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Circular Knowledge Development in Aviation Maintenance, Repair and Overhaul

A Knowledge Development Approach for Royal Netherlands Aerospace Centre

Master Thesis by J.R. (Julia) van Mens

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Landbergstraat 15, 2628 CE Delft

Author
J.R. (Julia) van Mens

Supervisors
S. N. (Shahrokh) Nikou - Chair (TU Delft)
B. (Benjamin) Sprecher - Mentor (TU Delft)
A. (Arjan) Derks - (Mentor NLR)

Company
NLR - Royal Netherlands Aerospace Centre
Anthony Fokkerweg 2, 1059 CM Amsterdam

PREFACE

Dear reader,

This thesis marks the end of seven wonderful years in Delft, and I can honestly say that I have enjoyed every minute. My early bachelor's degree years were busy and enjoyable, with long days at the faculty filled with hands-on work. This period taught me that hard work really does pay off. I developed a variety of skills, wrote my first paper and thoroughly enjoyed experimenting with materials, shaping ideas, sketching and modelling. However, I was most interested in the bigger strategic questions. This is why choosing the Strategic Product Design master's programme felt like a natural next step.

The course went by faster than I expected. Two years had passed before I realised they had even begun properly. I loved waking up feeling excited to go to university, simply because I was curious to find out what I was going to learn that day. At first, I was unsure what it would be like. I thought my life wouldn't change much since I had already been a student for a long time. But it turned out to be even better than I had hoped. I even made a few new friends along the way. Happy to have met you!

For my thesis, I was looking for a sustainability-related challenge. It didn't take me long to find the LDE for Sustainability programme (see Appendix A for extra content on the thesis lab). Its thesis labs offered a wide range of topics, but it was the ones about aviation that really caught my eye. I have a few friends who studied aerospace engineering, and I suppose I wanted to experience it for myself. The urgent challenges facing the aviation sector also made the topic even more interesting. Combining my design background with such a technical and complex industry seemed like an exciting challenge. This is how I ended up working with NLR on a project concerning maintenance and the circular economy.

It was not an easy challenge. The topic was unfamiliar to me, and it took time to grasp the context. On top of that, this was my first deep dive into the concept of the circular economy. However, thanks to the lab sessions, conversations at NLR, peer discussions, and support from my supervisors, I was able to manage it. I am grateful to everyone who supported me during this project. People often say that your thesis should not be the be-all and end-all of your degree; it should just be another course shaped by you. Nevertheless, it feels like a real accomplishment.

I hope you enjoy reading this report and learn something new along the way!

Julia

All photographs in this report are taken by *Jelle Joustra*.

ABSTRACT

Aviation maintenance, repair and overhaul (MRO) is essential for ensuring airworthiness and aircraft safety. With its inherent focus on repair and life extension, it is also a natural contributor to the principles of the circular economy. However, the potential of MRO to foster a sustainable aviation sector remains largely unexplored. This thesis investigates how the MRO sector, in the context of the Royal Netherlands Aerospace Centre (NLR), can develop the necessary knowledge and capabilities to incorporate circular economy principles into its operations. Through a comprehensive literature review, company positioning analysis, qualitative empirical research and a design phase, the study identifies the key enablers and barriers to circular innovation in the aviation MRO sector. The findings reveal a fragmented understanding of sustainability, as well as structural and cultural obstacles to cooperation and critical knowledge gaps. To address these issues, the thesis proposes a phased knowledge development roadmap, as well as a practical learning tool. These include a circular economy knowledge development roadmap and storybook. These outcomes aim to support NLR in developing a shared language and paving the way for it to become a circular specialist.

Keywords

Circular Economy; Aviation Maintenance Repair and Overhaul (MRO); Sustainability; Knowledge Development

Abbreviations

ASAM	Avionics Systems and Maintenance Engineering
ASAM/MAE	The maintenance professionals of ASAM
CE	Circular Economy
CEAP	Circular Economy Action Plan
CRMA	Critical Raw Materials Act
EGD	European Grean Deal
ESPR	Ecodesign for Sustainable Products Regulation
EU	European Union
EU ETS	European Union Emissions Trading System
KPI	Key Performance Indicator
LCA	Life Cycle Assessment
LDEfS	The Leiden-Delft-Erasmus Centre for Sustainability
MoD	Ministry of Defence
MRO	Maintenance, Repair and Overhaul
NLR	Royal Netherlands Aerospace Centre
OEM	Original Equipment Manufacturer
SAF	Sustainable Aviation Fuel
TRL	Technology Readiness Level

TABLE OF CONTENT

1 INTRODUCTION

This chapter introduces the project, providing the necessary background to understand its scope and purpose. It outlines the broader sustainability challenges that the aviation sector faces and explains why the principles of the circular economy (CE) are becoming increasingly relevant in this context. It also describes the organisational setting of the project, defines the research problem and objectives, and presents the research questions. Finally, it outlines the methodology and structure of the thesis.

1.1 Domain and Background

The aviation industry is facing increasing scrutiny regarding its environmental impact. Globally, the sector accounts for around 2.5% of CO2 emissions, with Europe's contribution standing at 3.2% (Emissions of Greenhouse Gases by Country and Sector, 2018). Its cumulative contribution to global warming is estimated at around 4% (Ritchie, 2024) and is a figure which is expected to increase as demand for air travel continues to grow. Airbus forecasts over 42,000 new aircraft deliveries over the next 20 years (Global Market Forecast, 2024).

While most aviation emissions result from kerosene combustion during flight, other stages of the aircraft's lifecycle, including manufacturing, maintenance, and operations, also contribute to the sector's environmental footprint (Davydenko et al., 2024). The industry must decouple its growth from resource consumption, which requires technological innovation and systemic shifts in business models, policy and stakeholder behaviour.

CE principles provide a promising framework for addressing these challenges. The CE model promotes reuse, repair, refurbishment and recycling to reduce waste and environmental degradation. The European Green Deal (EGD) and the Circular Economy Action Plan (CEAP, 2020) set ambitious climate neutrality targets for 2050, with frameworks such as the 10R framework (Reike et al., 2022) guiding their implementation.

Maintenance, repair and overhaul (MRO) activities inherently align with certain CE principles as they extend the life of aircraft through repair and refurbishment (Al-Kaabi et al., 2007). Nevertheless, the aviation sector remains largely linear, and the application of CE frameworks in MRO remains limited and fragmented. While initiatives such as SustainAir, HACE and FutureSky highlight the potential for circular strategies in aviation maintenance (EREA, 2019; HACE, 2024; SUSTAINair Sustainability Snapshots, 2022), widespread adoption is hindered by economic, regulatory and organisational barriers.

This graduation project is situated within the domain of circular aviation, with a particular focus on maintenance management in MRO. It was initiated by the Avionics Systems & Maintenance Engineering (ASAM/MAE) department at the Royal Netherlands Aerospace Centre (NLR), in collaboration with the Leiden-Delft-Erasmus Centre for Sustainability Centre for Sustainability's (LDEfS) Green Skies Thesis Lab. The project investigates the knowledge required to integrate CE principles into MRO, supporting NLR's ambition to advance sustainable aviation practices.

1.2 Project Context

1.2.1 NLR - Royal Netherlands Aerospace Centre

NLR is an applied research institute that connects academia, industry and government. Operating within Technology Readiness Levels (TRL) three to eight, it fills the gap between early-stage research and market-ready solutions (Ministerie van Economische Zaken en Klimaat, 2022). NLR's mission is to make the aerospace sector more sustainable, safe, efficient and effective. Its strategy focuses on supporting the objectives of the EDG, the targets of the Advisory Council for Aeronautics Research in Europe (ACARE), defence modernisation and national aviation policy (Missie, Visie & Strategie, NLR, 2022).

1.2.2 Department: Avionics Systems and Maintenance Engineering (ASAM)

ASAM is one of NLR's departments, specialising in maintenance technology and management. Within the MRO domain, ASAM focuses on airworthiness-critical technical maintenance of engines, airframes and components, as well as line and base maintenance. The department's goal is to support operators, original equipment manufacturers (OEMs), and maintenance organisations in enhancing aircraft availability while reducing operational costs and environmental impact. The department recognises the importance of digitalisation and automation in improving the sustainability of MRO.

1.3 Project Assignment

1.3.1 Observation

NLR recognises that MRO activities already incorporate circularity through processes such as repair, replacement, overhaul and refurbishment. This observation raised the question of how MRO could contribute more systematically to circular aviation, particularly through maintenance management. The project explores the conceptual links between MRO and the CE, and identifies existing knowledge gaps. The initial outreach from NLR and the Project Brief can be found in Appendix I and J.

1.3.2 Project Scope

The project adopts a maintenance management approach that balances business, economic and technological factors with the tactical management of maintenance activities. The focus of maintenance management is to optimise the reliability, availability and lifespan of assets while controlling costs and minimising environmental impacts. This approach is particularly relevant when considering how CE principles can be applied to aviation MRO, as it links technical decisions to wider strategic and operational considerations.

Although maintenance management initially defined the project scope, early exploration revealed that maintenance technology and engineering also play a critical role in determining circularity outcomes. Decisions relating to technology selection, component design and engineering processes have a significant impact on what can be achieved in terms of circularity during operation and maintenance. Therefore, the research scope was expanded to include these areas, recognising that the effective adoption of CE strategies in MRO requires an integrated, multidisciplinary approach.

1.4 Problem Definition

NLR's expertise in aviation technology is a solid basis for innovation. However, when it comes to sustainability and CE strategies, the challenges extend beyond technology. These include mindset, strategic positioning and organisational awareness. Currently, NLR's maintenance department lacks a shared understanding of the CE, as well as the practical tools needed to support its adoption. This contributes to the perception of circularity as a constraint rather than an opportunity for innovation.

1.4.1 Problem statement

The problem definition leads towards the following problem statement:

"The aviation maintenance, repair and overhaul (MRO) sector, including organisations such as NLR, currently lacks the internal awareness, shared language and conceptual framework required to meaningfully engage with circular economy strategies in the maintenance, repair and overhaul of aviation. This prevents organisations from identifying opportunities, driving relevant innovation, and supporting clients in transitioning to a more circular aviation sector."

1.5 Research Objectives and Questions

1.5.1 Objectives and Deliverables

This project aims to help ASAM/MAE adopt CE principles by identifying relevant areas of knowledge and designing a strategy to create, use, and share this knowledge.

Objectives:

1) Understand how sustainability and circularity are viewed within NLR and the aviation sector, and the role of MRO in this context.
2) Identify relevant research within the project scope (MRO and circularity).
3) Explore how circularity is practised and identify related values and needs.
4) Define the key knowledge areas needed to support circularity in aviation maintenance.
5) Develop a strategy and tool to support circular knowledge building over the next decade.

This project aims to help NLR better understand how CE principles can be applied in the field of aviation maintenance. The study will provide an overview of the knowledge required to support circular thinking in MRO, and describe how this knowledge can be developed and utilised within the organisation. Additionally, it will examine the influence of current working methods and organisational structures on the adoption of circular practices. The project will also produce practical outputs to encourage learning and knowledge-sharing on this topic within the maintenance department. These outputs will be based on a combination of literature research, internal discussions and qualitative data. The recommendations will be shaped to NLR's context and aim to support future steps towards more circular maintenance practices.

1.5.2 Research Questions

In order to address the identified problem and achieve the project objectives, one main research question and three sub-questions were formulated. These questions will guide the investigation into how NLR can strengthen its capabilities in the CE within the aviation MRO domain. The questions reflect the project's focus on understanding the current situation, identifying knowledge requirements and designing pathways for knowledge development and application.

Main Research Question

"How can NLR develop and embed circular economy knowledge to support the transition towards more sustainable maintenance practices in aviation MRO?"

Sub Questions

1) How is the circular economy currently understood and applied within NLR and the wider aviation MRO context?
2) What types of knowledge are needed to support circular economy processes in aviation maintenance, and where are current knowledge gaps?
3) How can NLR effectively build, share, and apply this knowledge over time in a way that fits its organisational context and supports sustainable innovation in MRO?

1.6 Methodology

A combination of desk research, empirical research and creative methodologies was employed. The first phase involved conducting a systematic literature review alongside in-depth qualitative research. The second phase focused on co-creation and design.

Overview:

- A systematic literature review was conducted to establish theoretical foundations.
- Qualitative research (interviews and thematic analysis) was conducted to explore current perspectives and practices.
- Design methodologies (ideation, co-design and roadmapping) were used to develop practical outputs.

1.7 Project Structure

This thesis is structured according to the logic of the research and design process. The first part introduces the project background, the research problem and its context, and the project objectives. It also presents the theoretical framework on the CE in aviation. This is followed by an organisational positioning analysis of NLR and its maintenance department to gain an understanding of the current state of affairs. The next section describes the research methodology and presents the empirical findings, including thematic insights and a knowledge development framework. Based on these results, the design phase explores practical ways to support knowledge development, resulting in the creation of a knowledge roadmap and a storybook. The outcomes of the design phase are then validated and discussed in relation to their potential implementation within NLR. The thesis concludes by answering the research questions, providing recommendations for future work and offering a personal reflection.

2

SYSTEMATIC LITERATURE REVIEW

In order to understand how CE principles relate to aviation, it is important to review the existing academic and applied literature on the subject. A systematic literature review provides a basis for identifying current developments, recurring challenges and relevant frameworks in this field. It also helps to clarify which parts of the CE have already been adopted by the aviation industry, and where knowledge or implementation gaps still exist.

This review focuses on the intersection of the CE and aviation rather than on MRO specifically. The term 'MRO' is often too narrow to yield relevant academic results, and many applicable MRO insights are found under broader aviation or sustainability topics. The search was conducted primarily using the Web of Science database and was supplemented by Google Scholar, targeted Google searches and the exploratory use of ChatGPT to identify additional perspectives or terminology.

2.1 Search String

An initial search strategy was developed and refined through an iterative process to support the literature review. The aim was to compile a relevant body of literature on the relationship between the CE and aviation, focusing particularly on topics that could inform the maintenance, repair and overhaul (MRO) context.

The following search string was used as the primary query in the Web of Science database:

'*TS=(("circular economy" OR "sustainable economy" OR "closed-loop economy" OR "regenerative economy" OR "circular economy principles" OR "circular economy framework" OR "life cycle thinking" OR "eco-innovation" OR "resource efficiency") AND ("aviation" OR "aircraft" OR "aerospace" OR "aviation industry" OR "airline*" OR "aviation sector") AND ("implementation" OR "adoption" OR "best practices" OR "business model" OR "policy" OR "strategy" OR "life cycle assessment" OR "remanufacturing" OR "reverse logistics" OR "reuse" OR "sustainable operations" OR "maintenance" OR "repair" OR "overhaul" OR "MRO")*'.

The search string was designed so that 'maintenance, repair and overhaul' (MRO) was not a required term, as initial tests showed this would result in too few relevant hits. Taking a broader approach ensured that developments in the CE with potential relevance to MRO were also captured.

The initial search yielded 95 papers. After screening the abstracts to identify those relevant to the aviation industry and sustainable developments, 34 papers were selected for in-depth review. An additional eight papers were identified through complementary searches using Google, as well as through exploratory use of ChatGPT, to locate papers not captured through the main database.

2.2 Theoretical Background: Circular Economy Theory

This section provides the theoretical background to the CE, clarifying the key concepts and frameworks that underpin the analysis of circularity in aviation maintenance. A grasp of these concepts is essential for accurately interpreting both academic literature and the practical context of MRO.

