soon as the decision guide is entered, as the landing page explains the aims and the potential audience.

The validation session indicated that the prioritization of this goal across the three phases was legible to practitioners. An eco-design and sustainability specialist situated the awareness phase as a precondition for the rest, noting that *"having phase 1 in the mix is, I think, the most important; that it's all understood before you can even start implementing these kind of practices into your project"* (VAL 7), confirming that the sequencing of the goal, awareness before implementation, matched how participants understood the problem. A material and component expert validated the goal's relevance for practitioners without prior knowledge, finding it useful for early-stage decisions such as integrating environmental ambitions into grant proposals (VAL 6). An MRO representative raised a mixed response, appreciating the output of Phase 01 while questioning its actionability: *"I did like the results that gave us, but I'm curious, how to work with that further along the process"* (VAL 3). Three participants from project management and cabin design (VAL 1, VAL 2, VAL 4) were blocked by a technical error during the navigation in Phase 01, therefore limiting their substantive responses to Q1.

Method Procedure

Method Procedure describes the step-by-step mechanics of the tool. The procedure is the three-phase sequential journey documented in section 6.2. It is designed to be entered at any phase depending on immediate need, and the navigation assistant provides an alternative entry point for practitioners who can describe their situation in plain language.

An eco-design and sustainability specialist supported the linear structure, arguing it ensures foundational understanding before implementation (VAL 7). A cabin designer and engineer pushed back, reporting initial difficulty with the hierarchy: *"I struggled a bit on the structure. What is a phase? What is a method, tool or best practice? So, it took a bit of time needed to learn what is now the hierarchy between the items, but at the end it was quite clear"* (VAL 4). The same participant suggested that the justification phase is sometimes relevant from the outset, *"especially regarding stakeholder management and defining KPIs and requirements,"* proposing a cyclical reading in which *"phase three*

is also feeding phase one somehow" (VAL 4). An eco-design and sustainability specialist identified a specific friction point where the inputs in Phase 01 interrupted the navigation flow, noting *"the flow breaks"* (VAL 5). These critiques point to a procedure that is coherent in design but benefits from clearer onboarding and navigating between phases. The diagnostic logic of the procedure was supported separately, with the same participant noting being *"surprised how accurately EcoFlight could fetch the results of the barrier that I recognize"* (VAL 5).

Method Framing

Method Framing establishes the operational boundaries of EcoFlight: when, where, and by whom it should be used. While its primary context is scoped to practitioners in aviation technology development, it is relevant to anyone working on or adjacent to the preservation of eco-design and CE principles, including engineers, designers, project managers, sustainability coordinators, and communication departments. The prerequisites are minimal by design: no prior expertise in eco-design or lifecycle assessment is required, and the tool operates without login, installation, or specialist support. That accessibility is a deliberate decision, reflecting the finding from section 5.3 that a useful tool must be consultable without specialist involvement and reduce rather than add friction in the practitioner's daily work.

A cabin designer and engineer confirmed the content matched the realities of the industry, noting the challenges presented *"are really relevant and really industry or part of our industry"* (VAL 4). An eco-design and sustainability specialist found the tool tightly framed to a specific project context when tested against a real scenario (VAL 5). A material and component expert positioned himself as a low-prior-knowledge user, stating *"I'm one of the people with no prior knowledge,"* and reported the tool guided him on early-stage decisions, such as integrating environmental ambitions directly *"into a grant, for example, or into a project proposal"* (VAL 6).

Method Rationale

Method Rationale explains why practitioners are motivated to use EcoFlight in their specific context. The rationale is grounded in the empirical findings of chapter 5: the compounding barriers and conditions that prevent eco-design and CE principles from being preserved in technology development projects. Practitioners who understand which barriers are active, which methods could identify and address them, and how to translate environmental criteria into commercial language are better positioned to justify those principles. The rationale is not environmental but operational: EcoFlight helps motivated practitioners, to reduce the risk of environmental ambitions being dropped at, for example, TRL reviews or program handovers.

An eco-design and sustainability specialist highlighted why the framing is necessary, noting that practitioners frequently forget that eco-design *"needs to be justified and it needs to be reasoned... this is why it fits within our company"* (VAL 7). A cabin designer and engineer responded directly to this logic, identifying supply chain resilience as *"a kind of backdoor introduction of circularity, because that's a language commercial managers respond to,"* confirming that the Phase 03 framing *"does really help"* the justification (VAL 4). An eco-design and sustainability specialist reached Phase 03 and found the rationale useful for framing an upcoming stakeholder review, noting how the phase helped him communicate what was needed (VAL 5). A material and component expert found the rationale relevant to his own project context (VAL 6). Three participants from project management and MRO (VAL 1, VAL 2, VAL 3) did not engage substantively with this element due to time constraints following the technical error mentioned previously.

Method Mindset

Method Mindset captures the values, beliefs, and logic informing EcoFlight's use. That orientation is a translation mindset, treating eco-design and CE principles as positions to be reframed in the commercial and operational terms decision-makers already respond to, rather than argued on environmental ambitions alone. The requirement in section 5.3 grounds this, describing not a lack of intent among practitioners but a lack of the framing needed to carry environmental criteria through a commercial ecosystem.

No participant offered a direct response to a Mindset-targeted question. A cabin designer and engineer demonstrated the underlying logic implicitly, acknowledging that circularity must be translated into commercial concepts *"like supply chain resilience"* (VAL 4), indicating that the mindset EcoFlight requires is already present among at least some practitioners. An eco-design and sustainability specialist reflected a related mindset dimension in her suggestion that the tool should allow companies to integrate their own internal sustainability practices, signaling an understanding that the translation logic must connect to organizational context to be effective (VAL 7). The limited engagement with this element across the session means it remains the least evidenced of the five.

Synthesis

Taken together, the five elements suggest EcoFlight is perceived as internally coherent and relevant by the practitioners. The session provided preliminary evidence that the method content functions largely as designed across the elements it was able to test: the three-phase structure was recognized as a logical progression, the commercial framing resonated with multiple participants, and the barrier diagnostic was noted for its accuracy. These findings should be interpreted within the constraints of the session. Eight participants were involved, several already familiar with the research context through the CIRCADIS consortium, which may have elevated perceived relevance. A technical error prevented three participants from fully navigating Phase 01, limiting feedback on Method Goal and Method Mindset in particular. The ten-minute self-navigation window also meant that most participants could not explore all three phases in equal depth, a gap that a longer, task-based evaluation in a real project context could address. A project manager expressed frustration at being unable to engage: "*frustrated because I couldn't dig into it*" (VAL 1). The session therefore captures perceived relevance and potential usefulness after a short, facilitated navigation period, and does not demonstrate effectiveness in a live development project, sustained independent use, or adoption outside a consortium setting.

Two refinements emerged. The three-phase architecture may function better as a cycle than a strict linear sequence, as a cabin designer and engineer proposed. A clearer onboarding experience could address this as well, helping practitioners navigate the hierarchy more quickly without requiring time to orient themselves first.

Beyond the five elements, multiple signals of adoption intent were there. A material and component expert asked whether the tool would remain accessible so it could be shared with his team, stating *"I want to spend more time on it... I think it might be of interest to also share it with our team*" (VAL 6), and a project manager expressed interest in applying it directly to the CIRCADIS project, noting *"I think it could be interesting for our project to use it"* (VAL 1). These signals indicate intent rather than actual use, and their value lies in confirming that the tool's content and framing are recognized as relevant. Translating that intent into sustained use will be facilitated through a clear ownership decision for EcoFlight, whether within Airbus, the CIRCADIS consortium, or as an openly accessible resource.

07

CHAPTER SEVEN

Discussion and Limitations

What the findings mean in relation to existing knowledge and the research and design objectives: the theoretical and practical contributions of the work, its limitations, and the directions it opens for future research.

The previous chapters have established the theoretical conditions under which eco-design and CE principles are difficult to preserve in TRL-based aviation technology development, diagnosed the barrier and condition structure that produces those difficulties in practice, and presented EcoFlight as a designed solution. This chapter reflects on what those findings mean in relation to existing knowledge and the research and design objectives set out in chapter 1.

7.1 Theoretical contributions

The first objective of this research was to diagnose the barriers and conditions that complicate the preservation of eco-design and CE principles in aviation technology development, specifically applied to cabin components. The theoretical framework developed in section 2.5 provided a literature-derived starting point, organizing barriers into three categories: informational, organizational, and regulatory. Previously, these barriers described, either at the level of industry-wide infrastructure instead of scoped to development projects (EASA, 2023a; Papadaki & Maleviti, 2025), or theoretically without empirical validation in a specific context (Chebaeva et al., 2021). A close parallel, Hallstedt & Pigosso (2017), applied a sustainability framework across TRLs 1–9 at an aerospace engine manufacturer, but focused on integrating criteria into existing frameworks rather than identifying the barriers and conditions that prevent those criteria from surviving. The empirical findings of chapter 5 confirm that the literature-derived typology holds in aviation cabin component development: all ten barriers identified in the original framework are recognized across the value chain, providing the empirical grounding that previous frameworks left for future work.

The findings are also more detailed and specifically scoped to the TRL framework than existing aviation literature provides. Chebaeva et al. (2021) theorized how informational barriers shift in intensity across TRL stages, and Wiesner et al. (2025) empirically mapped data-exchange pain points across the aviation value chain. Chebaeva et al. (2021) left empirical validation for future work, while Wiesner et al. (2025) focused exclusively on informational barriers related to data transparency and Digital Product Passports, leaving the full spectrum of informational, organizational, regulatory and commercial barriers and conditions and its compounding nature across TRL stages unaddressed. Mankins (1995) presented the TRL 6–7 transition as a shift toward management confidence over research requirements. The empirical findings of chapter 5 confirm and extend this observation: the transfer of decision authority at this threshold brings a corresponding shift in values, from engineering intent toward financial risk and schedule. This confirms that ownership, and the values it carries, is a structural determinant of whether environmental ambitions survive development. The empirical analysis in chapter 5 maps this full spectrum of where specific barriers are most acute and how they interact as technology matures, producing a more extensive, granular and empirically grounded account than aviation literature had previously offered for this domain.

An important theoretical revision concerns the typology of the commercial barrier and condition category. The original framework derived from literature did not include commercial logic as a distinct category, distributing commercial conditions across organizational and regulatory barriers instead. Existing aviation literature identified commercial and financial logic as a barrier at the end-of-life or regulatory level (EASA, 2023a; Papadaki & Maleviti, 2025), and Santos et al. (2016) show that cost analysis acts as a filter in material selection. However, the interview findings found that the commercial logic operates outside of the initial three categories, as a foundational filter that determines whether other barriers are addressed or left in place. That the commercial category reached 16 of 17 interviewees, the highest reach of any category in the dataset makes the case for its distinctiveness difficult to dismiss.