2.2.1 Terminology: Sustainability, Circularity and the Circular Economy

Although the terms 'sustainability', 'circular economy' and 'circularity' are often used together in research and policy, they do not mean the same thing. In order to use them correctly in theory and in practice, it is important to understand the differences between them.

Sustainability is the broadest of the three terms. It refers to the ability to meet the needs of the present generation without compromising the ability of future generations to meet their own needs. It encompasses environmental, social and economic factors (Saha & Saha, 2024).

The CE is a strategy that contributes to achieving sustainability. It aims to reduce waste and keep products and materials in use for as long as possible. This model contrasts with the traditional linear economy, where items are produced, used, and then discarded. In a CE, materials are reused, repaired or recycled to keep them in circulation (Moesch, 2024).

'Circularity' is a more technical term. It describes how well a product, material, or system performs within this model. A product with high circularity might, for example, be designed to be easily recycled or made from reused materials. Circularity can be measured using indicators such as how long a material is used for and how much is recovered after use (Kasztelan & Kijek, 2025).

Although these terms are connected, they are not the same. The overarching goal is sustainability. One way to contribute to this goal is through the CE. The degree of circularity indicates how well the CE is functioning. However, a product being circular does not automatically make it sustainable. For example, a product that is fully recyclable may still require significant energy during production or generate pollution. This is why it is important to consider all three terms carefully. Researchers such as Köhler et al. (2024) have warned that confusing these terms can lead to misinterpretation or even greenwashing. In this study, it is important to use these terms clearly and consistently in order to correctly interpret both the literature and the practical context of MRO.

2.2.2 Circular Economy Theory

General definitions of the circular economy

The concept of the CE has been the subject of various literature studies and reviews. Many authors have sought to understand it and have proposed several variations on its definition. Most of these definitions are based on the work of the Ellen MacArthur Foundation (2015), which, although not an academic source, is widely regarded as a key reference point for CE theory due to its strong influence in policy and business contexts. Some definitions focus primarily on economic and business model innovation, while others emphasise environmental and resource efficiency. This diversity reflects the complexity of achieving a clear and comprehensive understanding of the CE.

The relevance of multi-level approaches

In the context of aviation MRO, it is important to use a definition that considers regulatory, technical and operational constraints, as well as applicability across different system levels. The CE aims to transform the entire economic system, which requires coordinated action across multiple scales (Suárez-Eiroa et al., 2019). This is why CE implementation is often described as a multi-level approach involving micro, meso and macro levels. Each level presents its own opportunities and challenges.

Kalmykova et al. (2018) describe this multi-level system as operating across the individual firm (micro), the sector (meso) and the broader, economy-wide scale (macro). Similarly, Korhonen et al. (2018) highlight firm strategies and inter-firm industrial symbiosis as key elements in CE implementation. The Ellen MacArthur Foundation (2013) also refers to changes at product and sector levels, further supporting the need for multi-level action.

Defining circular economy for aviation maintenance, repair and overhaul

The Ellen MacArthur Foundation's proposed definition conceptualises CE as an industrial system that is restorative and regenerative by design. This macro-level vision focuses on maintaining the value of products, materials and resources for as long as possible. While this definition has been influential, it lacks a clear structure for industry-specific implementation, which is required in highly regulated, technically complex sectors such as MRO.

Other definitions also offer valuable insights. For example, Velenturf and Purnell (2021) define the CE through the lens of natural ecosystems, highlighting the need for ecological sustainability. However, this definition does not directly address the operational and regulatory challenges faced by sectors such as aviation. Murray et al. (2017), meanwhile, offer a business-oriented definition that focuses on R-strategies (reduce, reuse, recycle), yet they do not fully incorporate the importance of cross-industry collaboration or regulatory frameworks.

For this study, the definition provided by Korhonen et al. (2018) is considered the most suitable. It explicitly addresses material and

energy flows, highlights the importance of high-value material cycles and recognises the importance of cooperation between different stakeholders. The definition is as follows:

"Circular economy is a sustainable development initiative that aims to reduce the linear material and energy throughput flows of societal production-consumption systems by applying material cycles and renewable and cascade-type energy flows to the linear system. CE promotes high-value material cycles alongside more traditional recycling, developing systems approaches to cooperation between producers, consumers, and other societal actors in sustainable development work."

2.2.3 Classifying and Structuring Circular Economy Strategies

In order to understand how the CE can be applied in practice, it is important to explore the frameworks that translate its principles into concrete strategies. These frameworks offer organisations and sectors practical guidance.

One such framework is the ReSOLVE framework, developed by the Ellen MacArthur Foundation in 2015. There are six key areas to consider: regenerate, share, optimise, loop, virtualise and exchange. The ReSOLVE framework offers a broad, systemic view of how CE principles can be implemented across different sectors. In the context of aviation MRO, for example, the framework provides useful ideas for improving efficiency and extending component lifespan. However, due to the highly specialised and regulated nature of the aviation sector, adaptation of the framework is required for it to be fully applicable (Dias et al., 2022).

Another widely used model is the 10R hierarchy, or 10R framework, proposed by Potting et al. (2017) and further developed by Hisan et al. (2024). This framework offers a prioritised approach to circularity, ranging from waste prevention (refuse, rethink, reduce) to product lifecycle extension (repair, refurbish, remanufacture) to material recovery (recycle, energy recovery, disposal).

The 10R framework is technical and practical, prioritising specific actions, which makes it particularly suitable for sectors such as aviation that operate within strict technical and safety constraints. While the ReSOLVE framework is conceptually strong for promoting systemic change, the 10R framework offers a more

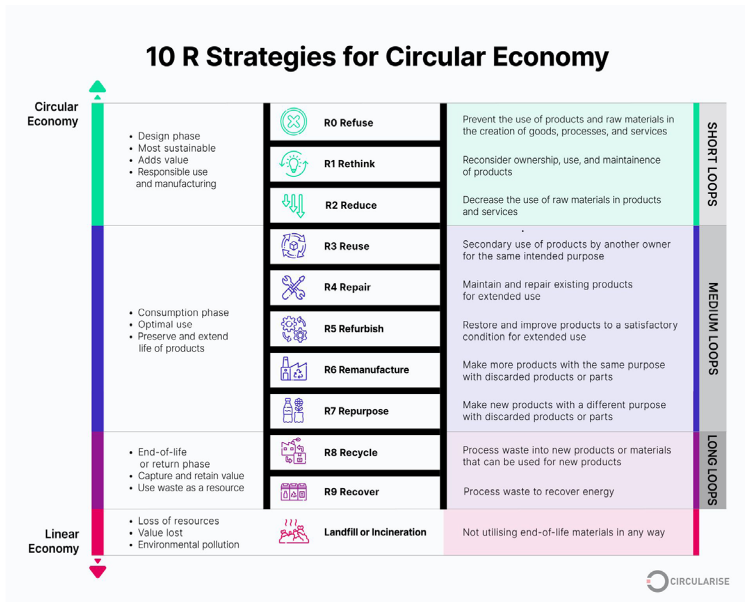


Figure 1. Visualisation of the 10R framework. The ten strategies are classified under three categories that demonstrate the length of the waste loop each represents. The shorter the loop, the more sustainable the strategy is. The higher they are on the ladder, the tighter the waste loop (Circularise).

detailed, industry-specific approach. For these reasons, the 10R framework will serve as an important reference in this study when analysing opportunities for circularity in MRO.

2.3 Part 1: Circular Initiatives in Aviation

This section reviews key initiatives and developments related to circularity in the aviation sector, as highlighted in recent literature on aviation and the CE. The aim is to demonstrate how these developments can contribute to more circular practices in aviation and their potential application in maintenance and repair strategies.

2.3.1 Sustainable Aviation Fuels

Sustainable aviation fuels (SAFs) are essential for decarbonising the aviation sector. It is expected that they will account for the majority of emissions reductions by 2050 (Destination 2050, 2025). SAFs include bio-based and synthetic fuels which significantly reduce lifecycle greenhouse gas emissions compared to conventional jet fuels (Ebadian et al., 2020). SAFs can be produced from various feedstocks, including agricultural residues, municipal solid waste (MSW) and industrial by-products such as black liquor (Arias et al., 2024; Pires et al., 2024). This flexibility in feedstock use enables waste valorisation and aligns with the principles of the CE by reducing dependence on virgin resources (Khalifa et al., 2020).

Despite their potential, SAFs face several barriers to widespread adoption. These include high capital investment, fluctuating feedstock availability and fragmented policy frameworks (Dodd et al., 2024; López-Gómez et al., 2024). Economically viable production scales of 300–600 tonnes per day require extensive infrastructure, supply chain integration and process innovation (Arias et al., 2024; Dubey et al., 2024).

While much of the research focuses on SAF production and regulation, the MRO sector also plays a supporting role in their implementation. Khalifa et al. (2020) argue that MRO organisations could contribute by developing advanced structural health monitoring systems, extending aircraft lifecycles and improving waste recovery for fuel conversion. Collaboration between airlines, MRO providers and SAF suppliers could accelerate fuel compatibility testing, streamline retrofitting processes and enhance operational efficiency (López-Gómez et al., 2024). Thus, MRO can support a more integrated approach to circular aviation, in which both fuel systems and aircraft assets are managed in accordance with the principles of the CE.

2.3.2 Extending Material Lifecycles

One of the key pillars of the CE is keeping materials in circulation for as long as possible. Critical raw materials are particularly important for high-tech industries, such as aviation. Instead of focusing solely on end-of-life recycling, current strategies increasingly emphasise extending the life of materials through repair, remanufacturing and digital innovation, with the aim of reducing dependence on virgin resources (Baldassarre, 2025; European Parliament and Council, 2024).

In the aerospace MRO sector, for example, life extension has already proven valuable. Case studies show that remanufacturing components such as turbine blades and impellers lowers environmental impact and reduces operational costs (Ferreira & Gonçalves, 2021). Frameworks such as the Generic Product Lifecycle Model (gPLC) integrate maintenance, repair and remanufacturing as core processes for achieving material circularity. Technologies such as additive manufacturing and predictive maintenance play a key role in enabling this (Gräßler & Pottebaum, 2021).

Digital tools further enhance circularity in MRO operations. Material passports integrated into digital component records provide real-time data on usage history, inspections, and remaining useful life. This supports informed maintenance decisions and minimises unnecessary disposal (Paramatmuni & Cogswell, 2023). Meanwhile, digital life cycle assessments and material flow analyses improve transparency and help quantify circular performance (Vogiantzi & Tserpes, 2023).

Together, these approaches facilitate the transition from linear consumption to regenerative material utilisation, positioning MRO as a pivotal enabler in sustaining material value across multiple life cycles.

2.3.3 Material Innovation

Although sustainability is gaining traction in the aerospace industry, material innovation is still primarily driven by performance, safety and regulatory compliance. Nevertheless, the growing interest in the CE has prompted research into eco-friendly materials, additive repair methods and enhanced recycling technologies.

One area of development is eco-composites, which incorporate bio-based fibres, recycled carbon fibres and bio-resins. The ECO-COMPASS project has demonstrated the potential of these materials for use in aircraft interiors, where green honeycomb structures could replace synthetic composites (Bachmann et al., 2021). While these materials offer environmental benefits, their limited mechanical strength and the strict fire safety standards currently restrict their broader adoption. Downcycling remains a practical way to keep these materials in circulation after their initial use.

Self-healing polymers also show promise in reducing waste by extending component lifespans. Systems based on Diels–Alder chemistry or embedded microcapsules can autonomously repair cracks, thereby improving durability and reducing maintenance requirements (Pandey et al., 2024; Paolillo et al., 2021). While these materials align well with circularity goals, they face commercialisation barriers due to cost and environmental constraints.

For metallic parts, Directed Energy Deposition (DED) enables the precise remanufacturing of worn areas of high-value components, such as turbine blades (Saboori et al., 2019). This technique reduces material waste while preserving functional performance; however, certification and process standardisation are required for wider adoption.

The management of composite materials at the end of their life remains a critical issue. Glass fibre-reinforced composites are difficult to recycle due to their thermoset resin structures. Although thermal decomposition can recover fibres, this process often compromises the material's mechanical properties (Săftoiu et al., 2024). Ongoing research into bio-based resins and hybrid recycling methods aims to improve recovery rates and enable closed-loop reuse.

Although these technologies are not yet the industry standard, they are an important step towards integrating circularity into the manufacturing and maintenance of aerospace products, where extending the life of materials and retaining their value are key opportunities for the MRO sector.

2.3.4 Analytical Tools

Life Cycle Assessment (LCA) is a widely used tool for evaluating the environmental impact of products and processes throughout their lifecycle. In aviation, LCA has been applied to systems ranging from the electrical distribution of next-generation aircraft to the production of biomass-based fuels and SAFs (Izquierdo et al., 2023; Kourkoumpas et al., 2024; Lan et al., 2024). These studies demonstrate how LCA can be used to evaluate the sustainability and circular performance of new technologies, ensuring compliance with standards such as ISO 14040/14044 and CORSIA, and helping to achieve long-term goals like Flightpath 2050.

Beyond environmental metrics, LCA informs decisions on material choices, energy use and waste streams, which are key considerations in design and maintenance. However, the quality of its insights depends heavily on data availability, system boundaries, and methodological consistency.

Alongside LCA, emerging analytical techniques are being explored to enhance circularity and operational performance. For instance, knowledge graph-based failure information fusion integrates various failure data sets to facilitate predictive maintenance, optimise spare parts, and enhance diagnostics (Zhang, Yang & Han, 2024). Such tools can strengthen MRO capabilities by enabling proactive, data-driven strategies for asset management.

As pressures to be more sustainable increase in both the regulatory and industry sectors, analytical tools such as LCA and complementary digital methods will play a central role in guiding circular innovation. These approaches also provide a valuable foundation for developing more structured methods of advancing circularity within aviation maintenance, which will be explored further in this study.

2.3.5 Strategic Decision-Making and Policy Enablers

The transition to sustainable aviation hinges on technological development, strategic decision-making, the adoption of circular business models and robust policy support. As profitability remains a key objective, business strategies must link environmental goals to value creation in a practical and measurable way.

Multi-criteria decision-making models such as M-SWARA and ELECTRE help aviation stakeholders prioritise investments in sustainable technologies (Aksoy et al., 2022). These tools support the evaluation of complex trade-offs involving cost, technical feasibility and sustainability performance. Product-service systems, as discussed by Bertoni (2019), further connect sustainability to profitability by focusing on the entire product lifecycle, including maintenance and reuse.

This approach aligns with the triple bottom line concept, considering environmental, economic and social outcomes. Saade et al. (2025) propose a framework that integrates quality management with CE principles to embed sustainability in business models. Markatos and Pantelakis (2023) take a similar approach to assessing aviation innovations, combining technical performance, cost, and environmental impact.

Policies are essential for enabling this transition. However, existing regulations and technologies can create inertia, a phenomenon known as epistemic lock-in (Bruce & Spinardi, 2018). To accelerate the adoption of circular approaches, regulatory incentives, clear definitions and industry-wide standards are needed. As Saade et al. (2025) point out, a shared understanding of green aviation is vital for aligning policy and industry efforts.

Therefore, establishing the right combination of business models, decision-making frameworks and supportive policies is critical to enabling more circular practices within aviation, including in the MRO domain. The next section will explore how such innovations are currently being adopted at different levels within the aviation sector.

2.4 Part 2: Circular Aviation Innovations Adoption Model

In order to understand how the principles of the CE can be adopted in the aviation industry, it is important to examine the factors that influence this process. The literature shows that these factors operate at multiple levels within the aviation system. This section applies the three-level model proposed by Suárez-Eiroa et al. (2019) to structure this understanding. This model distinguishes between micro, meso and macro levels of implementation.

The micro level focuses on how CE principles are implemented within individual organisations, including internal processes and business models. The meso level examines collaboration across the aviation sector, particularly in supply chains and cross-industry partnerships. The macro level considers how governments and regulatory frameworks influence the wider environment for CE adoption.

By examining these levels, this section provides a structured overview of the key factors that facilitate or delay the adoption of circular practices in aviation. This overview also informs the theoretical framework used in this study.

2.4.1 Micro Level

Technical and Operational Viability

The adoption of CE principles in aviation is heavily influenced by technical and operational considerations. Many promising technologies face significant practical challenges. Battery electric propulsion, hydrogen and e-kerosene, for example, remain commercially unviable due to high energy requirements and infrastructure limitations (Davydenko et al., 2024; López Gómez et al., 2023). Similarly, SAFs encounter scalability issues, especially when derived from waste materials (Arias et al., 2024; Dubey et al., 2024).

In MRO, technologies such as additive manufacturing and component remanufacturing must comply with strict quality and regulatory standards (Ferreira & Gonçalves, 2021; Saboori et al., 2019). Integrating digital systems and predictive maintenance also requires substantial investment and is further constrained by safety regulations and the long service cycles of aircraft (Gräßler and Pottebaum, 2021; Sebastian and Louis, 2021).

Business Incentives

Business incentives play a key role in promoting the adoption of circular practices in aviation. Without financial incentives, sustainable aviation fuels (SAFs) remain uncompetitive from an economic perspective (Davydenko et al., 2024; Ebadian et al., 2020). Measures such as environmental taxes, green procurement policies and product-as-a-service models can encourage circular behaviours.

Companies are more likely to invest in reverse logistics and eco-friendly materials when they perceive clear regulatory or financial benefits (Dodd et al., 2018; Bachmann et al., 2021). Airports can also contribute to this by providing incentives for circular initiatives (Sebastian & Louis, 2021).

Decision-making Models

Decision-making models help organisations to balance sustainability, cost and performance when adopting CE principles. Methods such as AHP (Analytical Hierarchy Process), WSM (Weighted Sum Model) and TOPSIS (Techno-Economic Analysis) allow organisations to evaluate different strategies based on environmental, economic and operational factors (Markatos & Pantelakis, 2023).

Tools such as life cycle assessment (LCA) and techno-economic analysis (TEA) support the evaluation of alternative fuels and waste-to-energy systems (Zhang et al., 2024; Lan et al., 2024). In MRO, advanced techniques such as artificial neural networks and digital twins support damage prediction, maintenance planning and real-time monitoring (Gordan et al., 2023; Paramatmuni & Cogswell, 2023).

Frameworks such as PESTEL and ISO 14001 guide sustainable practices in areas such as the adoption of SAFs and airport waste management (López Gómez et al., 2023; Sebastián & Louis, 2021).

Use of Circular Design

Circular design principles support the CE by ensuring that aircraft and components are designed for reuse, repair and recycling. Unlike linear strategies, circular design focuses on modularity, the use of eco-friendly materials, and long-term durability in order to minimise waste (European Research Establishments Association, 2019; MacArthur, 2013).

Examples include using standardised parts to facilitate refurbishment (Bertoni, 2019) and developing materials such as self-healing polymers to extend component life (Pandey et al., 2024). However, some materials, such as lightweight composites, remain difficult to recycle (Markatos & Pantelakis, 2023). Aerospace designers are therefore increasingly applying design-for-disassembly techniques and considering end-of-life scenarios, supported by advanced repair technologies such as Directed Energy Deposition (DED) (Vogiantzi & Tserpes, 2023).

2.4.2 Meso Level

Supply Chain Integration

Integrating the supply chain is essential for achieving circularity in aviation. Circular practices require collaboration across the entire value chain, from material sourcing to end-of-life recovery. Transparent supply chains enable better tracking of materials and facilitate reuse and recycling (Grässler & Pottebaum, 2021; MacArthur, 2013).

Technologies such as material passports improve traceability in complex networks (Paramatmuni & Cogswell, 2023), and supplier agreements for green components demonstrate the influence of upstream decisions on circularity outcomes (Salesa et al., 2023). Closed-loop supply chains and strong stakeholder collaboration are key to achieving sustainable design, production and end-of-life strategies (Baldassarre, 2025; Vogiantzi & Tserpes, 2023).

Cross-industry Partnerships

Accelerating CE in aviation requires cross-industry collaboration. No single sector can drive the transition alone. Collaboration between those in aviation, materials science, manufacturing and policy promotes innovation and shared infrastructure (Bachmann et al., 2021; MacArthur, 2013).

Projects such as ECO-COMPASS demonstrate how expertise from different sectors can support the development of more sustainable materials and practices. Public–private partnerships and industry alliances also play a pivotal role in coordinating decarbonisation initiatives and facilitating the adoption of circular processes (Baldassarre, 2025; Destination 2050, 2025).

Industry Guidelines and Certification Processes

In aviation, where safety and performance requirements are stringent, industry standards and certification processes are essential for the safe adoption of CE practices. Organisations such as ASTM, ICAO, EASA and ISO establish standards for fuels, materials and processes.

ASTM D7566, for example, defines blending requirements for SAFs, while ISO 14040 supports environmental assessments (Arias et al., 2024; Lan et al., 2024). However, certification gaps still exist for emerging technologies such as hydrogen propulsion. Although initiatives such as CORSIA and RED III help to set higher

sustainability standards (Davydenko et al., 2024; Pires et al., 2024), a consistent framework for circularity is lacking (Vogiantzi & Tserpes, 2023).

2.4.3 Macro Level

CE Promoting Policies

Policies play a crucial role in promoting circularity in aviation. Policies help create an environment in which circular practices can thrive by removing market barriers, guiding investment and stimulating innovation. The EGD provides an overarching framework for achieving climate neutrality and improving resource efficiency by 2050. Within this framework, initiatives such as the CEAP, the CRMA and the Fit-for-55 package promote circular design, repairability, recycling and clean energy use (Baldassarre, 2025; Davydenko et al., 2024; European Commission, 2020).

Sector-specific policies, such as ReFuelEU, promote the use of SAFs through blending mandates, subsidies, and carbon pricing (Ebadian et al., 2020). Additionally, public-private alliances and Green Deal research projects are supporting the development of sustainable aviation technologies (Arias et al., 2024; Destination 2050, 2025; Săftoiu et al., 2024).

Internationally, countries such as Colombia are adopting similar strategies by introducing carbon pricing and transition plans to promote SAFs and circular practices in aviation (López Gómez et al., 2023).

Standardisation of Circular Economy Practices

Standardising CE practices is critical for ensuring consistency, credibility and scalability in aviation sustainability efforts. Currently, the absence of shared definitions and frameworks hinders the assessment and certification of circular initiatives (Salesa et al., 2022; Vogiantzi & Tserpes, 2023).

Standardised principles for design, reuse and life cycle assessment would help to harmonise efforts across the industry. The CEAP is moving in this direction by providing tools such as the EU Ecolabel and Environmental Footprint methods (European Commission, 2020). As new technologies such as hydrogen propulsion are developed, the importance of common certification standards will increase (Destination 2050, 2025; Săftoiu et al., 2024).

2.5 Theoretical Framework

As demonstrated in previous sections, the adoption of CE principles in aviation is influenced by various factors operating at different levels. To structure this understanding and guide the project's empirical phase, a theoretical framework was developed based on insights from the literature review. A visualisation of this framework can be found in Figure 2.

A theoretical framework provides a structured approach to a research topic. It connects theoretical perspectives to the empirical investigation and offers a clear lens through which to analyse the data (Atlas.ti, 2025). In this project, the framework was used to develop the interview guide and will support the interpretation of the empirical findings.
Following the model proposed by Suárez-Eiroa et al. (2019), the framework distinguishes between three levels of influence on the adoption of CE principles. These levels are:

The micro level, which includes organisational factors such as maintenance strategies, business models and technical capabilities within MRO organisations.

The meso level covers industry-wide collaboration, supply chain integration, and the development of shared infrastructure.

The macro level involves the regulatory environment, government policies and international frameworks that shape the conditions for CE adoption.

In addition to these levels, the framework incorporates values central to the aviation industry. These include safety, compliance, and economic performance. These values strongly influence how circular practices are viewed and implemented in aviation and must be considered when exploring opportunities for change.

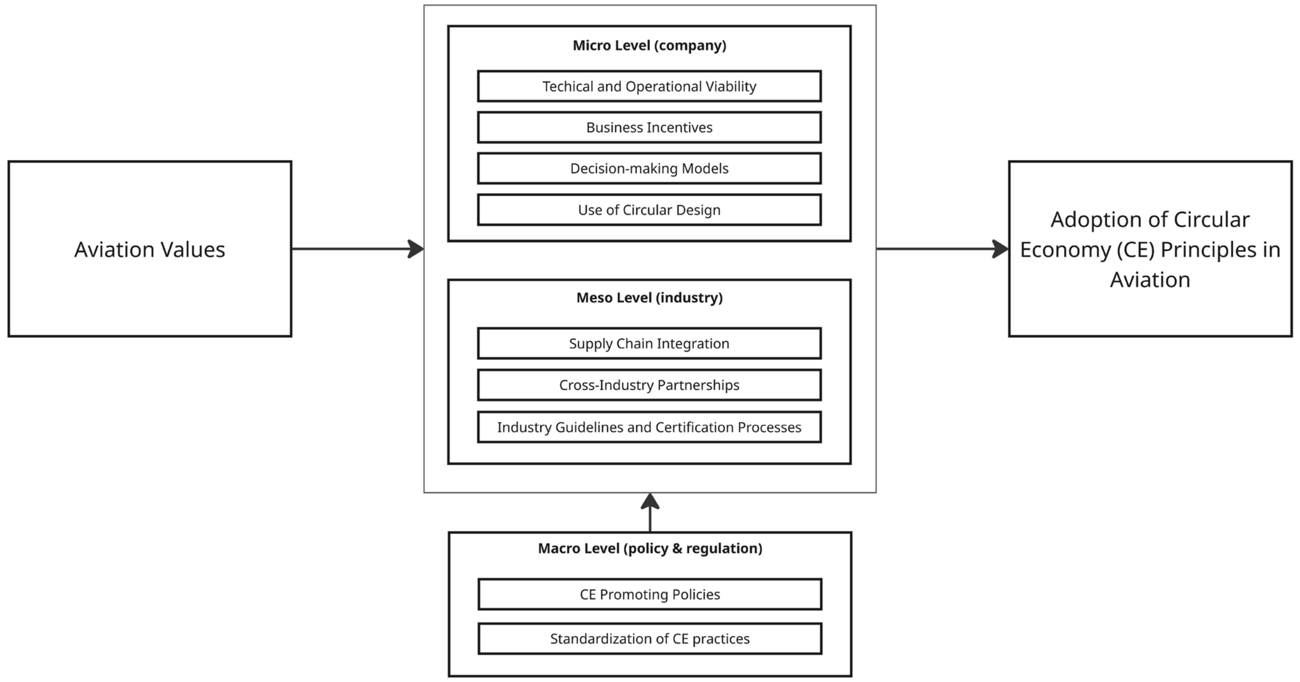


Figure 2. This theoretical framework illustrates how the different levels of influence (micro, meso and macro) interact to shape the adoption of circular economy principles in the aviation industry. This framework highlights the key factors that support or hinder circularity, and will guide the empirical phase of this study.

This theoretical framework will serve as a guiding tool for the rest of the project. It will structure the analysis of the empirical data and help identify the most relevant knowledge needs for NLR's efforts to adopt circular practices in maintenance. Thus, the framework establishes a clear link between the literature and the practical objectives of the project.

2.6 Conclusion of the Literature Review

This literature review has demonstrated that the CE is a promising approach to improving the sustainability of aviation. MRO is a key contributor to this. MRO promotes circularity by extending aircraft life, enhancing material recovery, encouraging the use of sustainable fuels, and enabling more informed maintenance practices.

The review also shows that adopting CE principles in aviation depends on a combination of technical, economic, organisational and regulatory factors. These factors operate at micro, meso and macro levels, requiring cooperation across the sector.

The 10R framework provides a useful structure for achieving circularity in aviation by offering practical strategies ranging from reducing material use to supporting reuse and recycling. Analytical tools such as LCA, as well as digital technologies, are playing an increasingly important role in supporting these efforts.

At the same time, however, the review highlights several challenges. While technical feasibility and business incentives are receiving increasing attention, other factors such as supply chain integration, standardisation and cross-industry cooperation remain underdeveloped. The aviation sector's strong focus on safety and regulatory compliance influences how circularity is addressed, and this context must be considered.

The theoretical framework developed in this chapter will guide the empirical phase of this study. It will help to identify key knowledge requirements and opportunities for advancing circularity within NLR's maintenance activities.

3

NLR CONTEXT AND STRATEGIC POSITION

This section presents the results of the desk research conducted on the case holder, providing context for this research. The central focus here is on the specific department on which the research is centred as well as on sustainability, partnerships, products and sustainability strategy at NLR.

3.1 Identity of NLR

As this project involves exploring how NLR can develop a strategic position in circular aviation, it is important to understand the organisation's identity and values. NLR's identity can be characterised by three key elements: purpose, positioning and organisational personality. The Van der Vorst (2017) model was used as a framework, supported by brand theory from Aaker (1997) and Mark & Pearson (2002).

NLR is one of five TO2 institutes in the Netherlands. These are government-related research organisations operating at the interface between science and industry. It is an independent applied research centre with approximately 800 employees, operating across the civil aviation, defence, and space sectors.

The purpose of NLR extends beyond commercial objectives. Its ambition is woven into the slogan 'Accelerating the future of aerospace' (NLR, 2024) and, more broadly, reflects a commitment to advancing aerospace for the benefit of society and the planet. To this end, NLR provides independent research and innovation services to government bodies, industry partners, and research organisations. The organisation's work aims to enhance safety, performance and environmental outcomes across the aerospace sector while fostering trust in the responsible development of new technologies.

NLR's organisational personality combines characteristics of the Sage and Hero archetypes (Mark & Pearson, 2002) (Figure 3). It presents itself as a reliable and expert partner while demonstrating a proactive and visionary approach to addressing complex challenges in the aerospace sector. This is reflected in its research portfolio and its growing involvement in advancing sustainability, including developing circular practices in aviation maintenance.

Figure 3. Brand Archetypes from Mark & Pearson (2002). NLR holds the archetypes Sage and Hero since it represents itself as a reliable and expert partner while demonstrating a proactive and visionary approach.

3.2 Operating Market

3.2.1 General Market Position

NLR operates across three aerospace domains: civil aviation, defence and space. It carries out project-driven work in collaboration with public bodies and private companies, connecting applied research with operational requirements across the sector (Figure 4).

In the civil aviation sector, NLR works alongside original equipment manufacturers (OEMs), Tier 1 and Tier 2 suppliers, airlines, air traffic control organisations, MROs and airports. The company's services cover the entire product lifecycle, from concept development and system engineering to maintenance optimisation and operational support. Projects typically focus on enhancing the safety, performance and cost-efficiency of clients operating in both regulated and competitive markets (NLR, 2024).