7.2 Practical contributions

The barrier and condition maps produced by this research represent its most transferable practical output: verified across 17 practitioners, spanning the majority of the aviation cabin value chain, they constitute an empirically grounded mapping applicable beyond only the CIRCADIS context. Where most existing barrier and condition typologies in the literature were constructed from general manufacturing or aerospace contexts, the maps developed here are specifically validated for aviation cabin component development across TRL stages, making them directly usable by teams, sustainability coordinators, and program leads working in this domain without requiring adaptation from a more generic framework.

The second objective of this research was to translate those findings into a practical, interactive decision guide that builds awareness of barriers and conditions, provides operationalizable methods to navigate them, and equips practitioners with the framing needed to justify circular design decisions at gate reviews. EcoFlight addresses that objective directly. It is the first empirically grounded, practitioner-facing guide developed for this domain across TRL stages, and designed to be consultable without specialist sustainability knowledge. In doing so, it addresses the gap identified in section 1.6: R&T teams working on cabin components currently lack a tool that is operationalizable within the constraints of commercial aviation development and capable of translating circular intent into terms that survive gate reviews. Its development through active participation in the CIRCADIS consortium, also represents a contribution: the design process was grounded in a live development context, allowing the tool's content and interaction model to be tested and refined against real practitioner experience rather than hypothetical scenarios.

For the Airbus and broader aviation ecosystem, EcoFlight's contribution extends beyond its immediate utility as a tool. By making the barrier and condition structure visible and actionable for practitioners who would otherwise operate without structured guidance, it creates the conditions for bottom-up diffusion of environmental ambitions across organizations. The lone wolf environmentalists described in section 5.2.2, practitioners with genuine ambitions but without organizational mandate or peer support, gain a structured reference that validates their position and equips them to communicate it in commercially legible terms. At the ecosystem level, EcoFlight represents an early example of the practitioner-facing decision support that the CirculAir Playbook and Green Cabin Alliance initiatives signal is increasingly recognized as necessary across the industry, demonstrating that the gap between sustainability ambition and operational guidance is both real and addressable.

7.3 Limitations

Although the theoretical and practical contributions are concluded, their accompanying limitations are important to consider when drawing conclusions from the findings of this research.

The first concerns the generalized scope of the research and its output. Addressing the full aviation cabin value chain produces findings that are broadly applicable across a wide range of practitioners and programs, but it also means that the results and EcoFlight's content cannot fully account for the technical, contractual, and organizational complexities specific to individual programs, products, or materials. Practitioners working on highly specialized components or operating within atypical organizational structures may find that the tool's guidance requires adaptation to their specific context.

The second limitation concerns stakeholder reach. While the interview sample spans the cabin component value chain across five stakeholder categories, it is weighted toward engineers, designers, and operational specialists, with limited representation from senior program managers and executive decision-makers. These are precisely the actors whose gate decisions determine whether circular criteria survive, and their perspective is underrepresented in the findings. Two compounding factors explain this gap: the difficulty of securing access to senior decision-makers within the timelines of a graduation project, and the confidentiality constraints that make it difficult for individuals in senior positions to speak openly on behalf of their organizations in a public research context.

The third limitation is directly connected to the CIRCADIS context. As established in section 1.5, the consortium represents a more collaborative and sustainability-conscious development environment than is standard across the industry. The interview sample reflects this: participants were, overall, more engaged with eco-design and CE principles than a random sample of aviation practitioners would be. In less supportive environments, where sustainability carries no formal consortium obligation and no grant mandate, the barriers identified in chapter 5 may operate with even more force and with fewer of the enabling conditions CIRCADIS practitioners could draw on. This favorable context does, however, have analytical value: it surfaced the enabling conditions and best practices that inform EcoFlight's Phase 03 content, providing a grounded account of what becomes possible when organizational conditions are aligned.

A final limitation concerns timing. The interview data was collected in early 2026, at a moment when, as also described by practitioners, the aviation industry's sustainability ambitions appear to have lowered compared to for example, the period between 2019 and 2022. During those years, sustainability ambitions appeared more prominently embedded in organizational strategy and customer demands, a period that coincided with the broader public attention to aviation's environmental footprint during and after the COVID-19 pandemic. Practitioners consistently described a shift in priorities toward defense spending, production ramp-up capacity, and schedule recovery, with sustainability initiatives deprioritized in the absence of client-driven demand or regulatory mandates. The barrier and condition intensities documented in chapter 5 may therefore reflect a somewhat unfavorable moment in the industry's sustainability trajectory rather than a stable structural condition. Alongside this, the regulatory landscape underpinning several of EcoFlight's content assumptions is actively evolving: the ESPR, CSRD, and anticipated end-of-life mandates were still developing at the time of writing, meaning both the findings and the tool's guidance may require updating as market conditions shift and regulatory obligations further develop.

7.4 Recommendations and future work

The limitations identified in section 7.3 point toward concrete directions for future research. These range from immediately actionable steps within existing organizational structures to longer-term developments that require institutional commitment or further research investment.

The most immediate priority concerns stakeholder reach. Future research should explicitly target senior program managers and executive decision-makers as a primary interview population rather than a supplementary one. Their decisions determine whether circular criteria survive gate reviews, yet their perspective is largely absent from the empirical foundation of this research. A dedicated interview round with this population, structured around specific gate review moments rather than general experience, would significantly strengthen the barrier typology and sharpen the commercial framing guidance in EcoFlight's Phase 03.

A second, near-term recommendation concerns the scope of the findings. Future work could scope the barrier typology and EcoFlight's content to a specific cabin component, such as overhead stowage compartment doors or passenger seat assemblies, testing whether the generalized findings hold at a more granular level and identifying component-specific barriers and enabling conditions that the current research could not capture. This would also allow for more precise method recommendations in Phase 02, replacing the current broad applicability with component-specific guidance. Developing a component-specific decision guide for thermoplastic composite cabin structures, for example, would build directly on the CIRCADIS case and test the scalability of EcoFlight's architecture to a narrower, more technically specific domain. Equally, the inverse direction is equally worth exploring. The barriers this research identifies are not unique to aviation: commercial gate logic, value chain fragmentation, and certification rigidity appear in other industries with similarly complex development processes, such as automotive. Testing whether the barrier and condition typology transfers to other contexts could therefore validate the generalizability of the findings

Validation beyond the CIRCADIS context represents a third priority. The consortium's favorable conditions mean that the barrier typology was validated in an environment more conducive to circular intent than most aviation programs. Extending validation sessions to programs operating under standard commercial constraints, without grant-mandated sustainability deliverables, would test the transferability of both the findings and EcoFlight's guidance under less favorable conditions. A longer, real-life validation would also address the time constraints of the current session, allowing participants to engage with all three phases in depth rather than only the features reachable within a short, facilitated window.

In the long term, a recommendation for EcoFlight itself is its formalization as a mandatory checkpoint within the TRL gate process. Section 5.3 established that tool adoption requires an explicit organizational mandate to avoid remaining a “nice to have.” For example, proposing EcoFlight's three-phase structure as a required input at TRL 3 and TRL 6 gate reviews, as part of Airbus R&T's internal gate preparation documentation, would create the institutional condition under which the tool's guidance moves from voluntary consultation to structural requirement. This recommendation connects directly to the enabling condition identified in section 5.2.4: environmental ambitions survive when they are embedded into formal project obligations rather than left to individual initiative.

A stateful, data-driven iteration of EcoFlight represents the logical next development step beyond formalization. The current tool is stateless by design, reflecting the constraints of a single research project and the preference for a lightweight, accessible instrument. A future version in which circular criteria, barrier assessments, and commercial framing arguments are tracked across successive gate reviews would allow teams to demonstrate at each gate how earlier environmental commitments have been maintained or deprioritized and why. This would also enable longitudinal research into whether EcoFlight's use changes gate outcomes over time, providing the empirical validation that the current research phase and validation sessions did not offer.

Finally, EcoFlight's content and structure lend themselves to deployment as a training instrument. Embedding the three-phase logic into onboarding programs for R&T engineers, or into continuing development curricula for sustainability coordinators, would build baseline eco-design and CE literacy across organizations in a way that does not depend on practitioners finding the tool independently. Evaluating the effectiveness of EcoFlight as an organizational learning instrument, and its role in building sustained eco-design capability across aviation R&T teams, represents a final and compelling direction for future work.

08

CHAPTER EIGHT

Conclusion

Answering the four subquestions and the main research question: how eco-design and circular economy principles can be preserved in TRL-based aviation technology development.

This research set out to answer a specific question about a structural problem in aviation technology development: how eco-design and circular economy principles can be preserved in TRL-based aviation technology development. The CIRCADIS consortium, developing a circular thermoplastic overhead stowage compartment door across TRL 2 to 5, served as the living laboratory in which this question was grounded. Workshops, value chain mapping sessions, and direct practitioner engagement conducted within the consortium illustrated the barriers identified by the research and confirmed the relevance of the conclusions drawn from them. The four subquestions below build the analytical foundation for the main research question, answered at the close of this chapter.

Subquestion 1: What eco-design and CE principles are relevant to cabin components?

A comprehensive basis for applying eco-design and CE principles to cabin components exists in the literature, mapped across principles, strategies, and design guidelines in Appendices B and C. In practice, however, their application collapses toward a single criterion: weight. Because the operational use phase accounts for up to 98% of a cabin component's lifecycle emissions, lightweighting functions as the dominant eco-design criterion in aviation, absorbing the environmental agenda at the expense of the broader range of CE strategies that operate across the full product lifecycle. Higher-value strategies such as reuse, remanufacturing, and design for disassembly remain largely underexplored, not because they are irrelevant but because the awareness, methods, and commercial arguments needed to pursue them are absent from most development processes. Making those strategies visible and actionable for practitioners represents one of the clearest opportunities for improving the environmental performance of cabin component development.

Subquestion 2: What criteria currently drive decision-making at TRL gates in aviation technology development?

TRL gate decisions in aviation technology development are governed primarily by financial viability, weight performance, schedule compatibility, and certification feasibility. Environmental criteria do appear at gate reviews, but consistently as the last item assessed after all technical and commercial criteria have been evaluated. Environmental assessments are conducted at specific gate moments but function as compliance exercises rather than design inputs, delivered by subcontracted departments in metrics that designers have neither the training nor the authority to act on. The program handover at TRL 6 represents the critical threshold: decision authority shifts from R&T engineers to program managers whose mandate is defined by cost, schedule, and industrialization, after which eco-design and CE principles that have not been translated into commercial terms are unlikely to survive.

Subquestion 3: What barriers and conditions cause eco-design and CE principles to be deprioritized during aviation technology development?