In the defence sector, NLR is a key technical and operational partner to the Ministry of Defence (MoD) and the Royal Netherlands Air Force (RNLAF). The company provides lifecycle management, testing, certification and advanced training services. These contributions support national and European defence capabilities, as well as facilitating long-term strategic planning (NLR, 2024).

The space sector is becoming an increasingly important part of NLR's activities. The organisation collaborates with European space agencies and private space firms to develop lightweight structures, satellite subsystems, and advanced manufacturing techniques. Insights gained in this area are regularly transferred to civil and defence aerospace applications, thereby fostering cross-sector innovation (NLR, 2024).

3.2.2 Sustainability Market

NLR is playing an increasingly active role in the aviation sustainability market. Through its involvement in Destination 2050, NLR contributes its expertise in aircraft design, SAFs and operational optimisation in order to support the aviation sector's climate-neutral goals (NLR, 2024). Technological initiatives such as NXTGEN Hightech and MAMTeC are driving progress in circularity. Recyclable thermoplastic composites and metal additive manufacturing are extending the lifecycle of components and reducing material waste (Propitius, 2025). Meanwhile, predictive maintenance solutions developed by NLR are helping airlines to adopt more resource-efficient maintenance strategies.

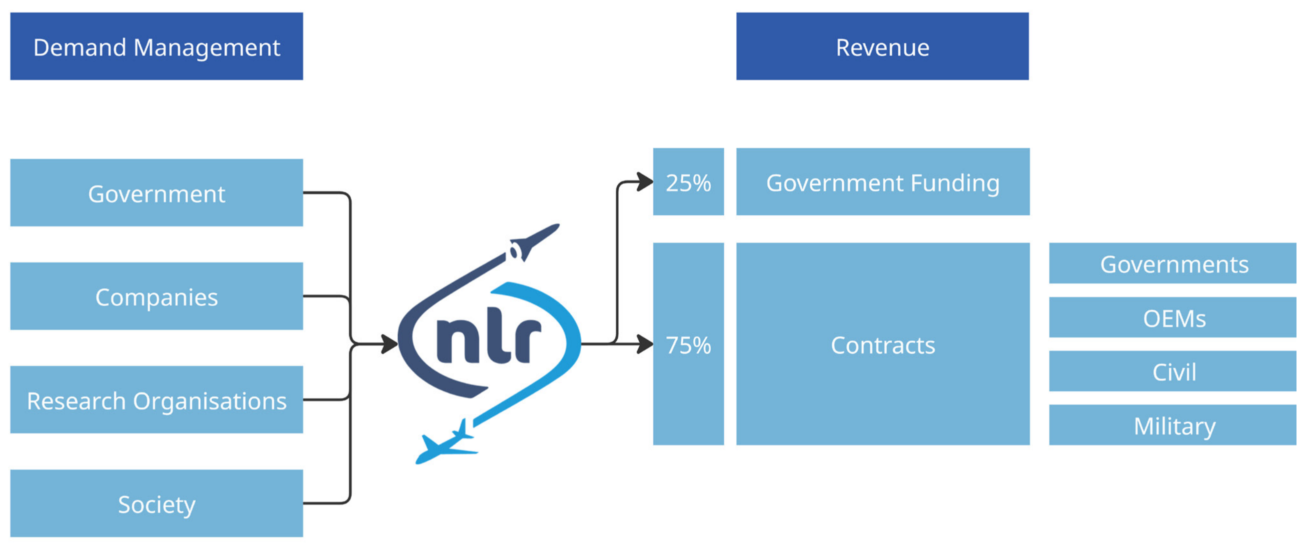


Figure 4. Visual representation of the demand management and revenue of NLR.

However, there are still opportunities for NLR to strengthen its position as a leader in this field. While the Sustainability Strategy 2024 sets out ambitions, it lacks detailed reporting on circular performance, such as CO2 savings, material recycling rates or the proportion of circular design in projects. Other organisations, such as the German Aerospace Center (DLR), already provide this level of transparency in their Green Aviation Roadmap (Scheelhaase et al., 2024).

NLR is also underrepresented in several emerging areas. For example, in the field of sustainable aircraft interiors, OEMs such as Airbus are actively pursuing eco-design innovations (Airbus, 2023), whereas NLR's portfolio in this area is limited. Similarly, large-scale aircraft recycling initiatives (AFRA, 2024) and climate adaptation strategies for airports (ACI Europe, 2019) present areas in which NLR could contribute its technical capabilities more visibly.

3.3 Competitive Landscape

NLR operates within a competitive European aerospace research landscape, which is shaped by public and private organisations. At the national level, its primary counterpart is the 'Nederlandse organisatie voor Toegepast-Natuurwetenschappelijk Onderzoek' (TNO), which is also an applied research institute. Although there is some overlap in areas such as defence, unmanned systems, advanced materials and AI, TNO's focus remains broad across sectors, whereas NLR specialises specifically in aerospace applications (Frinking et al., 2009; de Vries, 2010). Collaboration with Dutch universities, particularly TU Delft, is complementary rather than competitive (Botana, n.d.).

At the European level, competition is more present. Germany's DLR and France's ONERA are key players with larger budgets and stronger fundamental research capabilities (Niosi, 2012; Sorrentino & Grahn, 2012; Knoerzer, 2023). NLR often collaborates with these institutions on European programmes such as Clean Aviation, but also competes with them for leadership roles and funding in sustainability-driven aerospace innovation (Barber & Roediger-Schluga, 2008; Maoui, 2016). In particular, DLR plays a visible role in shaping circular aviation strategies through large-scale LCA projects and advanced materials research (Scheelhaase et al., 2024).

An increasingly important source of competition comes from the private aerospace industry. Major companies such as Airbus are investing heavily in research and development (R&D) into lightweight structures, lifecycle design and circular business models (Simmonds et al., 2015; Speier et al., 2017). These firms also influence European sustainability roadmaps and set the pace for innovation in MRO-related circularity.

For NLR, this competitive landscape highlights the strategic importance of establishing a clear research identity centred on knowledge and innovation in the circular economy. Active participation in European consortia and leadership in pre-competitive initiatives are essential for maintaining relevance and ensuring that NLR contributes meaningfully to shaping the circular future of aviation maintenance (Barber & Roediger-Schluga, 2008; Maoui, 2016).

3.4 Market Trends

The MRO sector in aviation is undergoing major changes, driven by new propulsion technologies, digitalisation and increasing demands for sustainability. These trends are reshaping the sector's knowledge base, maintenance processes and business models.

Firstly, the shift towards multi-fuel operations is transforming MRO. Over the next few decades, airports will handle a variety of fuels, including kerosene, SAFs, hydrogen, and electric propulsion (Khalifa et al., 2024). This will require maintenance organisations to develop new expertise in areas such as hydrogen storage, electric components, and updated inspection methods (Joensuu, 2023).

Secondly, changes in fleet composition are increasing the demand for advanced maintenance. Pandemic-related delays have resulted in an ageing fleet and increased maintenance requirements (Resendiz & Shrimali, 2025). Meanwhile, emerging aircraft featuring electric and hydrogen systems present unfamiliar architectures that require new knowledge of materials performance, repairability and life extension.

Thirdly, digitalisation is transforming maintenance strategies. Predictive maintenance, which uses sensor data and artificial intelligence, is helping operators to optimise maintenance and reduce waste (Santana & Gómez, 2024). Digital tools also facilitate more sustainable MRO practices by supporting repair, reuse and smarter end-of-life decisions (Khalifa et al., 2024). Furthermore, automation is bringing about additional changes, with robotic systems becoming increasingly revalent in inspections and repairs (Hisan & Yusof, 2024).

3.5 Product Portfolio

NLR has developed six specialised tools for the aviation MRO sector to optimise maintenance management (Figure 5 and Table 1). These tools originated from projects conducted by the ASAM/MAE department and have since been incorporated into NLR's product portfolio

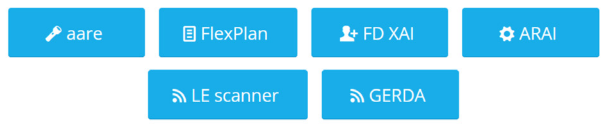


Figure 5. An overview of the NLR's MRO maintenance products (NLR, 2023).

for external clients (NLR, 2023). The portfolio reflects three clear trends: the increasing integration of AI and automation; a shift from reactive to predictive maintenance strategies; and a focus on supporting the operational phase of the aircraft lifecycle.

3.6 Sustainability Strategy

Sustainability is a core theme of NLR's operations and research agenda. The organisation is actively reducing its environmental footprint through initiatives relating to energy, waste and mobility, while also embedding sustainability into its research portfolio. This includes projects focusing on reducing emissions, improving fuel

Table 1. Description of the six MRO oriented products of NLR, which have the characteristics of automation, using AI, predictive, integrative and are used in the operational phase.

Product	Description
aare	Supports strategic decision-making by simulating the effect of budgets and resources on the long term availability of aircraft fleets.
FlexPlan	An AI-driven scheduling tool that automatically aligns maintenance tasks with flight schedules. It dynamically adjusts to changes in the flight schedule which allows maintenance to be scheduled more efficiently.
FD XAI	Uses explainable AI to analyse component usage and historical failure data. In this way, it predicts potential failures and provides insight into their causes, helping engineers make informed decisions.
ARAI	An autonomous robot that inspects aircraft surfaces for damage such as cracks or missing fasteners. This increases the accuracy and speed of inspections.
LE Scanner	An automated system that inspects the leading edges of aircraft wings for wear and damage. It provides detailed data for maintenance decisions.
GERDA	A robotic system that inspects engine components such as turbine blades using machine vision and AI. It identifies defects and supports repair decisions.

Figure 6. Front page of NLR's 'Strategieplan 2022-2025' (NLR, 2022).

efficiency, adopting circular design principles and exploring alternative propulsion systems (NLR, 2025).

One of NLR's strategic goals is to contribute to climate-neutral aviation by 2050. To achieve this, major innovations in aircraft design and propulsion technologies, such as hydrogen, will be required, as well as the restructuring of production and value chains to support circular economy models (NLR, 2025).

Sustainability is one of the three pillars of NLR's 2022–2025 Strategic Plan (Figure 6), alongside Competitive Aerospace and a Safe Society. Through cross-disciplinary, programme-based research, NLR aims to be a key contributor to the long-term transition towards net-zero aviation. Each programme generates relevant knowledge and links it to specific markets and strategic themes Figure 7).

In its current Strategy Plan, NLR recognises the importance of MRO in promoting a safe, sustainable and competitive aviation industry. The plan recognises the potential of MRO to promote circularity by extending asset life and

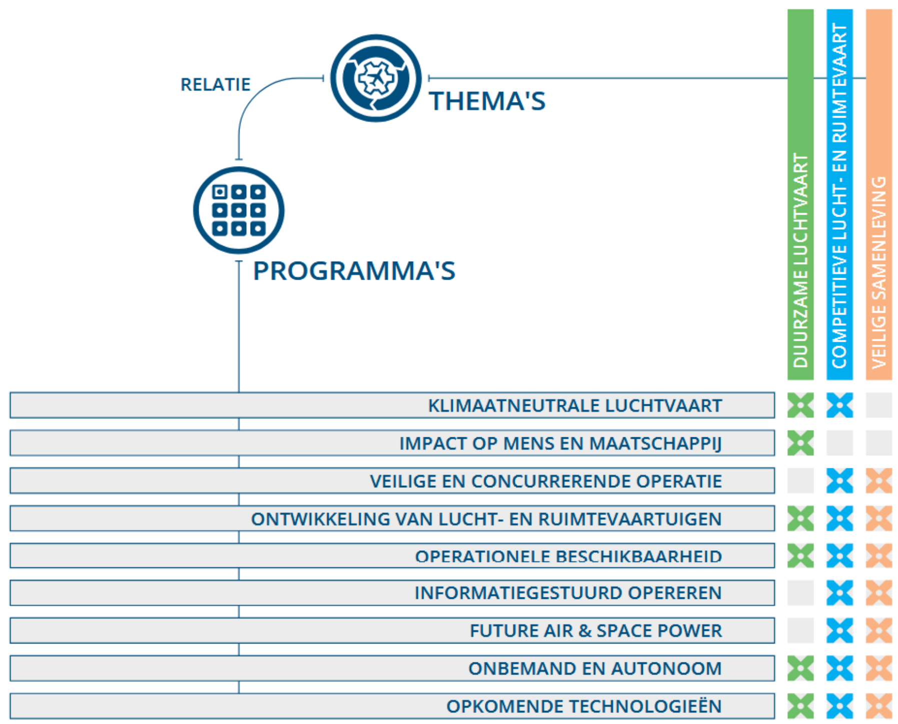


Figure 7. Overview of the connection between the themes with the programs (Strategieplan NLR, 2022).

improving resource efficiency. It highlights digitalisation and automation as key drivers of change, citing AI-driven maintenance planning, autonomous inspections and new maintenance concepts for electric flight as promising areas of development.

The Strategy Plan positions MRO innovation within broader sustainability and competitiveness objectives, paying attention to cost-effectiveness and maintaining a leading position in maintenance expertise. Material reuse and environmental considerations are also mentioned briefly, with a recommendation to adapt production and maintenance processes to reduce emissions and material consumption.

However, the plan does not present an operational strategy for circular MRO yet. Key circular principles, such as reuse, remanufacturing, lifecycle extension, and end-of-life management, are not explicitly addressed. Additionally, systemic enablers such as supply chain collaboration, reverse logistics, and regulatory alignment are absent from the discussion. The current emphasis remains largely technical, focusing on enabling technologies rather than on a more integrated, circular value chain perspective.

3.7 Regulatory Drivers for Circularity

In the highly regulated aviation sector, legal frameworks are now one of the most important drivers of sustainability and the adoption of a circular economy. Without regulatory pressure, efforts to decarbonise and make the sector more circular would remain limited. MRO organisations will increasingly be subject to requirements from both their airline clients and EU and international regulations.

The four most relevant types of regulatory development are climate legislation (EU ETS and ReFuelEU), raw materials regulation (CRMA), circular design mandates (ESPR and the DPP) and national policy frameworks (e.g. the Dutch Luchtvaartnota). Together, these developments will transform material choices, maintenance strategies, and lifecycle management practices across the MRO sector.

3.7.1 EU Emissions Trading System

The EU Emissions Trading Scheme (EU ETS) is the EUs primary tool for reducing CO2 emissions. It operates on the basis of a 'cap-and-trade' principle. This means that companies are only allowed to emit a certain amount of CO2. If they exceed this limit, they must purchase additional emission allowances. The aviation sector has been part of the EU ETS since 2012. Airlines must hold one allowance for every tonne of CO2 they emit. Previously, they received some of these allowances for free, but this is changing.

By 2026, they will no longer receive any free allowances. They will have to pay for all their CO2 emissions. This will make flying more expensive, particularly for those that use older, less fuel-efficient aircraft. Consequently, they will seek to reduce their fuel use and emissions. This will also influence the MRO sector. There will be a greater focus on reducing weight, improving fuel efficiency and finding smart engineering solutions (EU ETS, 2024).

3.7.2 ReFuelEU Aviation

ReFuelEU Aviation is an EU regulation that encourages airlines to use more SAF. From 2025 onwards, at least 2% of the jet fuel used must be SAF, with this figure increasing to 70% by 2050 (ReFuelEU, 2023). This will have technical consequences. MRO providers must ensure that aircraft systems and components remain compatible with SAF. At the same time, however, they can improve fuel efficiency by providing better maintenance and making smarter use of parts.

3.7.3 Critical Raw Materials Act

The Critical Raw Materials Act (CRMA) establishes regulations aimed at reducing Europe's reliance on critical materials such as titanium and rare earths. It introduces supply chain risk checks and recycling targets (CRMA, 2024). For MRO, this means adopting new sourcing strategies, improving the tracking of materials and handling end-of-life products more intelligently to recover more valuable parts.

3.7.4 Ecodesign for Sustainable Products Regulation & Digital Product Passport

The Ecodesign for Sustainable Products Regulation (ESPR) introduces new EU legislation aimed at making products more circular, energy-efficient and easier to reuse or recycle. It will apply across many industries and is expected to include the aerospace industry in the near future (ESPR, 2024). A key element of the ESPR is the Digital Product Passport (DPP), which stores detailed information about each product, such as the materials it contains, how it can be repaired and its lifespan.

For MRO, this will mean significant changes. Maintenance teams will need to collect and share more data about components, including repair history, material types, and how parts can be reused or recycled. These changes could lead to new standards in documentation, inspection, and parts tracking.

3.7.5 Other Relevant Frameworks

The Dutch Luchtvaartnota establishes national objectives for reducing CO2 emissions and encouraging circular innovation, but lacks binding measures. At an international level, ICAO's CORSIA scheme will require airlines to offset emissions from international flights from 2027 onwards.

Industry initiatives such as Destination 2050 demonstrate a collective commitment to achieving climate neutrality and circularity in the long term. These frameworks are in line with upcoming EU legislation such as the ESPR and DPP which will reinforce the shift towards better tracking of materials, reuse and lifecycle documentation in MRO.

3.8 Chapter Conclusion

This chapter has analysed the current positioning of NLR, its product portfolio, and the regulatory environment in relation to circularity in MRO Several conclusions emerge.

While NLR operates in a relatively collaborative national landscape, it faces competition from European research centres and private industry in the area of sustainable aviation. Within this landscape, its strategic partnership with the Dutch Ministry of Defence (MoD) provides opportunities to deepen circular knowledge and promote practical applications in MRO.

While NLR's current Strategic Plan recognises the role of MRO in promoting sustainability, it lacks a concrete operational roadmap and metrics for circularity. Concepts such as lifecycle extension and reverse logistics remain underdeveloped, indicating the need for a more systemic approach to circular MRO.

There is increasing regulatory pressure on the aviation sector, with CO2 reduction and critical material use emerging as dominant themes. The regulatory landscape is becoming increasingly complex and multi-layered, creating a clear need for tools, frameworks, and strategies to help organisations such as NLR and its partners translate these requirements into actionable circular practices.

The findings of this chapter suggest that NLR is well-positioned to contribute to the circular transition in aviation maintenance. However, further development is needed in three key areas:

1) Embedding circularity more explicitly in product design and KPIs;
2) Strengthening supply chain and lifecycle thinking within MRO activities;
3) Developing internal methodologies to manage the complexity of emerging regulatory frameworks.

These gaps provide a clear rationale for further exploration in the next phases of this research.

4

RESEARCH METHODOLOGY

This study aims to explore how the principles of the CE can be embedded within aviation maintenance practices. The research is guided by a theoretical framework developed from the literature and structured across three levels: micro, meso and macro. In order to test and enrich this framework, it was necessary to collect empirical data.

For this purpose, a qualitative research approach was selected. Such methods are particularly well suited to exploratory research into complex, multi-level phenomena such as the adoption of circularity within organisational contexts (Bryman, 2016; Guest et al., 2013). Quantitative approaches were considered less effective, since the study did not seek to measure variables on a large scale or test predefined hypotheses. The study's objective was to gather insights into how sustainability and circularity are understood and practised, using qualitative inquiry to uncover these perspectives and experiences (Patton, 2014).

The qualitative research had two main aims:

1) To assess the relevance and completeness of the theoretical framework by comparing it to real-world perspectives and experiences.
2) To identify new themes, barriers and opportunities that could inform the development of practical circular MRO strategies.

To achieve these aims, a combination of semi-structured interviews and thematic analysis was employed.

4.1 Research Design

The study adopted a multi-step qualitative design, combining an informal focus group with in-depth, one-to-one interviews.

An initial informal focus group (G1) was held at the beginning of the research process. This allowed for an exploratory discussion on the target group's perceptions of sustainability and circularity. This session helped to identify initial themes and informed the development of the interview guide. The full interview guide can be found in Appendix B.

Twelve individual interviews were then conducted. The interview questions were derived from the theoretical framework and initial observations made during the first weeks of the project at NLR.

The interviews were structured to explore:

- How sustainability and circularity are currently understood and operationalised within NLR's maintenance-related activities.
- Which factors from the theoretical framework are reflected in practice and whether new factors have emerged.
- How different organisational levels interact in shaping circular practices.
- The role of individual mindsets, organisational structures and external influences.

This approach supports the study's objective of identifying structural and cultural enablers and barriers to circularity in MRO.

4.2 Pilot Test

Before launching the full interview series, a pilot test was conducted with a fellow student. This served to refine the phrasing and flow of the interview questions. The first two interviews were also treated as extended pilot interviews. While their data was included in the analysis, these interviews also helped to adjust the interview guide based on initial feedback and responses.

4.3 Data Collection

Participants were selected using a snowball sampling method, starting with contacts in the maintenance engineering field. This method was deemed appropriate in view of the exploratory nature of the research and the requirement to access specialist knowledge at various organisational levels (Goodman, 1961). The sample was then expanded to include business managers, sustainability experts and external stakeholders to provide a broader, multi-level perspective.

In total, twelve participants were interviewed. The sample included maintenance researchers, engineering managers, sustainability managers, and specialists in key areas such as materials and SAF. This ensured coverage of the micro, meso and macro levels of the framework.

Semi-structured interviews were chosen to obtain a balance between structure and flexibility. This enabled the researcher to explore key themes while giving participants the opportunity to offer insights that were not anticipated by the theoretical model.

The interviews were conducted online or in person in March 2025. Each interview lasted 30–45 minutes. All participants provided informed consent. See Appendix C for the informed consent form. Participants were coded as P1–P12 to maintain anonymity. An overview of the sample of participants is provided in Table 2.

4.4 Data Analysis

A thematic approach to data analysis was adopted (Braun & Clarke, 2006), with Atlas.ti software used to support the coding process. Thematic analysis was chosen as it provides a flexible yet rigorous method of identifying patterns and meanings in qualitative data, which is well-suited to the exploratory and framework-building aims of the study.

Analysis began in parallel with data collection, enabling iterative refinement of the coding structure. While the initial codebook was informed by the theoretical framework, it remained open to inductive coding of emergent themes.

Table 2. Overview of the participants for the empirical research.

Description	Participant	Details
MRO Specialist	P1	Airline Engineering and Maintenance
	P2	Maintenance Researcher
	P3	Maintenance Researcher
Maintenance Research and Developer	P4	Maintenance R&D
	P5	Maintenance R&D
	P6	Maintenance R&D
Manager	P7	Business Manager
	P8	Sustainability Manager
	P9	Sustainability Manager
Sustainability Specialist	P10	Materials
	P11	SAF
	P12	LCA

In total, 293 codes were identified. These were grouped into clusters through an iterative process supported by Atlas.ti and assisted by clustering tools, such as Miro and ChatGPT, for sense-making and complexity reduction. (Figure 8). Clustering enabled the identification of overarching themes that cut across organisational roles and levels.

The analysis followed Braun and Clarke's six-phase process: 1) Familiarisation with the data; 2) Generation of initial codes; 3) Searching for candidate themes; 4) Reviewing themes for coherence and relevance; 5) Defining and naming themes; 6) Producing the final findings.

Both deductive and inductive approaches were employed. Deductive analysis involved testing the fit of the theoretical framework against the data. Meanwhile, inductive analysis enabled new themes and factors to be discovered that were not captured in the initial model. The interplay between these two approaches enriched the analysis and strengthened the final framework.

In addition to thematic analysis, the adoption factors of the theoretical framework were compared with the empirical data. The data were also examined through the lens of the 10R framework to identify current or emerging circular strategies in practice. Participant typologies were also constructed based on recurring patterns in mindsets and engagement with circularity. These personas illustrate the diversity of perspectives and priorities within the MRO ecosystem. Finally, the data emerged in the form of six knowledge areas that are relevant to the development of CE knowledge in an aviation maintenance context.

Figure 8. Visualisation of the thematic clustering process in Miro.

5

EMPIRICAL RESULTS

This chapter presents the empirical results of the study. These findings are based on a qualitative analysis of interviews conducted with stakeholders from the MRO sector. The analysis aimed to explore the current understanding, application and perception of CE principles, and to identify barriers and opportunities for their further integration into MRO practices.

5.1 Thematic Findings

Thematic analysis was employed to identify recurring patterns and insights within the interview data. Four main themes emerged from the analysis, each with several subthemes. These themes reflect the complex interplay between technical, organisational and cultural factors influencing sustainability and circularity in aviation MRO.

An overview of the themes and subthemes is provided in Table 3, and the following sections describe each theme in more detail.

A poster displaying the midterm results was created for an internal internship session at NLR. This poster can be found in Appendix D.

Table 3. Overview of the participants for the empirical research.

	Theme		Subtheme
1	Trade-offs in decision-making	1.1	Safety comes first
		1.2	Early stage design is crucial for circular maintenance
		1.3	Economics and market dynamics drive decision-making more than circular coals
2	The (mis) understanding of sustainability	2.1	MRO as a natural circular economy enabler
		2.2	Low feeling of ownership and understanding of the circular economy and sustainability
		2.3	Sustainability is about technical optimisation
		2.4	Looking beyond CO2
3	Wait and see attitude slows down sustainability innovation	3.1	Feeling of insecurity and instability
		3.2	A need for a clear incentive (policies, regulation, certification)
		3.3	Material supply and value chain are experienced as difficult
4	Cooperation remains unstimulated	4.1	Competitive pressures discourage open collaboration
		4.2	Need for a shared language
		4.3	Low communication on the topic of circularity and sustainability

Theme 1: Trade-offs in decision-making

This theme emphasises the numerous factors that must be taken into account when developing products and services for the aviation MRO sector. It reflects external influences, such as market dynamics and regulations, as well as internal priorities, such as safety and design choices. Consequently, achieving sustainability is rarely straightforward. While there is a willingness to innovate, decision-making is often influenced by necessary compromises.

Subtheme 1.1 - Safety comes first

Aviation depends on safety, and without it, there is no viable business model. As one interviewee put it: "If you throw safety overboard, it won't be long before we run out of passengers to board and we all run out of jobs." (P5). In other words, safety is not up for discussion. Another participant confirmed this: "If something isn't 100% safe, it will never be allowed in aviation, no matter how sustainable it is." (G1).

This way of thinking is deeply embedded in daily work, in decision-making, and in how systems are designed and operated. When sustainability comes into play, safety always takes priority, regardless of cost. As one respondent explained: "Nobody really looks at it because it's like, oh, it's necessary because then we're safe. So it's not a waste, is it?" (P2).

Subtheme 1.2 - Early stage design is crucial for circular maintenance

The awareness of the impact and the importance of the design of the operation, but also the impact of the aircraft, is really high. It is not something that people say just to get rid of some problems, to blame things on bad design for example. But it is seen as something important and something that people want to focus on more. Also specifically within maintenance, if design choices are made with end-of-life or repairability in mind, maintenance becomes more efficient and less wasteful. "The choices you make in your design have a huge impact on your in-service phase." (P6). Conversely, the absence of early consideration limits what can be done later: "When the plane is already gleaming on the ramp, anything else you do is collateral damage control." (P5).

Subtheme 1.3 - Economics and market dynamics drive decision-making

Financial factors play a key role in decision-making. Sustainable solutions are more likely to be adopted when they also reduce costs or increase profits. One interviewee said it clearly: "If you say: we know how to reduce your costs and increase your profits, then you have everyone at the table. But if you say: this is better for the environment… then it becomes not so interesting anymore." (P4).

This shows that economic incentives often outweigh environmental motivations. However, this does not mean that people are resistant to change. If sustainable options become more affordable or show clear benefits, adoption can happen quickly. As one participant put it: "It will be easier to adopt if we can get the prices on the same level." (P9).

There is also a critical mindset when it comes to prioritising investments. People are aware that optimisation efforts sometimes miss the bigger picture. For example: "If three people are working on saving one kilo of weight on an aircraft, so to speak, I sometimes wonder if that really makes a difference in terms of sustainability. Wouldn't it be better to employ those people on the commercial side, so that we make more money and use it to fund bigger sustainability initiatives – which often cost more?" (P8).

Theme 2: The (Mis)understanding of Sustainability

The concept of sustainability is understood and applied differently across teams, disciplines and roles. While some see it as an integral part of maintenance, others lack clarity or ownership of the concept. This theme explores the diverse and sometimes fragmented understanding of sustainability and circularity within the aviation MRO sector.

Subtheme 2.1 - MRO as a natural circular economy enabler

MRO is not something that is now clearly linked to circularity, even though maintenance does improve the lifespan of an aircraft. When bringing up this topic, many interviewees shared the opinion that MRO indeed is an enabler of the circular economy. One participant argued: "Maintenance, I think, is the tool that enables circularity." (P6). Another explained: "You can do maintenance to ensure that the aircraft's fuel consumption stays as low as possible… that's also very sustainable to do that." (P5).

Subtheme 2.2 - Low feeling of ownership and understanding of the circular economy and sustainability

Despite MRO's potential, awareness and ownership around circularity remain low. One participant shared an insight they got when talking to another colleague: "Someone once said to me that they never actually talk about sustainability with other people in other departments… sustainability is kind of your responsibility, right?" (P11). Others noted a lack of shared language or engagement: "Yes, my perception of circularity is that it is a very long and laborious story." (P7). These perceptions show how sustainability can still feel distant or abstract to many within the organization.

Subtheme 2.3 - Sustainability is about technical optimisation

In many corners, sustainability is seen as a matter of technical efficiency rather than values or ideology. For instance: "If you can extend maintenance intervals, you need to produce less frequently - that is also sustainable." (P5). Rather than asking what is best for the planet, respondents tend to ask what can be optimised, and then retrospectively label the results as sustainable. Predictive maintenance and condition-based monitoring are typical examples: "We're trying to get rid of fixed intervals and replace them with condition-based checks - it's better for operations, but it's also more sustainable." (P7). This approach, though pragmatic, misses broader system-level thinking around circular economy principles.

Subtheme 2.4 Looking beyond CO2

While CO2 emissions dominate the path where sustainable innovation is headed, many specialists argue that sustainability should be understood in a broader perspective. For instance, one participant noted: "You can't just optimize for CO2, because then NOx emissions might go through the roof. It's always a compromise." (P5). Several contributors highlighted issues such as material use, noise pollution, circularity and waste management as equally important. There's also increasing awareness that end-of-life challenges, like the disposal of composites and hazardous materials, pose serious sustainability issues that CO2 metrics do not capture: "It's fantastic that composites make the aircraft lighter, but in 15 years those planes just end up in landfills." (P4).

Theme 3: Wait and see attitude slows down sustainability innovation

Even when technical solutions exist, progress can be slow due to uncertainty and a lack of incentives. This theme illustrates how unclear rules and unstable supply chains can hinder progress.