Four compounding barrier and condition categories explain why eco-design and CE principles are systematically deprioritized. Informational barriers, including lifecycle data deficits, material traceability gaps, and TRL-staged data availability, prevent meaningful environmental assessment at the stages where design decisions are still open. Organizational barriers, including value chain fragmentation, EOL and MRO actor exclusion, IP restrictions, institutional risk aversion, and sustainability marginalization, structurally prevent the coordinated action that circular strategies require. Regulatory barriers, including FST certification rigidity, substance compliance tensions, requalification complexity, and the absence of binding end-of-life mandates, eliminate alternatives that managed to survive the first two barrier categories. Commercial barriers, emerging from the interview data as a fourth category: financial gate logic, the unfavorable economics of recycled versus

virgin materials, and weight as a dominant commercial proxy collectively determine whether environmental ambitions come through at all.

Subquestion 4: What characteristics must a decision guide possess to effectively support practitioners in preserving eco-design and CE principles throughout TRL-based development projects?

Three characteristics are necessary for a decision guide to be effective in this context. It must be lightweight and consultable without specialist involvement, providing immediate and contextually relevant output without requiring a dedicated sustainability department to interpret the results. It must translate sustainability criteria into commercial and operational language, presenting environmental criteria in terms of cost reduction, risk mitigation, and supply chain resilience rather than environmental value alone. Finally, it must integrate with existing workflows rather than add to them, operating within gate preparation routines rather than alongside them as a parallel process.

Main Research Question: How can eco-design and circular economy principles be preserved in TRL-based aviation technology development?

Eco-design and CE principles can be preserved in TRL-based aviation technology development by equipping R&T practitioners with three capabilities: stage-scaled visibility of which barriers and conditions are active in their development context, operationalizable methods for identifying and navigating these barriers and conditions in a specific project, and commercial framing that allows practitioners to justify environmental ambitions to the program management and other stakeholders who govern gate outcomes. EcoFlight, the browser-based interactive decision guide developed in this research, delivers these capabilities without requiring practitioners to prioritize sustainability on its own terms.

What this thesis does not claim is that EcoFlight reforms the gate logic of aviation development, resolves the commercial barriers that dominate gate decisions, or guarantees that environmental criteria will survive. The contribution is narrower and more defensible: it shows that eco-design and CE principles can be made visible, actionable, and commercially defensible within the existing logic, and that practitioners equipped with the right awareness, methods, and framing are better positioned to act on environmental ambitions they already hold. The CIRCADIS consortium, as the living laboratory in which these findings were grounded and tested, demonstrated that the conditions for this kind of practitioner-level action can be created.

Aviation has the ambition, the practitioners, and increasingly the external pressure to lower the environmental impact of the industry, and more specifically, cabin components. What it has lacked is a structured, commercially legible way for individual practitioners to act on that ambition within the gate logic that governs their work. This research demonstrates that the barriers and conditions preventing environmental intentions from surviving TRL gate decisions are significant, compounding, and difficult to address directly. However, where practitioners are aware of what these barriers and conditions are, they have the methods to identify them, and the language to justify them, environmental criteria could survive. EcoFlight is designed to give more practitioners access to all three, and in doing so, to contribute to an aviation ecosystem whose structural environmental impact is no longer a given.

09

CHAPTER NINE

Personal Reflection

Looking back on the thesis through three lenses from industrial design practice: desirability, feasibility, and viability, and a closing personal note on the goals set at the start.

This reflection looks back on the thesis through three lenses derived from industrial design practice: desirability, feasibility, and viability. Each offers a different angle on what this research achieved, and where its limits lie.

Desirability

Desirability is where the results really stood out to me. The co-creation sessions and informal feedback consistently showed that practitioners responded positively to having the barrier and condition typology, methods, and commercial framing brought together in a single guide. What people noted most was accessibility: not another report, not another presentation, but something they could actually open at their desk and interact with. More striking, however, was what the interviews had already revealed: across the value chain, practitioners are intrinsically motivated to work on environmental problems, often within organizational conditions that work against them. That finding shaped the ambition of the tool as much as the barrier typology did. The open questions that remain, who will use this beyond the immediate research context, how it will spread, how it will stay up-to-date, are important to keep the guide desirable.

Feasibility

Feasibility as a lens reveals a set of trade-offs. The stateless, browser-based architecture kept the tool buildable within the scope of a single thesis project, improved accessibility, and removed institutional dependency between tool and user. That constraint also creates a ceiling: a more data-driven version, one that adapts to a user's specific project context and tracks criteria across projects, could increase operational value significantly but requires technical investment and infrastructure decisions that sit beyond this project's scope. If fully adopted by an organization like Airbus, this could prove feasible in the future though. With the internal knowledge already there, combined with the foundation this report and guide has built, an upgraded version of EcoFlight could be within reach.

Viability

Viability also covers some limits. Without a named owner after this project concludes, EcoFlight will become outdated, and the time-bound regulatory and commercial landscape described in chapters 3 and 5 means that outdated content erodes its credibility quickly. The current, most realistic path to lasting impact is rapid spread: if the tool reaches enough practitioners before its content ages, it might shift how people think about eco-design and CE in aviation. Nonetheless, the tool has proven adoptable within the ecosystem, and with a possible handover near the end of the research, this guide might receive a structural place in Airbus.

9.1 Personal notes

Looking back at the goals I set for myself at the start of this project, I can say with confidence that all of them were met, and several were exceeded in ways I did not anticipate.

Understanding a large corporate environment from the inside was something I could not have learned from a classroom or a case study. Seeing how a company of over 150,000 people is structured, how colleagues experience it day to day, and how new ideas, including the kind this thesis produces, find their way through or get lost in organizational layers, gave me a perspective that will stay with me. What I found most interesting was not the complexity itself but the people within it: genuinely motivated, often frustrated, and more open to change than the system around them might suggest.

My knowledge of the aviation industry deepened in ways I had hoped for, but also in directions I had not expected. I entered, knowing the industry was technically sophisticated and commercially demanding. I left understanding how deeply those two things shape each other, and how that shapes everything else, including what sustainability can and cannot look like in practice. This results in a real tension between ambitions and institutional conservatism, and navigating it taught me more about strategic design than any project I have worked on before.

As for whether aviation and sustainability can go hand in hand: yes, they can. Not easily, not yet at scale, and not without the kind of structural and commercial alignment that this thesis tries to grasp. But the people are there, the ambition is there, and increasingly the tools are beginning to catch up. EcoFlight is one small contribution to that. Whether it spreads, whether it changes how even a handful of practitioners approach their next gate review, is something I will not be able to measure from here. As a strategic designer, I found that enabling change in complex industrial systems does not always require redesigning the system itself. In this project, it meant giving practitioners and like-minded people within it better ways to see, frame, and argue for what they already believe in, and trusting that knowledge, once it spreads, can shift what feels possible.

Boaz van Lith, Leiden, June 2026

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A–K

SUPPORTING MATERIAL

Appendix

Supporting material referenced throughout the report: literature search queries, the full CE strategy and eco-design-guideline mappings, the literature barrier typology with supporting evidence, the value chain, interview and validation protocols and participants, and the overview of methods and tools used in EcoFlight.

A Search Queries Literature Review

In Table 2 below, the search queries can be found with the accompanying results, followed by the exclusion criteria.

#	Query	Results
1	(eco-design OR ecodesign OR circularity OR "Circular Economy") AND ("aircraft cabin" OR "aircraft interior" OR "cabin interior" OR aviation)	126
2	("aircraft interior" OR cabin) AND (LCA OR "environmental assessment") AND aviation	5
3	aviation AND (“circular economy” OR ecodesign OR eco-design)	104
4	(airworthiness OR certification OR compliance) AND ("circular economy" OR "sustainable materials") AND (aircraft OR aviation)	8
5	("technology readiness level" OR TRL) AND sustainability AND (assessment OR integration OR "product development") AND (aviation OR aerospace OR aircraft OR cabin)	8
6	("stage-gate" OR "eco-stage-gate" OR "design gate" OR "decision gate") AND sustainability AND (R&D OR "product innovation")	5
7	("eco-design decision support" OR "decision-support system" OR DSS) AND (LCA OR "life cycle assessment") AND (product development OR design)	79
	Total (excluding duplicates)	**225**

***TABLE 2**: Search queries*

The combined results were filtered within WoS using exclusion keywords targeting irrelevant domains: Fuel*, Airport*, Engine*, Material Properties, Household, Agroforestry, Wings, Welding, Nanocomposite*, Wastewater, Pavement, Fashion, Building*, and seawater*. This reduced the results to **88 papers**.

B CE strategies relevant to aircraft cabin interiors

In Table 3 below, the CE strategies relevant to cabin components are mapped to the R-strategies with their accompanying sources.

Strategy	Description	Hierarchy position	Sources
R0 Refuse	Making a product or function redundant through digital or alternative solutions	Narrowing-loop	Paletti et al. (2025); Vogiantzi & Tserpes (2023)
R1 Rethink	Reconsidering design to make product use more intensive and efficient	Narrowing-loop	Paletti et al. (2025); Joustra (2022); Vogiantzi & Tserpes (2023)
R2 Reduce	Decreasing raw material and energy use through lightweighting and circular sourcing	Narrowing-loop	Paletti et al. (2025); Carvalho et al. (2025); Vogiantzi & Tserpes (2023)
R3 Reuse	Reusing discarded but functional components for their original purpose	Slowing-loop	Paletti et al. (2025); Papadaki & Maleviti (2025); EASA (2023a); Joustra (2022)
R4 Repair	Restoring defective components to working condition through MRO	Slowing-loop	Paletti et al. (2025); EASA (2023a); Vogiantzi & Tserpes (2023)
R5 Refurbish	Restoring a product to useful condition with similar performance	Slowing-loop	Paletti et al. (2025); Vogiantzi & Tserpes (2023)
R6 Remanufacture	Returning an item to like-new condition through industrial reprocessing	Slowing-loop	Paletti et al. (2025); Joustra (2022); EASA (2023a)
R7 Repurpose	Adapting redundant components for a different function without major modification	Slowing-loop	EASA (2023a); Paletti et al. (2025); Joustra (2022)
Cascade	Shifting recovered materials to another industry or application loop	Closing-loop	Paletti et al. (2025); EASA (2023a)
R8 Recycle	Processing materials to obtain new input materials	Closing-loop	Papadaki & Maleviti (2025); Paletti et al. (2025); EASA (2023a); Joustra (2022)
R9 Recover	Generating energy from non-recyclable waste materials	Closing-loop	Paletti et al. (2025); EASA (2023a); Vogiantzi & Tserpes (2023)

***TABLE 3**: CE strategies*

C Design guidelines relevant to cabin components

In Table 4 below, the design guidelines relevant to cabin components are mapped with their accompanying sources.