Subtheme 3.1 - Feeling of insecurity and instability

A recurring theme was the sense of uncertainty, both about the direction of the sector and about what truly matters in the sustainability transition. One respondent explained: "There is a lot of uncertainty about what is important and what isn't." (P4). This ambiguity makes it difficult for individuals and organizations to set clear priorities. Others mentioned how long-term investments are hard to justify amid short-term unpredictability: "Long-term investments are especially difficult to make when there is more uncertainty in the short term." (P9). Such sentiments reflect a broader hesitancy that undermines innovation.

Subtheme 3.2 - A need for a clear incentive (policies, regulation, certification)

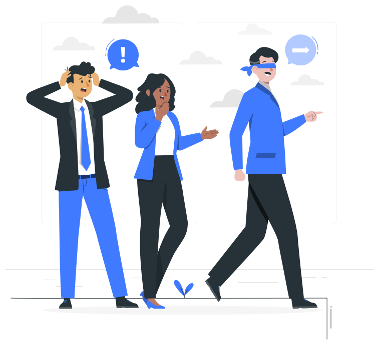
A lack of clear and enforceable incentives emerged as a major barrier to sustainable progress. Several interviewees stressed that voluntary action alone is insufficient. One participant stated plainly: "It really has to come from laws and regulations." (P9). Others echoed this sentiment, noting that without a systemic shift, the current pace of change would not be enough: "Without a step change, I don't think we're going to make it at this rate." (P6).

Participants argued that relying solely on market forces or individual initiatives is not realistic. Instead, strong institutional frameworks, such as binding policies, updated certification standards, and regulatory mandates, are needed to create the necessary push. Without these, sustainability remains a fragile ambition rather than a guaranteed trajectory.

Subtheme 3.3 - Material supply and value chain are experienced as difficult

Circularity can be problematic when it comes to materials and the supply chain. While some materials, such as composites, are useful for making planes lighter, they are very difficult to recycle. One interviewee said: "Composites are fantastic because they make aircraft lighter, but you can't do anything with them once you take them apart" (P4).

Another issue is the lack of viable markets for reused parts. As one participant noted: "They make bags from seat covers, but those are just hobby projects." (P4). These examples demonstrate that, without effective recycling systems and clear demand, the concept of circularity cannot truly be realised. The supply chain is too fragmented, and materials are not designed to be reused.



Theme 4: Cooperation remains unstimulated

Collaboration is vital for circular innovation, but it remains limited by competitive dynamics, poor communication, and fragmented language. This theme explores the cultural and structural reasons why cooperation often fails to take off.

Subtheme 4.1 - Competitive pressures discourage open collaboration

Sharing data could help make maintenance smarter and support circular strategies. But many companies are careful not to share too much. One participant explained: "If you would share the data with each other, then we would speed up the process… but then you don't have the competitive advantage anymore." (P2).

This shows that commercial competition often blocks collaboration. Even if working together would help the whole sector, companies still choose to protect their own position.

Subtheme 4.2 - Need for a shared language

Working together becomes difficult when people don't speak the same language. Not just in words, but also in methods and definitions. Without clear agreements on how to calculate or define things, collaboration can quickly become confusing. One interviewee said: "We need shared standards for certain definitions in how you calculate things." (P7).

Even basic terms can cause misunderstandings. For example, what counts as "Sustainable Aviation Fuel" (SAF) is not always the same: "The terminology is sometimes quite important." (P11). Another interviewee added: "Sometimes one report talks about three R's, another about five, and then another about seven – it's not clear what we mean by circularity." (P8).

These examples show that without a shared framework, good ideas can get lost in translation. A common language is needed to align efforts and make collaboration more effective.

Subtheme 4.3 - Low communication on the topic of circularity and sustainability

Circularity and sustainability are not common topics of conversation in many teams. As a result, awareness stays low, and opportunities to improve are often missed. One participant shared: "We're not overwhelmed with questions… we just do what we can." (P6).

Another noted a lack of connection to the topic: "I don't really have a warm feeling about it." (P6). Others said they rarely talk about sustainability outside their own department: "Someone once told me they never actually discuss sustainability with people from other departments… it's kind of your thing, right?" (P11).

This silence makes it harder to build shared goals or develop stronger initiatives. When sustainability is not part of the everyday conversation, it easily stays in the background.

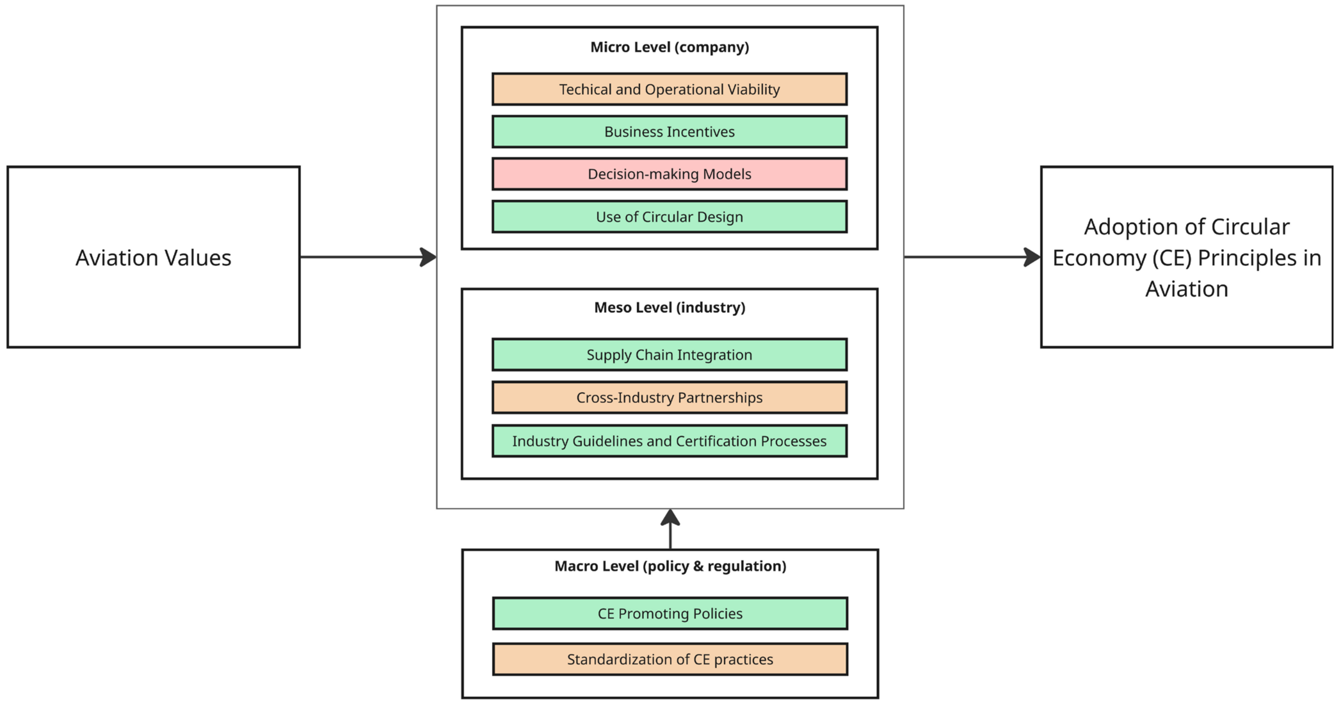


Figure 9. Validation of the factors in the qualitative data. Only decision-making is not visible in the data and can therefore be excluded from the framework.

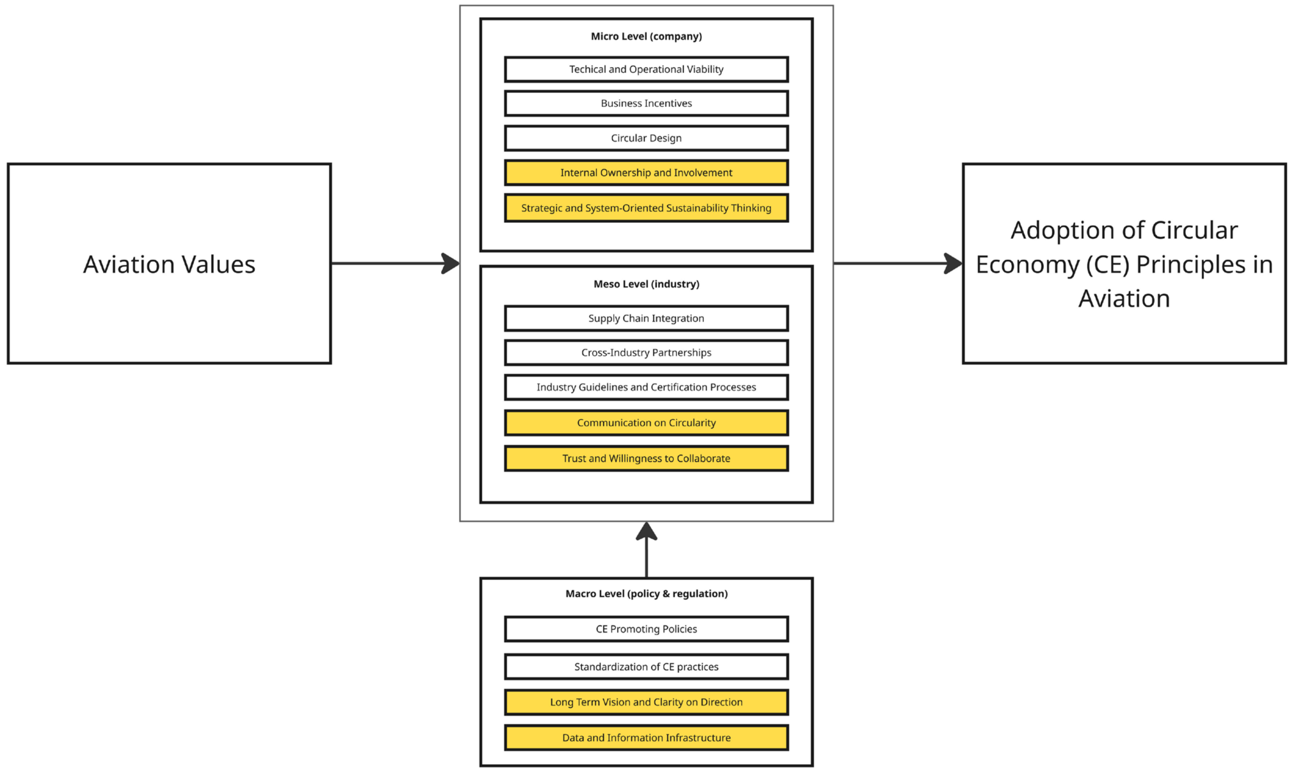


Figure 10. An overview of the new, more human-driven factors that were found in the empirical data.

5.2 Framework Validation

5.2.1 Validating the Theoretical Framework

A validation study was conducted to understand how well the theoretical framework reflects practice in aviation MRO. The framework comprises nine factors at the micro, meso and macro levels, all of which are expected to influence the adoption of CE principles. These factors were then compared to the themes and insights that emerged from the interview data.

Validation was based on two criteria: whether the factor was discussed during the interviews and its perceived importance. Some factors were raised spontaneously, while others were prompted by the interviewer. In certain cases, participants were unable to comment on a factor due to a lack of experience or relevance. The importance of each factor was judged by how frequently it was mentioned, the depth of the discussion and whether participants spoke about it emphatically or with emotional engagement.

The analysis shows that not all factors are perceived as equally important in current practice (Figure 9). Business incentives, certification processes, government policy, supply chain integration and circular design were the factors that were mentioned most frequently and emphasised most strongly. Participants consistently described these as major barriers to, or enablers of, advancing CE in aviation MRO. In contrast, factors such as technological readiness and cross-industry partnerships were acknowledged but discussed with less depth or urgency. While these were considered relevant, they were not seen as central to the current challenges. Finally, some factors, such as decision-making models, received little attention. Participants often indicated that they do not actively use such models in their daily work, despite their prominence in the academic literature.

In summary, the findings suggest that the practical adoption of CE in aviation MRO is currently more influenced by business logic, policy, certification pressures and supply chain dynamics than by formal decision-making tools or cross-industry structures.

5.2.2 New Factors Theoretical Framework

In addition to validating the original framework, the interviews revealed several new factors influencing CE adoption in practice. These factors were not explicitly included in the theoretical model, but emerged frequently during the conversations. In most cases, the participants raised them spontaneously, often in moments of frustration, uncertainty or reflection on organisational dynamics.

The newly identified factors emphasise the significance of organisational culture, communication, and behavioural dynamics in shaping the adoption of circular practices. Many participants pointed to a lack of internal ownership of sustainability, limited cross-departmental communication and an overly technical or operational view of sustainability, which restricts strategic thinking. Issues of trust and collaboration across the value chain also emerged as significant barriers, alongside concerns about long-term policy clarity and the current limitations of data infrastructure for tracking materials and components.

In total, six additional factors were identified across the micro, meso, and macro levels (Figure 10). Internal ownership and involvement, a strategic and system-oriented view of sustainability, trust and a willingness to collaborate, and a long-term vision and future clarity were particularly prominent. Communication on circularity and the availability of data and information infrastructure were also frequently mentioned as influencing factors.

These findings enrich the original framework by highlighting the organisational and cultural aspects of CE adoption. They also help to explain why circular ambitions often remain confined to small-scale pilot projects, despite significant technological and policy advances. Therefore, achieving more widespread and systemic adoption of CE principles in aviation MRO will require external incentives and technological solutions, as well as stronger internal engagement, clearer communication and environments that foster collaboration and trust.

5.3 10R-Framework Mapping

As introduced earlier in this thesis, the 10R framework offers a useful lens through which to explore the potential for circularity in aviation MRO. To apply the framework meaningfully, an analysis was conducted to assess the current understanding and application of each of the ten R-strategies in practice (Figure 11). This assessment is based on qualitative interview data and considers whether each strategy is already part of aviation maintenance or if there is awareness of, and potential for, further integration.

5.3.1 Well Established Strategies

Some R-strategies are already firmly established in daily maintenance practice. In particular, 'Reduce' (R2) and 'Repair' (R4) are integral to aviation MRO. These activities are driven by the need for operational efficiency and are also considered to contribute to sustainability. Efforts to reduce material use, optimise maintenance intervals and lower energy consumption are commonly pursued. One participant explained: "Optimising maintenance intervals reduces the need for spare parts." (P5). Another added: "We are trying to get rid of fixed intervals… it is also more sustainable." (P7).

Repair is a core activity in MRO and widely recognised as supporting circularity. As one interviewee stated: "Repair is just part of normal operations, of course we do it." (P3), while another commented: "Maintenance… is the tool that enables circularity." (P6).

5.3.2 Strategies with Emerging Potential

Other R-strategies show partial presence or emerging potential. Rethink (R1), Reuse (R3), Remanufacture (R6), and Recycle (R8) were discussed frequently, although practical barriers remain. Several participants highlighted the need to rethink how maintenance value is defined. For example: "We need to think differently about what we define as valuable maintenance." (P6).

Reuse of components is more common in military contexts, where budget constraints encourage this practice. One interviewee noted: "Military planes have been converted to fire-fighting aircraft." (P6), and another added: "In the military, reusing parts is more common due to budget limits and self-sufficiency." (P7).

Remanufacturing of high-value components, such as avionics, already takes place. One participant explained: "We take out the component, fix it, clean it, and send it back 'as new'." (P6). However, the potential for broader application is not yet fully realised.

Recycling, especially of complex materials such as composites, remains challenging. One interviewee said: "You can't do anything with composites once you take them apart." (P4), and another commented: "Lots of material ends up as landfill or low-grade filler." (P6).