Guideline	Description	Key design aspects	Enabled CE strategies	Sources
Design for disassembly	Designing components to enable non-destructive removal and reassembly	Reversible connections; avoiding permanently bonded assemblies; optimizing disassembly paths; standard tool access	Reuse, remanufacturing, recycling	Joustra (2022); Paletti et al. (2025); Papadaki & Maleviti (2025); Mügge et al. (2023)
Material selection	Selecting materials that balance use-phase performance with end-of-life recoverability	Substituting thermoset matrices with thermoplastics; limiting material complexity within assemblies; avoiding mixed biological and technological materials	Recycling, structural reuse	Joustra (2022); Carvalho et al. (2025); Bachmann et al. (2017); Santos et al. (2016)
Design for modularity and accessibility	Grouping components into sub-assemblies aligned with maintenance intervals, ensuring serviceability	Matching sub-assemblies to maintenance intervals; grouping chemically similar materials; disassembly maps	Repair, refurbishment, reuse, lifetime extension	Joustra (2022); Papadaki & Maleviti (2025); Paletti et al. (2025)
Design for material traceability	Maintaining continuous material and lifecycle information across stakeholder handoffs	Physical markers and embedded identifiers; Digital Product Passports; blockchain-based traceability; electronic part lifecycle records	Recycling, reuse, remanufacturing	Joustra (2022); Wiesner et al. (2025); Papadaki & Maleviti (2025); Mügge et al. (2023)
Function integration	Combining multiple functions into a single structural part to reduce material intensity	Integrating connectors with parts; combining structural and acoustic functions; embedding sensors into composites	Rethink, structural reuse	Joustra (2022); Paletti et al. (2025)
Standardization	Using standard components and interfaces across product lines and aircraft generations	Cross-fleet compatible dimensions; standardized laminate layups; components transferable between aircraft generations	Structural reuse, product recovery	Joustra (2022); Paletti et al. (2025)

***TABLE 4**: Eco-design guidelines*

D Barrier typology with supporting evidence

Tables 5 to 7 below map the informational, organizational and regulatory barriers with their supporting evidence.

Barrier	Description	Mechanism	Sources
Missing lifecycle data at early stages	Designers lack environmental impact data for novel materials at the stages where design decisions are still open	Without hard data, sustainability criteria cannot be defended at gate reviews, leading to selection of conventional materials	Chebaeva et al. (2021); Poudelet et al. (2012); Hallstedt & Pigosso (2017)
Loss of material traceability	Material composition, hazardous substance data, and maintenance history are routinely lost across stakeholder handoffs	Without accurate material mapping, dismantlers cannot separate materials cleanly, forcing downcycling or landfilling over closed-loop recovery	EASA (2023a); Wiesner et al. (2025)
Unknown end-of-life recovery rates	Precise EOL recovery rates and degradation profiles for novel sustainable materials remain unavailable	Developers cannot build a complete LCA business case, causing gatekeepers to reject novel materials in favor of conventional materials	Bachmann et al. (2017); Fischer et al. (2024)

***TABLE 5**: Informational barriers*

Barrier	Description	Mechanism	Sources
EOL actors excluded from early design	OEMs and design engineers operate in silos focused on beginning-of-life; dismantlers, recyclers, and MRO operators are structurally excluded from design decisions	Disassembly and recyclability insights are never integrated into design, locking in unrecyclable configurations before manufacturing begins	EASA (2023a); Wiesner et al. (2025)
Supply chain fragmentation and supplier dependency	The aerospace supply chain is highly fragmented and globalized, with OEMs dependent on lower-tier suppliers for environmental data and sustainable materials	Fragmentation prevents the volume consolidation and data exchange required to make closed-loop recycling economically viable	Vogiantzi & Tserpes (2023); Papadaki & Maleviti (2025)
IP concerns restricting data sharing	Companies protect material formulations, proprietary designs, and manufacturing processes from supply chain partners	Lack of transparency blocks environmental impact calculation and prevents dismantlers from safely processing materials at EOL	Fischer et al. (2024); Wiesner et al. (2025)
Prioritization of cost efficiency	Gate reviews are driven by cost reduction, schedule adherence, and short-term profitability	Circular innovations requiring higher upfront investment and longer development timelines are systematically filtered out at decision gates	Santos et al. (2016); EASA (2023a)

***TABLE 6**: Organizational barriers*

Barrier	Description	Mechanism	Sources
Airworthiness and FST certification hurdles	Aviation components must meet strict structural integrity, fatigue, fire, smoke, and toxicity standards mandated by EASA and FAA	Emerging circular materials frequently fail flammability and mechanical limits, creating a hard regulatory stop regardless of eco-design intent	Carvalho et al. (2025); Bachmann et al. (2017); Santos et al. (2016)
Costly recertification for component reuse	Reusing existing components requires meticulous back-to-birth documentation and recertification by an approved maintenance organization	Administrative and legal burden makes virgin replacement cheaper and legally safer than reuse, regardless of component condition	Papadaki & Maleviti (2025); EASA (2023a)
No binding end-of-life regulation	Aviation lacks binding EOL regulations or extended producer responsibility mandates, unlike the automotive sector	Absence of legal mandate removes financial and regulatory incentive to invest in design-for-disassembly or circular materials at early design stages	EASA (2023a); Papadaki & Maleviti (2025)

***TABLE 7**: Regulatory barriers*

E Detailed Value Chain

In the infographic below (Figure 17), the detailed value chain of the CIRCADIS consortium can be found, created during the Value Chain and Circular Strategy Mapping workshop. Below, two photos are shown of this workshop (Figure 18)

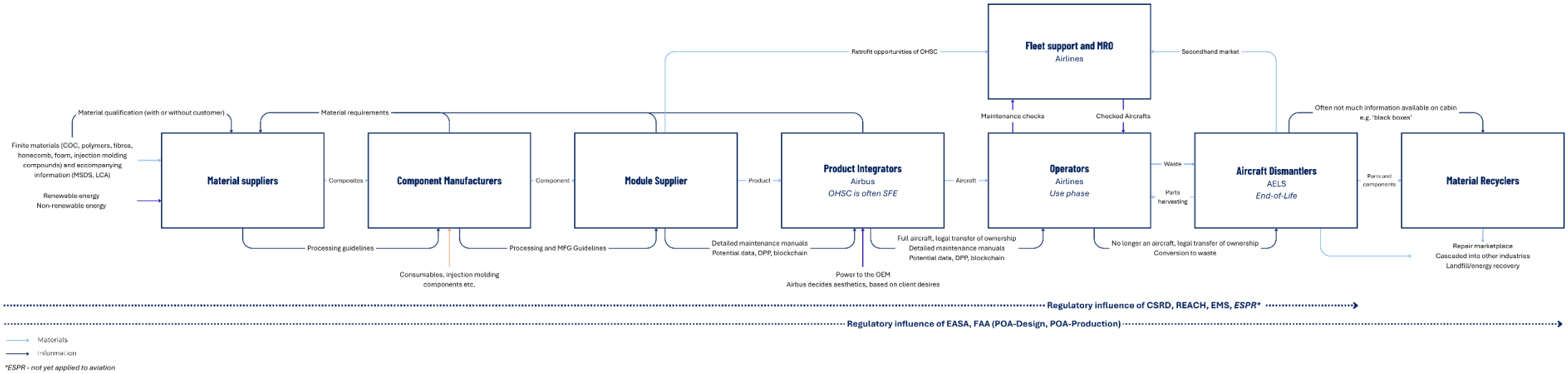

***FIGURE 17**: Detailed Value Chain*

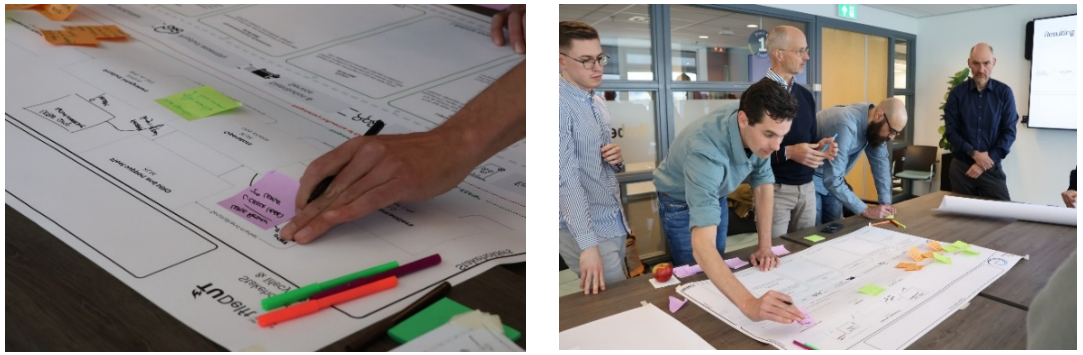

***FIGURE 18**: Two photos taken during the CIRCADIS workshop*

F Interview protocol

Semi-structured interviews were conducted with 17 practitioners across the aviation value chain between March and April 2026. The protocol was designed to test, refine, and extend the theoretical framework developed in section 2.5 through engagement with practitioners. Five thematic sections structured each session: role and context, eco-design and circular economy in practice, barriers, framework and tool requirements, and commercial context. Interviews lasted 45 to 60 minutes and were conducted in English or Dutch depending on participant preference. All sessions were audio-recorded with prior informed consent, fully anonymized in analysis, and coded using the Gioia methodology described in section 4.4. The guiding questions are listed below. Italic sub-questions are optional follow-up probes, used where a response required deepening or clarification.

Section 1: Role and context

Q1. Can you briefly describe your role and how it relates to the aviation industry?

- *To what extent does your work involve cabin components specifically?*
- *At what stage of the development process or product lifecycle does your work typically sit?*
- *What kinds of decisions do you influence?*

Q2. What role does sustainability play in your day-to-day work?

- *Is it something you actively work on, or does it tend to arise at specific moments?*
- *Has that changed over the past few years?*

Section 2: Eco-design and circular economy in practice

Q3. When sustainability considerations enter a development project, how does that typically happen?

- *Who drives it, and what tends to trigger it?*
- *Does it tend to play a role at a specific stage, or is it present throughout?*

Q4. Which sustainability principles tend to get applied in practice, and which fall away?

- *Can you provide a concrete example where an eco-design guideline or circular strategy was considered but not pursued?*
- *What determined the outcome?*

Q5. How are sustainability requirements weighed against other requirements like weight, cost, or certification at decision points?

- *Is there a formal process for this, or is it handled informally?*
- *What tends to win out?*

Section 3: Barriers

Q6. What are the main obstacles that prevent sustainability considerations from being implemented in the development process?

- *Can you think of a case where a sustainability criterion did survive? What made that possible?*
- *Can you provide a specific situation where a sustainability criterion did not survive a decision point, and what caused it to drop out?*

Q7. At what point in the development process do these obstacles tend to be most acute?

- *Is there a specific moment where you feel the window for integrating sustainability closes?*
- *Do barriers tend to build up gradually, or do they emerge at particular decision points?*

Q8. Is the information you need to make sustainability-informed decisions always available?

- *Is material composition, lifecycle history, or end-of-life data accessible when you need it?*
- *At what stage do information gaps tend to be most present?*

Q9. How does the organizational structure, within your organization or across the value chain, support or hinder sustainability integration?