5.3.3 Strategies with Limited Current Relevance

In contrast, strategies such as Refuse (R0), Refurbish (R5), Repurpose (R7), and Recover (R9) are rarely applied in aviation maintenance. Safety and certification requirements make it difficult to refuse certain materials or radically change existing supply chains. As one participant explained: "We can't just refuse certified parts, even if they're not sustainable." (P10).

Refurbishment is not commonly addressed as a distinct strategy, although certain MRO activities, such as upgrading aircraft interiors, do align with refurbishment principles. One interviewee stated: "You do not see refurbished parts often in commercial aviation." (P4). Repurposing tends to occur in small-scale or symbolic projects. Recovery of energy or materials is not part of current MRO practice. As one respondent put it: "We do not do energy recovery in aviation." (P5).

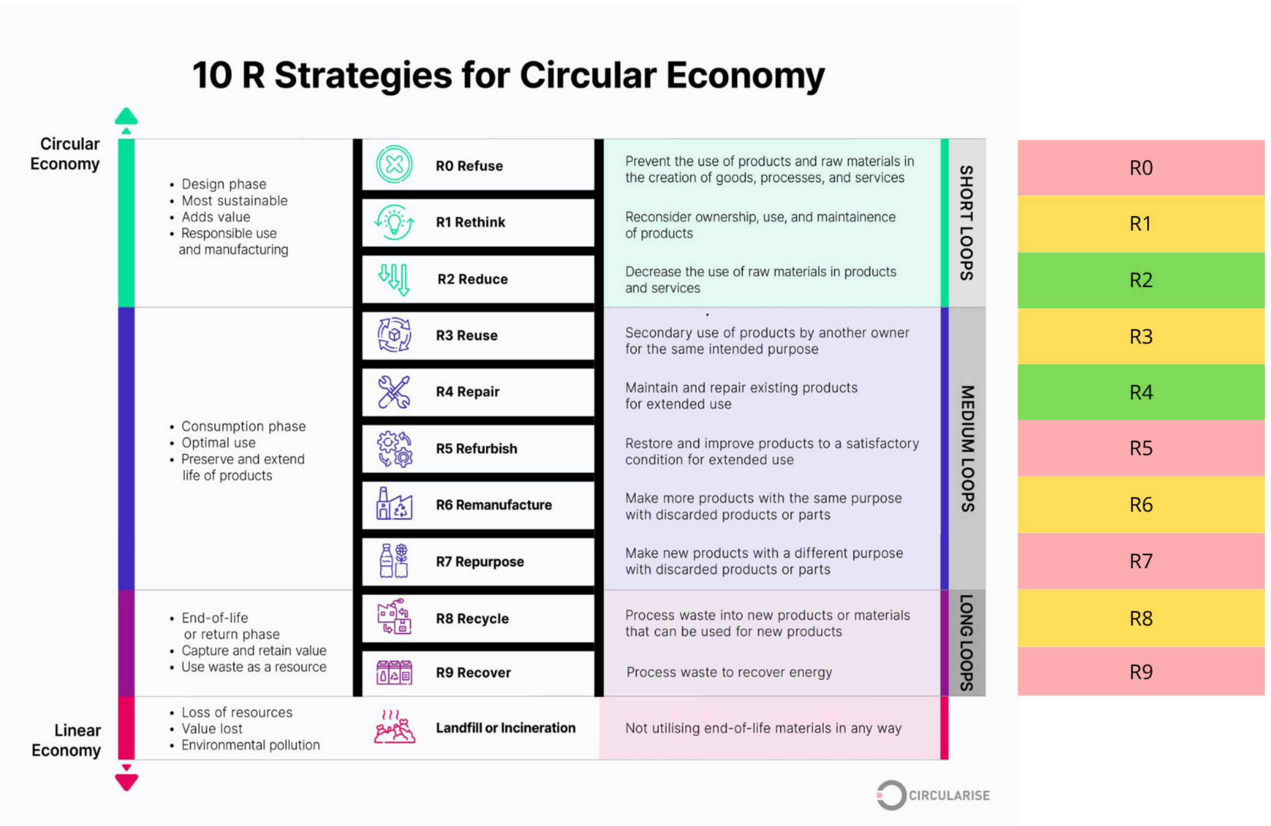


Figure 11. An overview of the new, more human-driven factors that were found in the empirical data.

5.3.4 Conclusion

Overall, the 10R framework is valuable for identifying the strengths and gaps in current circularity efforts. While 'Reduce' and 'Repair' are well established, 'Rethink', 'Reuse', 'Remanufacture' and 'Recycle' represent areas with clear potential for further development.

Rethinking maintenance approaches could involve introducing new performance metrics that consider environmental impact. The increased reuse of components could be supported by improved tracking systems and evolving certification processes. Remanufacturing could be expanded by designing components with disassembly and reprocessing in mind. Progress in recycling technologies will also be essential, particularly in addressing end-of-life challenges related to composite materials.

5.4 Typologies of Stakeholder Perspectives

Strategic typologies were developed to improve understanding of how professionals in the aviation maintenance sector approach circularity and sustainability (Figure 12). These typologies help to explain behavioural patterns, underlying motivations and decision-making barriers. They provide a practical framework through which organisations such as NLR can reflect on their internal dynamics and adapt their approach accordingly.

The typologies were derived through thematic analysis of qualitative data. After clustering related quotes into key themes and sub-themes, recurring attitudes and response patterns were identified. These were then abstracted into four distinct types, each of which is grounded in the language used by the participants.

5.4.1 The Cautious Guardian

This type prioritises safety, certainty and compliance. They are reluctant to engage in sustainability efforts unless the risks are fully understood and regulatory frameworks are in place. Their actions are driven by the need to maintain safety and avoid unintended consequences. As one interviewee stated:

"If something isn't 100% safe, it will never be allowed in aviation, no matter how sustainable it is." While this cautious stance can hinder innovation, it is deeply rooted in the sector's safety culture.

5.4.2 The Business Realist

The Business Realist embraces sustainability when it aligns with financial or operational goals. For this group, cost-efficiency and competitiveness are the main drivers. Sustainability is seen as an added bonus, rather than a primary objective. One participant summarised this view clearly: "We will consider sustainability, but only if it doesn't affect the business case." However, Business Realists can be powerful allies for circularity when business incentives are aligned with sustainable outcomes.

5.4.3 The Technically-Driven Doer

This type of person sees sustainability as a matter of smart engineering and optimisation. They prefer to focus on concrete improvements rather than broad strategic debates. They see optimising maintenance processes, predictive monitoring and extending component life as natural ways to contribute. As one interviewee explained: "We are trying to get rid of fixed intervals... It is also more sustainable." These individuals often make important contributions through practical, data-driven innovations.

5.4.4 The Motivated Explorer

The Motivated Explorer is intrinsically motivated to advance sustainability, but they often lack institutional support and a shared language. This type of person tends to work in isolation and may become frustrated when broader organisational priorities do not align with their own. One participant expressed this sentiment: "I've never actually talked to people in other departments about this... You're the sustainability team, right?". While Motivated Explorers can drive valuable change, they need stronger support and clearer pathways to collaborate effectively.

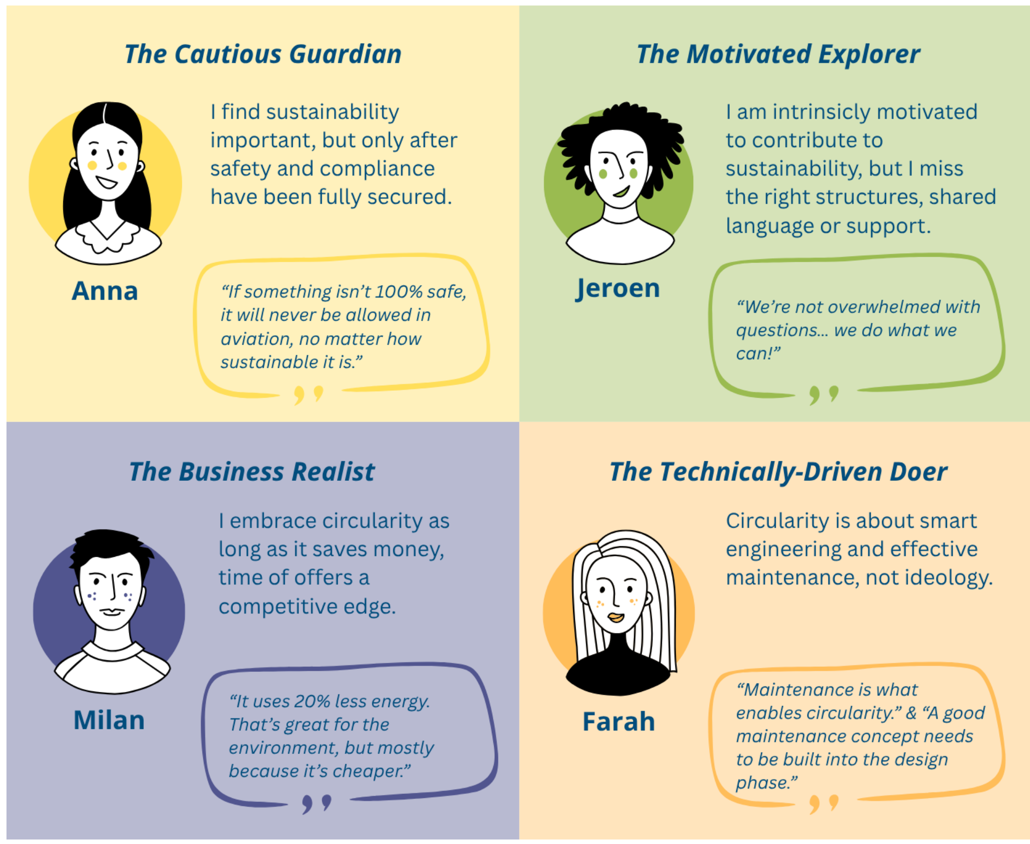


Figure 12. An overview of the new, more human-driven factors that were found in the empirical data.

5.4.5 Conclusion

These types represent fluid mindsets, not fixed roles. Depending on the context, task, or organisational pressures, individuals may shift between them. Understanding these dynamics can facilitate more targeted collaboration, leadership strategies, and policy design. For organisations such as NLR, recognising and addressing these differing perspectives can help to build stronger internal alignment and foster more effective circularity initiatives.

5.5 Circular Economy Knowledge Development Framework

To support the adoption of circular economy principles in aviation maintenance, specific types of knowledge must be developed within the organisation and across the wider sector. This section presents a knowledge development framework that summarises the empirical findings of this research into six key knowledge areas.

The framework provides a practical structure for understanding the required knowledge and its relationship to the various stages of circular innovation. It also facilitates the transition from the research findings to the design phase of the project by informing the roadmap and the storybook.

The knowledge domains were derived from framework validation and thematic analysis. They reflect the current gaps and future needs for enabling circularity in aviation maintenance. While the framework does not prescribe specific solutions, it does highlight areas where capacity building and learning are required.

5.5.1 Key Knowledge Areas

The analysis identified six types of knowledge that are essential for supporting circular economy processes in aviation maintenance (Figure 13):

Foundational knowledge is required in order to develop a shared understanding of circularity and establish clear, simple terminology. Without this shared foundation, communication and collaboration are hindered.

Practical knowledge enables circular strategies to be translated into daily maintenance tasks. It also helps professionals to navigate trade-offs between safety, cost and operational performance.

Strategic knowledge clarifies the value of circularity and defines who is responsible for making circular choices. This knowledge supports long-term planning and decision-making that is aligned with organisational goals. Institutional knowledge relates to rules, policies and certification procedures. This helps professionals to understand the regulatory environment and identify opportunities to influence policy in support of circularity.

Behavioral and cultural knowledge focuses on the mindsets, behaviours and cultural factors that influence how circularity is perceived and practised. This includes fostering a sense of ownership, encouraging collaboration, and promoting openness to change. Without addressing these human and cultural dimensions, even well-designed circular strategies may fail to gain traction.

Systems knowledge involves understanding circularity across the entire value chain. This knowledge supports collaboration between organisations and helps visualise long-term material flows and impacts.

Circular Economy Knowledge Framework
Systems Knowledge
Institutional Knowledge
Strategic Knowledge
Bahavioral and Cultural Knowledge
Practical Knowledge
Foundational Knowledge

Figure 13. An overview of the new, more human-driven factors that were found in the empirical data.

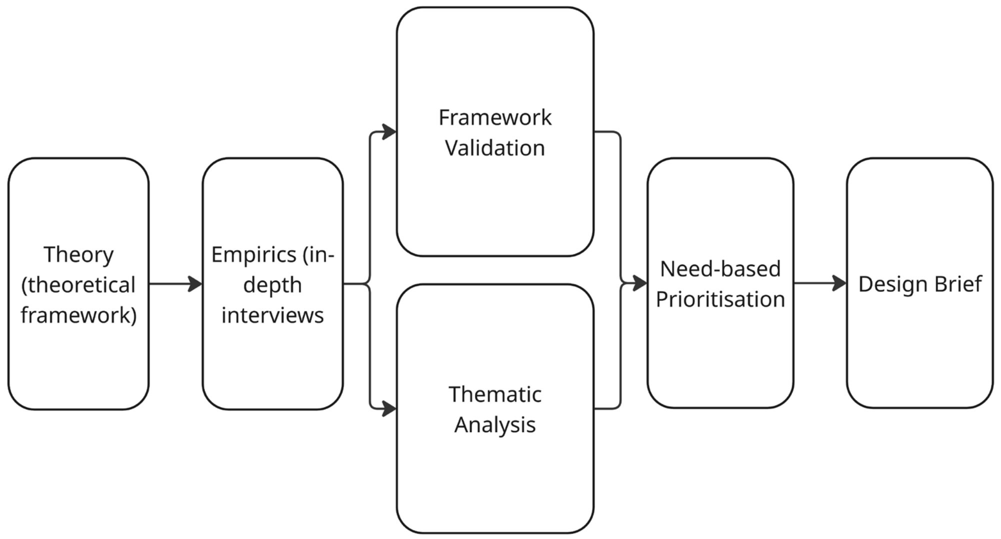


Figure 14. An overview of the new, more human-driven factors that were found in the empirical data.

Currently, foundational, practical and behavioural knowledge are the most urgent priorities. These enable awareness to be raised, initial capacity to be built, and the cultural conditions needed for circular innovation to be created. As circularity matures, however, strategic, institutional and systems knowledge will become increasingly important.

5.6 Synthesising Empirical Insights

This section connects the research and design phases of the project. It summarises key empirical insights and translates them into practical priorities. These priorities then form the basis of the roadmap and storybook (Figure 14).

The empirical results revealed a wide variety of challenges, ranging from communication gaps and cultural barriers to the absence of circular standards and limited collaboration across the value chain. As it is not possible for this project to address all issues at once, it was necessary to prioritise the most relevant areas.

The MoSCoW method was applied to support this prioritisation. This method distinguishes between 'Must-have', 'Should-have', 'Could-have', and 'Will-not-have (for now)' priorities. This provided a clear structure for focusing design efforts on the areas most likely to enable progress.

The MoSCoW analysis was informed by the validated framework and the thematic findings. From this, a set of priority 'needs' was identified. For instance, although circular design is recognised as important in theory, the interviews revealed that circularity has not yet been embedded in design processes. The resulting need is to address this gap by integrating circular design principles into the early stages of the design process. The full list of needs is provided in Appendix F.

The analysis supports a phased approach (Figure 15):
Phase 1 – Making circularity visible and understandable: Establish shared understanding, promote ownership, and equip employees with practical tools to integrate circularity into their work. Behavioural and cultural knowledge is critical at this stage.