- *Is sustainability owned by a specific team, or is it distributed?*
- *Are end-of-life or maintenance actors involved early enough in the process?*

Q10. To what extent do certification and regulatory requirements impact sustainability decisions?

- *Does regulation feel like a hard stop, or more of a complication to navigate?*
- *Can you provide an example of a case where a more circular option was blocked by certification constraints?*

Section 4: Framework and tool requirements

Q11. Are there any tools or methods you currently use to guide sustainability decisions, and how well do they work?

- *What does work, and what makes it effective in your context?*
- *What do they fail to capture, and is there a stage where you feel most under-supported?*

Q12. What would a framework need to look like to be genuinely useful in your context?

- *What format and level of detail would be realistic or needed?*
- *What would make it trusted by the people who approve decisions?*

Q13. What conditions would need to be in place for such a framework to be adopted and used?

- *Are there organizational or commercial conditions that would need to change?*

- *Who would need to be on board for it to have real influence?*

Section 5: Commercial context

Q14. How do commercial pressures, such as cost, weight, or schedule, shape what sustainability decisions are actually feasible in your context?

- *Is passenger-facing sustainability becoming a real driver, or is it still secondary to cost?*
- *Where do you see potential for the commercial logic to shift?*

Q15. Do you think the current commercial incentives in the sector are aligned with higher-value circular strategies?

- *Where do the economics work, and where do they still work against circularity?*

Closing questions

Q16. Is there anything important about the practical reality of eco-design and circular economy in aerospace that we have not covered?

Q17. Based on your experience, what would be the single most important thing that would need to change for eco-design and circular economy to become integrated into aerospace product development?

G Interview and validation participants

Table 8 shows an overview of all 17 interview participants with their corresponding interview IDs, and Table 9 shows the 8 validation session participants.

ID	Organization (anonymized)	Aggregate Category
INT 1	Product Manager at Aircraft Manufacturer (OEM)	Cabin Designers and Engineers
INT 2	Cabin Engineer at Aircraft Manufacturer (OEM)	Cabin Designers and Engineers
INT 3	Eco-design Specialist at Aircraft Manufacturer (OEM)	Eco-design and Sustainability Specialists
INT 4	Researcher at Aircraft Manufacturer (OEM)	Eco-design and Sustainability Specialists
INT 5	Founder of EOL and Recycling Company	EOL and Recycling Specialists
INT 6	Founder of Composite Recycling Company	EOL and Recycling Specialists
INT 7	Researcher Advanced Materials at Material Supplier	Material and Component Experts
INT 8	Material Qualification Expert at Aircraft Manufacturer (OEM)	Material and Component Experts
INT 9	MRO Representative at Airline	MRO Experts
INT 10	Cabin Expert at Aircraft Manufacturer (OEM)	Material and Component Experts
INT 11	Manufacturing Expert at Component Manufacturer	Material and Component Experts
INT 12	End-of-Life specialist at Aircraft Manufacturer (OEM)	EOL and Recycling Specialists
INT 13	Cabin Designer at Aircraft Manufacturer (OEM)	Cabin Designers and Engineers
INT 14	Cabin Engineer at Aircraft Manufacturer (OEM)	Cabin Designers and Engineers
INT 15	Founder at Industry Alliance	Eco-design and Sustainability Specialists
INT 16	Project Manager and MRO at Aircraft Manufacturer (OEM)	MRO Experts
INT 17	Researcher at EOL and Recycling Company	EOL and Recycling Specialists

***TABLE 8**: Interview participants*

ID	Organization (anonymized)	Aggregate Category
VAL 1	Project Manager at Aircraft Manufacturer (OEM)	Project Management
VAL 2	Project Manager at Aircraft Manufacturer (OEM)	Project Management
VAL 3	MRO Representative	MRO Experts
VAL 4	Cabin Designer at Aircraft Manufacturer (OEM)	Cabin Designers and Engineers
VAL 5	Eco-design Specialist at Aircraft Manufacturer (OEM)	Eco-design and Sustainability Specialists
VAL 6	Material Qualification Expert at Aircraft Manufacturer (OEM)	Material and Component Experts
VAL 7	Researcher at University	Eco-design and Sustainability Specialists
VAL 8	Manufacturing Expert at Component Manufacturer	Material and Component Experts

***TABLE 9**: Validation session participants*

H Informed consent form

You are being invited to participate in a research study conducted as part of a TU Delft Master's graduation project titled: *"Eco-Design and Circular Economy Principles in Aerospace TRL-Based Product Development."*

This study is being conducted by Boaz van Lith (MSc student, TU Delft) under the supervision of Shahrokh Nikou (Associate Professor, TU Delft). The research is carried out in collaboration with Airbus Netherlands.

The purpose of this study is to develop a framework that helps integrate eco-design and circular economy principles during the transition from low-TRL research to high-TRL engineering and validation in aerospace product development. The study aims to identify practical friction points, decision moments, and conditions that influence whether sustainability intentions are preserved or filtered out during later development phases.

If you agree to participate, you will take part in a semi-structured interview of approximately 45–60 minutes. The interview will cover topics such as:

- How eco-design and circularity principles are considered in practice, and where they tend to get deprioritized.
- What barriers, whether informational, organizational, or regulatory, prevent criteria from surviving gate decisions.
- How sustainability is weighed against weight, cost, and certification requirements at decision points.
- What a framework would need to look like to be credible and usable in your context.

With your permission, the interview will be audio-recorded to enable accurate transcription and analysis. If you do not permit recording, the interview can still proceed using written notes. Your participation is entirely voluntary. You may refuse to answer any question, and you may stop the interview at any time without giving a reason and without any negative consequences.

The study will collect Personally Identifiable Information (PII) for practical communication purposes (e.g., your name and contact details), and Research data from the interview (audio recording if you consent, and/or notes and transcript). During the research process, your interview will be handled in a pseudonymized way: you will be assigned a participant ID, and your name/contact details will be stored separately from the interview content. Before the end of the research period, the interview material used for analysis will be anonymized by removing or generalizing identifying details. In the thesis and any other outputs, reporting will be anonymized, and quotations will only be used in a form that cannot reasonably identify you. Raw interview data (audio recordings, transcripts, and notes) will not be shared publicly and will not be deposited as a research dataset in a repository. Signed informed consent forms will be stored separately for validation purposes in line with TU Delft requirements and will not be shared publicly.

Audio recordings (if made) will be transcribed, and the transcript will be used for analysis. Access to raw interview data will be restricted to the researcher and (if required for academic oversight) the TU Delft supervisory team. Research data (including raw interview data) will be stored on an Airbus-managed laptop used by the researcher, in accordance with Airbus information security policies. As a result, access to the data by Airbus (including the Airbus supervisor) is technically possible due to device management, but is not actively exercised as part of the research process. Airbus does not direct data collection, analysis, or reporting decisions. Research data will be retained for the duration of the research project and will be permanently deleted once the graduation project has been completed and assessed.

There are no expected physical risks. Potential risks relate to professional or reputational sensitivity if statements could be linked back to you. This risk is mitigated through anonymized reporting (removal/generalization of identifying details), secure storage, restricted access, and careful removal of identifying details during reporting.

If you have questions about the study or your rights as a participant, you can contact:

Researcher: Boaz van Lith, TU Delft
Responsible Supervisor: Shahrokh Nikou**,** TU Delf

By signing below, I confirm that:

I have read and understood the participant information, have had the opportunity to ask questions, and voluntarily agree to participate in a semi-structured interview of approximately 45–60 minutes. I understand that participation is voluntary and that I may withdraw at any time without consequences. I understand that I will not receive financial compensation.

Regarding audio recording, please indicate your preference:

☐ I give permission for the interview to be audio-recorded.

☐ I do not give permission for the interview to be audio-recorded.

I understand that all data will be used solely for this study, that reporting will be anonymized, and that raw data will be accessible only to the researcher and, if required for academic oversight, the TU Delft supervisory team. Research data is stored on an Airbus-managed laptop; Airbus may have technical access due to device management, but this is not actively exercised as part of the research process. Personal data will be permanently deleted once the graduation project has been completed and assessed. Anonymized quotations may be used in the thesis and related academic or professional publications.

Signatures
Participant
Name: _____
Signature: _____
Date: ___ / ___ / 2026

Researcher
Name: Boaz van Lith
Signature: _____
Date: ___ / ___ / 2026

I Approved HREC documents

See below for the approval of the HREC and the original documents.

Ethics Approval Application: A strategic framework for the integration of sustainable design in aerospace product development
Applicant: Lith, Boaz van

Dear Boaz van Lith,

It is a pleasure to inform you that your application mentioned above has been approved.

Thanks very much for your submission to the HREC which has been approved.

In addition to any specific conditions or notes, the HREC provides the following standard advice to all applicants:

• In light of recent tax changes, we advise that you confirm any proposed remuneration of research subjects with your faculty contract manager before going ahead.

• Please make sure when you carry out your research that you confirm contemporary covid protocols with your faculty HSE advisor, and that ongoing covid risks and precautions are flagged in the informed consent - with particular attention to this where there are physically vulnerable (eg: elderly or with underlying conditions) participants involved.

• Our default advice is not to publish transcripts or transcript summaries, but to retain these privately for specific purposes/checking; and if they are to be made public then only if fully anonymised and the transcript/summary itself approved by participants for specific purpose.

• Where there are collaborating (including funding) partners, appropriate formal agreements including clarity on responsibilities, including data ownership, responsibilities and access, should be in place and that relevant aspects of such agreements (such as access to raw or other data) are clear in the Informed

Consent.

Good luck with your research!

Sincerely,

Dr. C. Shelley-Egan
Chair HREC
Faculty of Technology, Policy and Management

I. Applicant Information

PROJECT TITLE:	A strategic framework for the integration of sustainable design in aerospace product development
Research period:	2 February 2026 – 3 July 2026
Faculty:	Industrial Design Engineering
Department:	Design, Organisation and Strategy
Type of the research project	Master's thesis (graduation project)
Funder of research:	None
Name of Corresponding Researcher:	Boaz van Lith
E-mail Corresponding Researcher:	b.d.vanlith@student.tudelft.nl
Position of Corresponding Researcher:	Master's student
Name of Responsible Researcher:	Shahrokh Nikou
E-mail of Responsible Researcher:	S.N.Nikou@tudelft.nl
Position of Responsible Researcher:	Associate Professor

II. Research Overview

a) Please summarise your research very briefly (100-200 words)
What are you looking into, who is involved, how many participants there will be, how they will be recruited and what are they expected to do?

This Master's thesis research develops a decision-support framework to help integrate eco-design and circularity principles during the transition from low-TRL research to high-TRL engineering and validation in aerospace product development. The study focuses on identifying practical friction points, decision moments, and organizational conditions that influence whether sustainability intentions are preserved or filtered out in later development phases. Data will be collected through semi-structured interviews (45–60 minutes) with professionals involved in aerospace R&D, sustainability integration, engineering, and/or compliance-related decision-making. Participants will be recruited via professional networks connected to TU Delft and Airbus Netherlands (and/or relevant project partners). The study aims to include approximately 8–15 participants, with the final number determined by data saturation and practical availability. With participant permission, interviews will be audio-recorded for transcription and qualitative analysis; if permission is not granted, written notes will be taken instead. Participation is voluntary, participants may skip questions or withdraw at any time, and all reporting will be fully anonymized (name, organization, and identifying details removed or generalized).

b) **If your application is an additional project** related to an existing approved HREC submission, please provide a brief explanation including the existing relevant HREC submission number/s.

Not applicable. This application is not an additional project related to an existing approved HREC submission.

c) **If your application is a simple extension of, or amendment to,** an existing approved HREC submission, you can simply submit an HREC Amendment Form as a submission through LabServant.

			If YES please complete the Risk Assessment and Mitigation Plan columns below.		*Please provide the relevant reference #*	
ISSUE	**Yes**	**No**	**RISK ASSESSMENT – what risks could arise?**	**MITIGATION PLAN – what mitigating steps will you take?**	**DMP**	**ICF**
3. Has this research been approved by another (external) research ethics committee (e.g.: HREC and/or MREC/METC)?		X				
B: Location						
4. Will the research take place in a country or countries, other than the Netherlands, within the EU?		X				
5. Will the research take place in a country or countries outside the EU?		X				
6. Will the research take place in a place/region or of higher risk – including known dangerous locations (in any country) or locations with non-democratic regimes?		X				
C: Participants						
7. Will the study involve participants who **may** be vulnerable and possibly (legally) unable to give informed consent? (e.g., children below the legal age for giving consent, people with learning difficulties, people living in care or nursing homes,).		X				
8. Will the study involve participants who **may** be vulnerable under specific circumstances and in specific contexts, such as victims and witnesses of violence, including domestic violence; sex workers; members of minority groups, refugees, irregular migrants or dissidents?		X				
9. Are the participants, outside the context of the research, in a dependent or subordinate position to the investigator (such as own children, own students or employees of either TU Delft and/or a collaborating partner organisation)?		X				
10. Is there a high possibility of re-identification for your participants? (e.g., do they have a very specialist job of which there are only a small number in a given country, are they members of a small community, or employees from a partner company collaborating in the research? Or are they one of only a handful of (expert) participants in the study?	X		Participants are expert professionals in a specific domain and may be part of a small or identifiable group (e.g., within Airbus Netherlands or a niche sustainability/compliance function). Even without names, specific role descriptions or project details could enable re-identification, which could create reputational or professional risk.	All outputs will be fully anonymized. Role descriptions will be generalized (e.g., "aerospace R&D professional") and potentially identifying details (exact team, project names, unique events, timelines) will be removed or abstracted. Quotes will be paraphrased or shortened where necessary to avoid indirect identification.		
D: Recruiting Participants						
11. Will your participants be recruited through your own, professional, channels such as conference attendance lists, or through specific network/s such as self-help groups	X		Recruitment through professional networks may create a perceived pressure to participate or to respond in a socially desirable way, particularly when participants are connected through the collaboration context.	The invitation and consent process will clearly state that participation is voluntary, that declining has no consequences, and that participants may skip questions or withdraw at any time. Interviews will be scheduled directly with participants, and consent will be collected individually.		
12. Will the participants be recruited or accessed in the longer term by a (legal or customary) gatekeeper? (e.g., an adult professional working with children; a		X				

			If YES please complete the Risk Assessment and Mitigation Plan columns below.		*Please provide the relevant reference #*	
ISSUE	**Yes**	**No**	**RISK ASSESSMENT – what risks could arise?**	**MITIGATION PLAN – what mitigating steps will you take?**	**DMP**	**ICF**
community leader or family member who has this customary role – within or outside the EU; the data producer of a long-term cohort study)						
13. Will you be recruiting your participants through a crowd-sourcing service and/or involve a third party data-gathering service, such as a survey platform?		X				
14. Will you be offering any financial, or other, remuneration to participants, and might this induce or bias participation?		X				
E: Subject Matter						
15. Will your research involve any of the following: • Medical research and/or clinical trials • Invasive sampling and/or medical imaging • Medical and *In Vitro Diagnostic Medical* Devices Research		X				
16. Will drugs, placebos, or other substances (e.g., drinks, foods, food or drink constituents, dietary supplements) be administered to the study participants?		X				
17. Will blood or tissue samples be obtained from participants?		X				
18. Does the study risk causing psychological stress or anxiety beyond that normally encountered by the participants in their life outside research?		X				
19. Will the study involve discussion of personal sensitive data which could put participants at increased legal, financial, reputational, security or other risk? (e.g., financial data, location data, data relating to children or other vulnerable groups)		X				
20. Will the study involve disclosing commercially or professionally sensitive, or confidential information? (e.g., relating to decision-making processes or business strategies which might, for example, be of interest to competitors)	X		Interview discussions about decision-making, development processes, sustainability strategies, compliance constraints, and organizational practices may involve commercially or professionally sensitive information. If such information were disclosed, it could pose confidentiality, reputational, or competitive risks.	Participants will be instructed not to disclose confidential information and can decline to answer any question. The interview guide will avoid requesting sensitive technical specifications or proprietary data. Full anonymization will be applied, and any potentially sensitive details will be removed or generalized during transcription and reporting.		
21. Has your study been identified by the TU Delft Privacy Team as requiring a Data Processing Impact Assessment (DPIA)?		X				
22. Does your research investigate causes or areas of conflict?		X				
23. Does your research involve observing illegal activities or data processed or provided by authorities responsible for preventing, investigating, detecting or prosecuting criminal offences		X				

			If YES please complete the Risk Assessment and Mitigation Plan columns below.		*Please provide the relevant reference #*	
ISSUE	**Yes**	**No**	**RISK ASSESSMENT – what risks could arise?**	**MITIGATION PLAN – what mitigating steps will you take?**	**DMP**	**ICF**
F: Research Methods						
24. Will it be necessary for participants to take part in the study without their knowledge and consent at the time? (e.g., covert observation of people in non-public places).		**X**				
25. Will the study involve actively deceiving the participants? (For example, will participants be deliberately falsely informed, will information be withheld from them or will they be misled in such a way that they are likely to object or show unease when debriefed about the study).		**X**				
26. Is pain or more than mild discomfort likely to result from the study? And/or could your research activity cause an accident involving (non-) participants?		**X**				
27. Will the experiment involve the use of devices that are not 'CE' certified?		**X**				
• Was the device built in-house?						
• Was it inspected by a safety expert at TU Delft?						
• If it was not built in-house and not CE-certified, was it inspected by some other, qualified authority in safety and approved?						
28. Will your research involve face-to-face encounters with your participants and if so how will you assess and address Covid considerations?	**X**		The study includes face-to-face interviews, which can create minor logistical and privacy risks (e.g., being overheard, discomfort with the setting, or participants feeling less free to withdraw). There are no expected physical risks; COVID-19 is not treated as a specific research risk.	Interviews will be conducted in a quiet, private room where participants cannot be overheard. Participants will be reminded that participation is voluntary, they may skip questions, and they may stop the interview at any time without consequences. Audio recording will only occur with explicit permission; otherwise, written notes will be taken.		
29. Will your research involve **either:** a) "big data", combined datasets, new data-gathering or new data-merging techniques which might lead to re-identification of your participants **and/or** b) artificial intelligence or algorithm training where, for example biased datasets could lead to biased outcomes?		**X**				
G: Data Processing and Privacy						
30. Will the research involve collecting, processing and/or storing any directly identifiable PII (Personally Identifiable Information) including name or email address that will be used for administrative purposes only? (eg: obtaining Informed Consent or disbursing remuneration)	**X**		The study will collect directly identifiable personal data (PII) such as participant name and contact details for scheduling and consent administration. If mishandled, this could compromise participant privacy and increase the risk of re-identification.	PII will be collected only to the extent necessary for communication and scheduling. Access to PII will be restricted to the researcher and supervisory team. PII will be stored on an Airbus-managed laptop used by the researcher, in accordance with Airbus information security policies. As a result, access to the data by Airbus (including the Airbus supervisor) is technically possible due to device management, but is not actively		

			If YES please complete the Risk Assessment and Mitigation Plan columns below.		*Please provide the relevant reference #*	
ISSUE	**Yes**	**No**	**RISK ASSESSMENT – what risks could arise?**	**MITIGATION PLAN – what mitigating steps will you take?**	**DMP**	**ICF**
				exercised as part of the research process. Access to raw data is restricted to the researcher and (if required for academic oversight) the TU Delft supervisory team. Reporting will be fully anonymized. Research data will be retained for the duration of the research project and will be permanently deleted once the graduation project has been completed and assessed.		
31. Will the research involve collecting, processing and/or storing any directly or indirectly identifiable PIRD (Personally Identifiable Research Data) including videos, pictures, IP address, gender, age etc and **what other Personal Research Data** (including personal or professional views) will you be collecting?	**X**		Interview data may include directly identifiable research data (e.g., voice in audio recordings) and indirectly identifiable details (e.g., specific role, team context, unique experiences). If such data were disclosed or insufficiently anonymized, participants could be re-identified, creating professional or reputational risk.	Audio recording will occur only with explicit permission; otherwise, written notes will be taken. Recordings will be transcribed, and transcripts/notes will be anonymized by removing or generalizing names, organization details, roles, and other identifying details (including unique project/context information). Quotes will be used only in an anonymized form that cannot reasonably identify participants; if necessary, quotes will be shortened, paraphrased, or omitted to prevent indirect identification. Research data will be retained for the duration of the research project and will be permanently deleted once the graduation project has been completed and assessed.		
32. Will this research involve collecting data from the internet, social media and/or publicly available datasets which have been originally contributed by human participants		**X**				
33. Will your research findings be published in one or more forms in the public domain, as e.g., Masters thesis, journal publication, conference presentation or wider public dissemination?	**X**		Publishing findings can increase the risk of indirect identification, particularly when using quotes or describing niche professional roles or collaboration contexts.	All outputs (Master's thesis and any related publications/presentations) will be fully anonymized. Identifying details will be removed or generalized, and quotes will be reviewed for re-identification risk and adjusted (paraphrased/shortened) or excluded if necessary. Only anonymized and aggregated insights will be reported. Raw data will remain restricted-access and will not be publicly shared.		
34. Will your research data be archived for re-use and/or teaching in an open, private or semi-open archive?		**X**				

IV. Signature/s

Please note that by signing this checklist list as the sole, or Responsible, researcher you are providing approval of the completeness and quality of the submission, as well as confirming alignment between GDPR, Data Management and Informed Consent requirements.

Name of Corresponding Researcher: Boaz van Lith

Signature of Corresponding Researcher: LITH

Date: 06.02.2025

Name of Responsible Researcher: Shahrokh Nikou

Signature Responsible Researcher: Shahrokh Nikou

Date: 06.02.2025

ECOFLIGHT

Preserving eco-design and circular economy principles through aviation technology development

WHAT IT IS

EcoFlight is a browser-based, **three-phase decision guide** for practitioners in the aviation ecosystem. It maps the **barriers and conditions** that cause eco-design and circular economy principles to be deprioritized through TRL-based decisions, provides structured methods and tools to identify them, and equips practitioners with the **commercial framing** needed to defend circular criteria at the moments that matter most. It does not tell practitioners what to design, it tells them which barriers to expect, which methods to use, and how to make the case in the language that decision-makers respond to.

WHO IT IS FOR

Anyone working across the **aviation ecosystem**, who encounters eco-design, circular economy principles, or **environmental ambitions** in their project. This includes engineers, cabin designers, material specialists, component manufacturers, MRO operators, and end-of-life specialists. EcoFlight is a **bottom-up tool**: it does not require a sustainability mandate from above to be useful.

PHASE 01 — AWARENESS

01 BARRIERS & CONDITIONS

Map the barriers and conditions that cause eco-design and CE principles to be deprioritized in development projects.

20 BARRIERS & CONDITIONS
Across informational, organizational, commercial, and regulatory categories.

FILTER
By category or TRL stage to surface what is most active in your context.

AI SELECTOR
Describe your project and get a personalized shortlist of the 3–5 most relevant barriers and conditions.

COMMERCIAL NOTE
Each entry translates the barrier into commercial language.

PHASE 02 — OPERATIONALIZE

02 METHODS & TOOLS

Thirteen methods, mapped to barrier type and TRL stage, that translate circular design intent into defensible evidence.

13 METHODS
Covering informational, organizational, commercial, and regulatory barriers.

FILTER
By barrier type and TRL stage to find what fits your situation.

SEQUENCE
Early-stage methods feed and unlock the later ones.

GATE-READY
Outputs are gate review inputs, not standalone reports.

PHASE 03 — JUSTIFY

03 REFRAME & COMMERCIALIZE

Seven structural conditions under which environmental ambitions survived aviation gate decisions in practice.

7 CONDITIONS
Observed patterns from real aviation cabin development projects.

IDENTIFY
Recognize which conditions are present or achievable in your project.

REFRAME
Frame sustainable ambitions as cost reduction, supply chain resilience, or regulatory risk.

FOUNDATIONAL CONCEPTS

ECO-DESIGN

Environmental criteria integrated at the earliest stage of development. In aviation, weight is the primary lever, every kilogram saved reduces fuel burn and enables circular impact.

CIRCULAR ECONOMY

Keeping materials in use through reuse, remanufacturing, and recycling, in that order. In aviation, most end-of-life material goes to downcycling or energy recovery.

TECHNOLOGY READINESS LEVELS

Nine-level aviation maturity scale: concept (TRL 1) to deployment (TRL 9). Gate decisions at every level were built around performance and cost, not environmental value.

EcoFlight ecoflight.pages.dev github.com/Boazvl04/EcoFlight

Boaz van Lith · MSc Strategic Product Design · TU Delft · 2026

K Overview of methods and tools

This Appendix contains an overview of all methods and tools listed in Phase 02 of EcoFlight, the browser-based decision guide. Each consists of a name, what it is and what it is based on, connecting it to the empirical or literature findings, when to use it, how to apply it, and possible templates included.

Fast-Track LCA

Barrier type: Informational · TRL 1–3

The Fast-Track LCA is a simplified lifecycle assessment method developed at TU Delft that bypasses the complex classification and characterization steps of a full LCA. Instead of building a complete impact model, it multiplies material and process inputs and outputs directly by eco-costs factors from the IDEMAT or Ecocosts LCA databases, producing directional eco-costs estimate per kilogram of material or per component (Ecocostsvalue, n.d.a). The method is grounded in the informational barrier identified in section 5.2.1: at early TRL stages, a full LCA cannot be meaningfully executed, but directional environmental evidence is still needed to inform gate review arguments.

The Fast-Track LCA is most appropriate at TRL 1–3, when competing material or design concepts are being evaluated before key decisions are locked in. It produces sufficient evidence to identify which materials or lifecycle stages carry the highest environmental risk, without requiring complete resolved datasets or specialist LCA software.

Prospective LCA (pLCA)

Barrier type: Informational · TRL 3–6

The prospective LCA is a forward-looking lifecycle assessment that models the anticipated environmental profile of a technology not yet in production. Unlike a retrospective LCA, which assesses a product already manufactured and in use, the prospective LCA works with proxy datasets, material family averages, and anticipated process configurations to produce an environmental hotspot map before the design window closes. It is grounded in the methodological framework developed by Arvidsson et al. (2017), who establish that prospective LCA is particularly suited to emerging technologies where conventional background data does not yet exist. The method directly addresses the TRL-staged data availability condition identified in section 5.2.1: by the time a full LCA becomes technically feasible, the design is no longer open to the changes it would recommend.

The prospective LCA is most appropriate at TRL 3–6, when enough material and process data exists to move beyond proxy assumptions, but a full LCA is not yet technically executable. It is most critical at TRL 4–5, when system integration testing is beginning to resolve key parameters and the design window is narrowing. Application does require a specialist eco-design or LCA practitioner and paid LCA software.

Full LCA

Barrier type: Informational · TRL 6–9

The full LCA is a complete lifecycle assessment conducted according to the ISO 14040 series, covering the full product lifecycle from cradle to grave. It builds a complete life cycle inventory, a mass and energy balance of all subsystems, and processes this through impact assessment steps including

classification, characterization, normalization, and weighting, to produce a comprehensive environmental impact profile (Ecocostsvalue, n.d.b; ISO, 2006). Unlike the Fast-Track LCA, which bypasses these steps for speed, the full LCA applies specialist software such as SimaPro or OpenLCA to aggregate emissions across impact indicators covering climate change, human health, and resource scarcity.

The full LCA is not an instrument for informing design decisions. By the time it is executable, the design is effectively frozen, confirming the eco-design paradox established in section 2.2. Its primary functions are regulatory compliance under CSRD reporting obligations, documentation of environmental performance for program handover, and establishing a baseline for the next development cycle. Application requires a specialist LCA practitioner or external consultancy, LCA software, and complete foreground data from the project team.

Circular Composites Design

Barrier type: Informational · TRL 1–5

The Circular Composites Design framework is a structured approach for integrating circularity criteria into composite component development from the earliest design stages. Developed by Joustra (2022) at TU Delft, the framework addresses a gap that generic eco-design methods do not cover: the specific material, connection, and end-of-life characteristics of fibre-reinforced composite components. In an aviation cabin context, this means thermoplastic and thermoset composite panels, overhead bin structures, and interior components where material selection, connection reversibility, and structural reuse potential must be addressed. The framework moves from recovery strategy selection through lifecycle mapping and design aspect connection to fastener and disassembly evaluation, producing a finalized circular product design as its output. It is grounded in the informational and organizational barriers identified in sections 5.2.1 and 5.2.2: composite components present unique material traceability and end-of-life challenges that standard eco-design guidelines do not resolve.

The framework is most appropriate at TRL 1–5, and it is most effective when used in parallel with the Value Chain and Circular Strategy Mapping method, as the two together cover recovery ambition, stakeholder structure, and component-level design decisions simultaneously. The full framework, including design aspect cards, fastener evaluation tools, and worked examples, is available as an open access publication (Joustra, 2022).

Value Chain and Circular Strategy Mapping

Barrier type: Organizational · TRL 1–4

Value Chain and Circular Strategy Mapping is a two-phase facilitated method that combines value chain exploration with circular strategy mapping in a single session. Phase one traces how materials, components, information, and decisions flow across all actors involved in a product's lifecycle, from raw material suppliers through design, manufacturing, operation, maintenance, and end-of-life processing. In an aviation context, this makes visible where circular information is lost, where stakeholder handoffs break traceability, and where end-of-life actors are structurally excluded from decisions that affect them. In section 3.2, the output of this method is shown in the CIRCADIS context. Phase two maps the R-strategy hierarchy against the material composition, design constraints, and end-of-life context revealed in phase one, identifying which circular strategies are technically feasible at the current TRL, which require specific design commitments to remain achievable, and which are already foreclosed. The method is grounded in the organizational barriers identified in section 5.2.2,

specifically EOL and MRO actor exclusion and organizational silos, and draws on the methodology developed by Joustra (2022).

The method is most appropriate at TRL 1–4, before supplier contracts are finalized and before material family decisions are locked in. It is also useful at mid-stage to check which circular strategies remain open before the TRL 6 program handover. The EcoFlight Lifecycle Exploration Sheet (See Figure 19), adapted from the EcoBulk template developed by Joustra (2022) at TU Delft, provides the facilitation structure for both phases, with aviation cabin-specific lifecycle stages and circular strategies pre-mapped. A cross-functional team of at minimum a design engineer, a procurement representative, and ideally an MRO or EOL specialist is required, along with two to three hours for the full session.

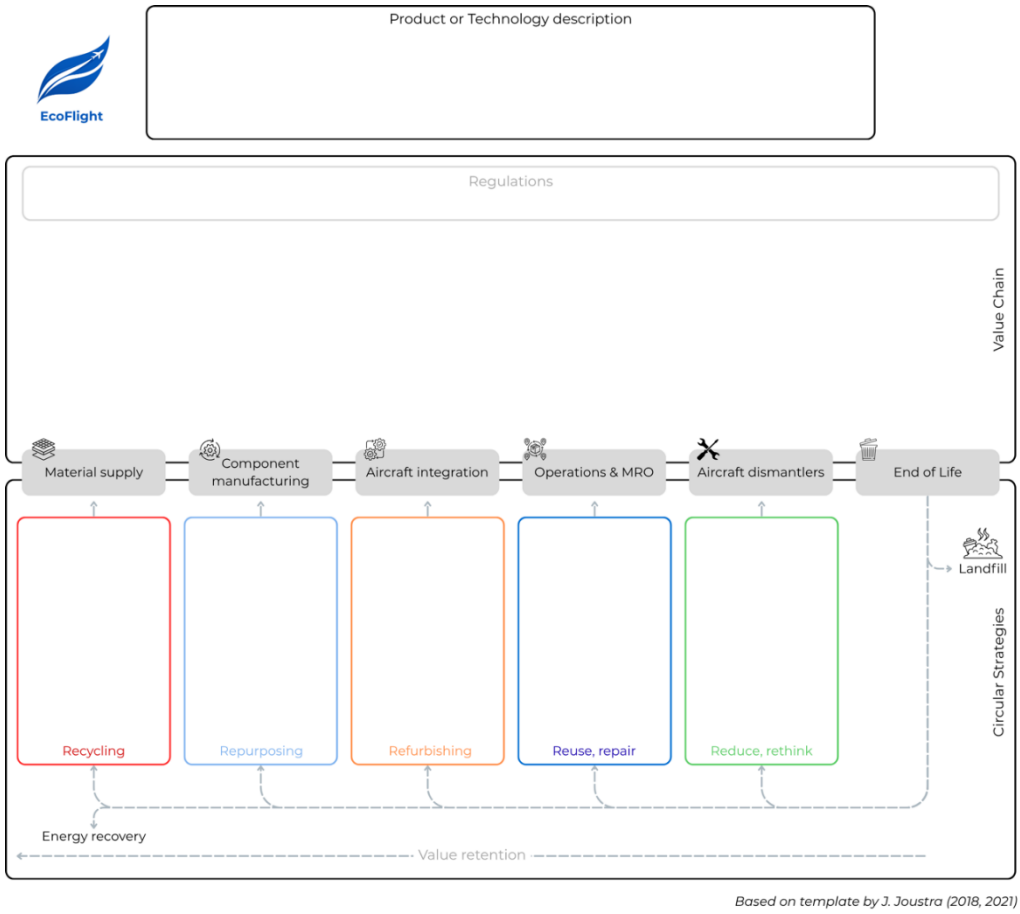

FIGURE 19: *Ecobulk Template adapted from Joustra (2022)*

Stakeholder Mapping

Barrier type: Organizational · TRL 1–3

Stakeholder Mapping is a method for identifying and organizing all actors who influence or are affected by a product's development and lifecycle, based on their role, their power over design decisions, and their level of interest in circular outcomes (TU Delft OpenCourseWare, n.d.). In aviation cabin development, stakeholder mapping consistently reveals a structural imbalance: the actors with the greatest influence over design decisions are concentrated at early stages, while those who determine whether circular strategies are achievable in practice, MRO operators, aircraft dismantlers, and material recyclers, are structurally absent. The power-interest matrix provides the organizing framework, mapping actors across two axes to identify who needs to be actively managed, consulted, informed, or brought into the consortium. The method is grounded in the EOL and MRO actor exclusion

condition identified in section 5.2.2 and connects directly to the organizational silo barrier: without a structured actor map, the absences that produce data gaps and design misalignment remain invisible.

The method is most appropriate at TRL 1–3. In this window, it is easier to identify which missing actors can still be included or consulted before design decisions lock in without their input. At mid-stage, it can be used to identify which stakeholder gaps are producing assumptions in environmental assessments. A project lead or sustainability coordinator is needed to facilitate, along with the current consortium or supplier list as a starting point and one to two hours for a structured mapping session.

Digital Product Passport Framework

Barrier type: Regulatory · TRL 4–9

The Digital Product Passport (DPP) is a digital identity record for products, components, and materials that stores lifecycle information to support sustainability, circularity, and regulatory compliance. Introduced by the Ecodesign for Sustainable Products Regulation (ESPR), which entered into force on 18 July 2024, the DPP makes product information electronically accessible to all actors across the value chain, enabling informed decisions at every lifecycle stage (European Commission, 2024). For aviation cabin components, the DPP directly addresses the material traceability and identification gap identified in section 5.2.1: dismantlers currently receive components without material labeling or composition data, making high-value recovery strategies practically impossible regardless of what early-stage design intentions specified. The method is also grounded in the regulatory vacuum identified in section 5.2.3: given that aviation cabin components are not yet a priority product category in the ESPR Working Plan 2025–2030, early DPP adoption positions organizations favorably ahead of anticipated future mandates.

The DPP is not a single workshop or analysis but an infrastructure requirement that must be anticipated from early TRL stages and built incrementally as design decisions are resolved. Implementation should begin at TRL 4–6 when material specifications and supplier relationships are sufficiently resolved to populate the passport with reliable data. Physical material identifiers, including QR codes, RFID tags, or embedded markers, should be specified at design stage rather than retrofitted after manufacturing. At TRL 7–9 and later stages, the DPP transitions from a tool to a regulatory deliverable and an operational asset for MRO and end-of-life actors.

Material Flow Analysis

Barrier type: Informational · TRL 4–7

Material Flow Analysis (MFA) is a quantitative mapping method that traces material volumes and qualities through all stages of a product's value chain, from raw material extraction through manufacturing, use, and end-of-life (Brunner & Rechberger, 2016). MFA makes visible where material value is lost, where materials are downcycled below their recoverable potential, and where stakeholder handoffs break traceability. In an aviation cabin context, MFA is particularly relevant for identifying where composite material streams are lost or degraded across the value chain, from OEM through airline operations, MRO, dismantling, and recycling. The method is grounded in both the lifecycle data deficit identified in section 5.2.1 and the organizational silo condition in section 5.2.2: Wiesner et al. (2025) apply this logic directly to aviation, showing that the absence of material and product information exchange across stakeholder handoffs is a primary barrier to circular material flows in the sector.

MFA is most appropriate at TRL 4–7, when material specifications are sufficiently resolved to enable quantitative flow mapping and supplier and end-of-life relationships are established enough to gather real flow data. It could be effective as a precursor to Digital Product Passport implementation: MFA identifies which material flows need to be tracked, and the DPP provides the infrastructure to track them. Application requires access to material specification data from suppliers, end-of-life flow data where available, and (paid) MFA software.

End-of-Life Actor Workshop

Barrier type: Organizational · TRL 1–3

The End-of-Life Actor Workshop is a facilitated session that brings MRO operators, aircraft dismantlers, and composite recyclers into the early design process, specifically to surface disassembly constraints, material identification requirements, and end-of-life processing realities that are not visible to design teams working exclusively within the OEM environment. The workshop directly addresses the EOL and MRO actor exclusion condition identified in section 5.2.2: without a structured occasion for end-of-life input, the missing feedback loop from service and end-of-life back into new design persists by default. The method is empirically grounded in the interview findings of chapter 5, where practitioners across the value chain consistently described the absence of end-of-life actors from early design as a structural condition rather than an oversight.

The workshop is most appropriate at TRL 1–3, before connection types, material combinations, and component boundaries are fixed. Participants should include at minimum one MRO operator familiar with the component category, one aircraft dismantler, and one composite recycler. A facilitator familiar with both design and end-of-life contexts is required, along with current design materials to use as concrete discussion anchors and half a day for the session.

Business Case Translation

Barrier type: Commercial · TRL 1–6

Business Case Translation is a structured method for converting environmental criteria and circular design decisions into the commercial and operational language that gate decision-makers respond to. The core insight from the interview findings in chapter 5 is that sustainability arguments do not fail at reviews because decision-makers are hostile to the environment, but because the framing is wrong. Presenting raw LCA outputs, ozone depletion percentages, or abstract circularity ambitions gives practitioners nothing to act on. Business Case Translation reframes the same circular criteria in terms of cost reduction, weight savings, supply chain resilience, and regulatory risk, language that already exists in commercial logic. The method is grounded in the commercial barriers identified in section 5.2.4, specifically financial gate logic and ROI dominance, and in the decision guide requirement established in section 5.3 that sustainability criteria must be translated into commercial and operational language to survive management decisions.

The method is most appropriate throughout TRL 1–6, but most critically in the two to three months before reviews where environmental criteria are at risk of being deprioritized. Application requires access to weight targets and fuel burn data for the aircraft type, MRO cost data for comparable components where available, and an understanding of CSRD and ESPR reporting obligations as regulatory risk framing inputs.

Circular Canvas

Barrier type: Organizational · TRL 1–3

The Circular Canvas is a structured canvas tool for mapping the business model, material flows, and circular economy ambitions of a product or project in one visual overview. Developed by Circulab, the canvas helps project teams move beyond linear thinking by making visible the full system of value creation, incoming and outgoing flows, and social and environmental impacts simultaneously (Circulab, n.d.). In an aviation cabin development context, it is most useful for establishing a shared circular economy ambition across a multi-stakeholder consortium before technical workstreams begin. The method is grounded in the organizational silo condition identified in section 5.2.2: where consortium partners hold different assumptions about what circular economy means in the context of the specific product being developed, the canvas surfaces those differences before they produce downstream misalignment.

The Circular Canvas is most appropriate at TRL 1–3, in combination with stakeholder mapping and value chain mapping, when the project consortium is first coming together and circular economy ambitions need to be made explicit and shared. The process of completing it together is as valuable as the output, as it surfaces different assumptions and creates a shared reference document for the project's circular economy ambition that can be revisited at mid-stage to assess which ambitions survived the development process and which were deprioritized. No specialist sustainability knowledge is required.

Circularity Calculator

Barrier type: Informational · TRL 1–6

The Circularity Calculator is a quantitative screening tool that estimates the circularity score of a product based on its material composition, connection reversibility, and end-of-life pathway availability (Circularity Calculator, n.d.). It translates design choices into a single circularity metric that can be tracked across design iterations and used as a directional indicator in gate review arguments. In an aviation cabin context, the calculator makes visible how material selection, connection type, and anticipated end-of-life pathway collectively determine how circular a component actually is, rather than how circular it was intended to be. The method is grounded in the lifecycle data deficit identified in section 5.2.1: at early TRL stages, designers need a lightweight instrument to assess the circularity implications of design choices without requiring complete lifecycle data.

The calculator is most appropriate at TRL 1–6, when material and connection decisions are still open and the circularity score can still meaningfully inform design choices. It is particularly useful for comparing design alternatives and for tracking how circularity score evolves as the design matures. No specialist software is required beyond a structured spreadsheet.

Memorandum of Project

Barrier type: Organizational · TRL 1–9

The Memorandum of Project is a single written document that establishes a shared baseline for all consortium members before technical workstreams begin. It defines the project's scope, circular economy ambitions, sustainability deliverables, roles and responsibilities, and the conditions under which eco-design and CE criteria will be treated as formal project requirements rather than optional outputs. The method is grounded in the sustainability as checkbox and strategic marginalization

condition identified in section 5.2.2: without a formal written agreement that elevates circular criteria to contractual obligations, sustainability ambitions are consistently deprioritized when schedule and cost pressures mount. The enabling condition identified in section 5.2.4 provides the direct rationale: in the CIRCADIS project, LCA and CO_2 footprint reporting were written into the grant agreement as mandatory deliverables, which structurally protected those criteria from being dropped at reviews.

The memorandum is most appropriate for the beginning of a new TRL, before the first working sessions, and should be completed and agreed upon by all partners before technical workstreams begin. It spans the full TRL range as a reference document that can be invoked at any gate review to reaffirm the project's environmental commitments. No specialist sustainability knowledge is required to complete it. A project lead or consortium coordinator should draft the initial version and circulate it for input from all partners, with particular attention to ensuring that sustainability deliverables are specified with the same precision as technical milestones.