Phase 2 – Support learning through practical experience: Focusing on experiments and pilots creates room for experimentation and provides an opportunity to develop initial ideas about balancing safety with sustainability and standardisation. At the same time, the strategic vision is aligned with policy and market trends.

Phase 3 – Embedding circularity into maintenance tools and systems: Strengthen value chain collaboration and integrate circularity into design and material flows.

Phase 1 is particularly significant for this project. It establishes the cultural and practical groundwork for long-term progress. Without this, more advanced circular innovations are unlikely to succeed.

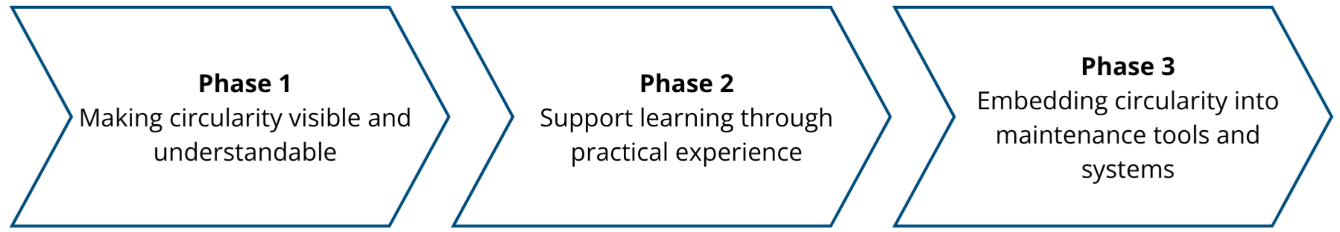


Figure 15. An overview of the new, more human-driven factors that were found in the empirical data.

5.7 Chapter Conclusion

One of the key conclusions drawn from the empirical results is that technology is not the main barrier to the adoption of circular economy principles in aviation maintenance. Although technical readiness and openness to sustainability are present, circularity currently lacks visibility, ownership and a shared structure within maintenance teams. People are not resistant, but tend to operate within narrow definitions, often equating sustainability with efficiency. There is therefore a clear design opportunity to make circularity more tangible and actionable, and to support its integration into daily practice.

The R-strategies offer promising areas for intervention. In particular, the 'Rethink', 'Reuse', 'Remanufacture' and 'Recycle' strategies represent an area where design can help shift mindsets, bridge communication gaps and enable new forms of collaboration. Overcoming barriers relating to material supply, certification, and fragmented standards will also necessitate improved coordination across the wider maintenance ecosystem.

Among the identified stakeholder typologies, Motivated Explorers provide an important starting point. They already demonstrate interest and motivation, and are actively seeking practical tools to facilitate change. Engaging this group will be critical in driving early progress and building momentum.

Overall, the findings highlight that achieving circularity in aviation maintenance requires more than just technical solutions. It necessitates cultural change, cross-organisational collaboration, and targeted knowledge development. These insights will inform the next phase of the project, which involves designing practical interventions to build capacity, foster ownership and encourage the adoption of circular thinking within NLR and its wider MRO context.

6

DESIGN PHASE

As the previous chapter demonstrated, achieving circularity in aviation maintenance requires more than just technical solutions. It necessitates cultural change, practical tools and targeted knowledge development. The research also identified an opportunity to increase the visibility, understanding and actionability of circularity within maintenance teams.

This chapter describes the project's design phase. The focus is on translating empirical insights into practical interventions that support circular thinking in daily maintenance practice.

The design phase follows the structure of the Double Diamond model (British Design Council, 2005) (Figure 16). This model consists of four phases: Discover, Define, Develop and Deliver. It supports an iterative, user-centred approach to problem solving, moving from understanding the challenge to creating and testing concrete solutions. The following sections describe how this process was applied, and how the resulting designs address the identified needs.

6.1 Design Brief

6.1.1 Refined Problem Statement

In the field of aviation maintenance, circularity is often overlooked or dismissed as a low-priority issue. In environments where safety and efficiency dominate decision-making processes, circular strategies are rarely viewed as valuable opportunities. Instead, they are perceived as difficult to implement and justify, and sometimes as incompatible with the high standards of aviation maintenance.

This perception is reinforced by the absence of a shared language, clear communication and practical tools to support circular thinking in daily operations. Without education, facilitation or ownership across teams, circularity remains abstract and disconnected from the realities of maintenance work.

Several systemic challenges underlie this situation. Current processes do not fully account for emerging regulations or long-term policy shifts, contributing to a 'wait and see' attitude. There is no clear vision of what sustainability should mean for the future of maintenance or of how to balance it with aviation safety requirements. Consequently, conversations about sustainability tend to focus primarily on carbon emissions, while critical issues such as resource scarcity, material reuse, and nitrogen emissions often remain overlooked. Circularity as an enabler of a more future-proof maintenance system is not yet recognised or actively supported.

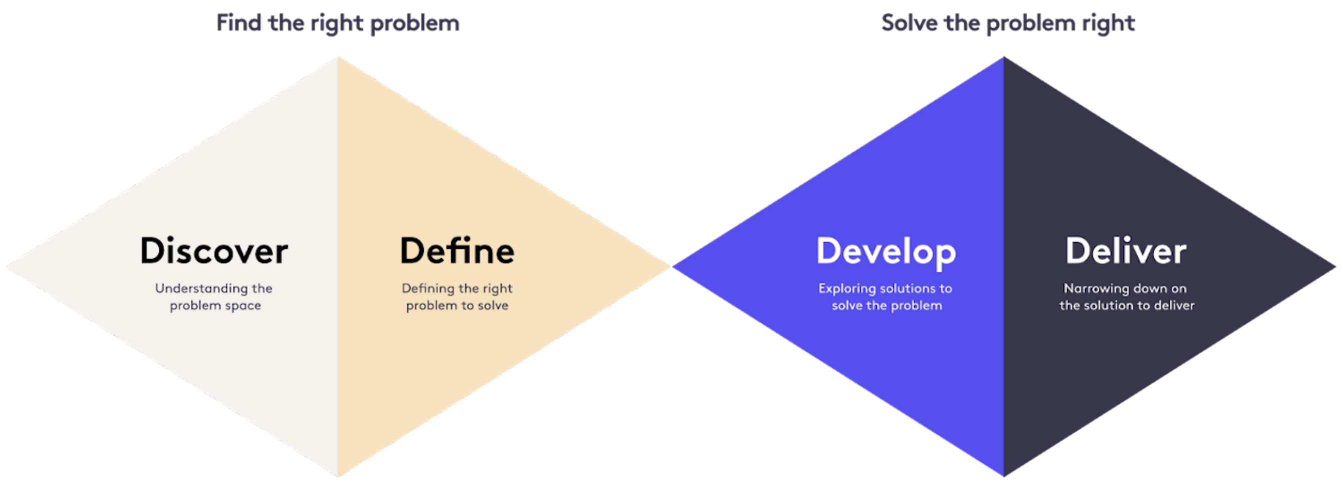


Figure 16. An overview of the new, more human-driven factors that were found in the empirical data.

This leads to the refined problem statement:

"Circularity is not widely recognised as a valuable or actionable concept due to a lack of shared understanding, ownership and practical facilitation. Without these foundations, it is challenging to develop a long-term strategic vision or integrate circular thinking into daily practice."

6.1.2 Design Scope

The concept of circularity in aviation maintenance is often perceived as abstract and distant from strategic decision-making processes. Although awareness of sustainability is growing, a lack of shared understanding, ownership and practical tools prevents maintenance teams from recognising the value of circularity as an actionable concept.

This challenge is reinforced by the sector's strong focus on safety, efficiency and compliance. In these areas, circular strategies have yet to be fully integrated. Despite long-term sustainability goals and mounting policy pressure, circularity is still widely perceived as incompatible with existing processes and priorities.

This project therefore aims to design a practical, accessible tool to help ASAM/MAE identify, discuss and experiment with circular strategies that fit their operational reality.

The project does not seek to redesign technical maintenance processes. Instead, it represents a first step towards integrating circular thinking into daily practice. This is achieved by exploring how existing maintenance tools can be adapted and extended to support circularity. Rather than introducing entirely new solutions, the goal is to enhance current tools with a circular perspective and gradually make circular strategies more actionable (see Figure 17).

6.1.3 Design Goal

Based on the problem statement, theoretical framework and thematic analysis, the following design goal has been defined to guide the design phase:

"The design aims to raise awareness around circularity among maintenance professionals and to highlight the value proposition that circular strategies offer. It seeks to make circular principles tangible and relatable through practical examples and accessible communication. which fosters a mindset shift from obligation to opportunity."

The goal is closely linked to two factors from the theoretical framework: encouraging a sense of ownership of circularity within the organisation and promoting a more strategic, system-oriented approach to sustainability. These elements are both essential for enabling maintenance professionals to engage with circular thinking in their daily work and longer-term decision-making processes.

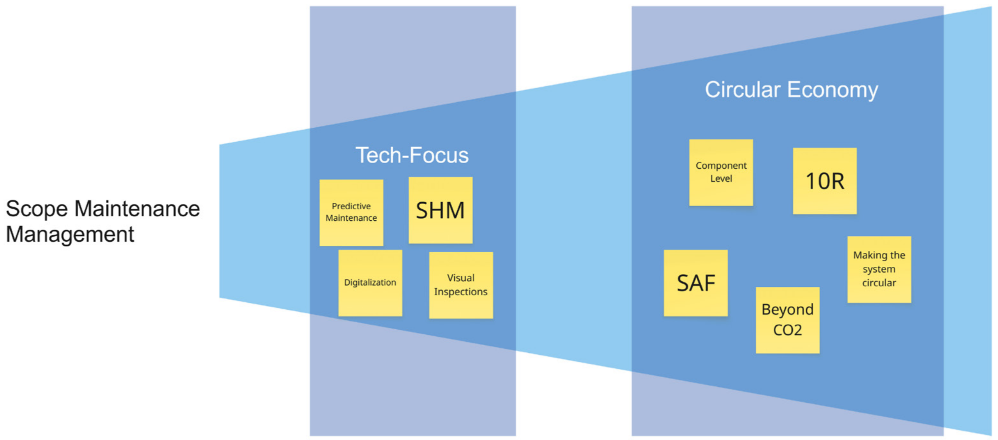


Figure 17. An overview of the new, more human-driven factors that were found in the empirical data.

6.1.4 Target Group

This design is intended for the maintenance experts at ASAM/MAE. These professionals play a pivotal role in promoting circularity in the field of aviation maintenance. Their daily decisions directly influence the evolution of maintenance processes and the integration of circular strategies into practice.

Research shows that this group is generally open to and curious about circularity, with many professionals exhibiting characteristics of the Motivated Explorer mindset. However, their specific concerns and hesitations vary. For some, these concerns are primarily technical or safety-related, while for others, they are more business- or risk-driven. Therefore, addressing these different perspectives is essential for building engagement and ownership within this target group.

6.1.5 Design Requirements

The design requirements were developed by combining insights from the validated theoretical framework, thematic analysis and 10R mapping. Together, these requirements reflect the key barriers and enablers that were identified during the research phase, providing a practical foundation for the subsequent design stage.
To ensure a balanced and actionable set of requirements, they were organised around three perspectives:

Desirability focuses on the needs, motivations and working context of maintenance professionals.

Feasibility considers what can realistically be implemented within current technologies, processes and organisational constraints.

Viability ensures that the design will contribute positively to long-term organisational goals and have a positive wider system-level impact.

By combining these perspectives, the design requirements aim to support meaningful innovation that resonates with target users, is practical to implement, and aligns with business and sustainability objectives.

Table 4 provides an overview of the requirements. It also indicates whether each requirement is primarily grounded in the theoretical framework (TF), qualitative research (QR), or both.

6.1.6 Future Vision

In order to provide a long-term perspective on the development of circularity within aviation maintenance, a future vision has been formulated for ASAM/MAE. This vision supports the design goal and illustrates how circular thinking and practice could evolve over time.

"By 2035, NLR's Maintenance Professionals speak a shared and practical language of circularity — enabling daily decisions that balance environmental impact with safety, compliance, and operational value. Circularity is used not to make everything circular, but to design a system that can sustain itself — resilient against material scarcity, regulatory pressure, and rising energy demands. From early ideas to certified solutions, it's a strategic mindset embedded in engineering reality."

6.2 Discover

The first phase of the double diamond model involves exploring the problem space. This divergent phase aims to gather a wide range of insights and perspectives and understand the broader context of the design challenge. In this project, the Discover phase was addressed through an extensive research process, as detailed in previous chapters.

The literature review provided a theoretical basis for understanding circularity in aviation MRO, highlighting conceptual opportunities and practical challenges alike. The organisational analysis positioned NLR and the ASAM/MAE department within this context, identifying

Table 4. Overview of the design requirements, categorized by desirability, feasibility and viability. Also showing where the requirement comes specifically from: theoretical model or qualitative research.

#		Requirement	TF	QR
1	D1	The design must facilitate the use of shared, simple, and consistent terminology.		X
2	D2	The design must help users understand how MRO activities connect to circularity in a clear, relatable, and practical way.		X
3	D3	The design must include educational elements that build a shared understanding of circularity and systems thinking.		X
4	D4	The design must provide relatable narratives, such as personas or user stories, that help users see themselves in circular roles.	X	X
5	D5	The design must introduce the broader circularity context of micro, meso, macro and operations in a way that supports user comprehension and relevance.	X	X
6	D6	De design must enable maintenance specialists to articulate and communicate circular definitions and concepts to external partners.	X	X
7	D7	The design must show the relevance of early stage design decisions on a circular system.	X	X
8	F1	The design must be easily integrated in the current workflow to encourage interdisciplinary use and reduce barriers to adoption.	X	X
9	F2	The design must support internal sharing of knowledge and insights to promote collective understanding (including different departments).		X
10	F3	The design must be adaptable in structure and content to support evolving user understanding and organizational needs.	X	X
11	F4	The design must have consistency across different forms and applications.	X	X
12	V1	The design must help identify areas where circularity creates knowledge gaps or conflicting priorities (e.g., with safety, cost, availability).		X
13	V2	The design must position circularity as a shared responsibility, not only as a sustainability team's domain.	X	X
14	V3	The design must help users explore the potential added value of circularity.	X	X
15	V4	The design must show the systemic boundaries, by showing relevant sustainability laws and regulations in aviation.	X	X

structural and cultural factors influencing the perception and application of circular strategies. Qualitative research added depth to this understanding by uncovering the specific barriers, enablers and stakeholder perspectives that influence the approach to circularity in daily maintenance practice.

The Discover phase revealed several key insights that now inform the design phase. These include the need for a shared language and sense of ownership, the importance of practical, relatable tools, and the potential to foster existing curiosity within maintenance teams. It also highlighted systemic challenges, such as fragmented communication, certification barriers and limited reuse and recycling infrastructure.

These insights provide a clear starting point for the next phase of the Double Diamond process. Define. The following section describes how the design challenge was further refined and translated into concrete development instructions.

6.3 Define

In the Define phase of the Double Diamond process, the design space is narrowed down. During this phase, the broad insights gathered in the Discover phase are synthesised and translated into a clear, actionable design direction.

For this project, the Define phase was supported by a combination of framework validation, thematic analysis and MoSCoW prioritisation. Together, these elements helped to identify the most urgent needs and the most relevant design opportunities for supporting circularity in aviation maintenance.

A key outcome of this phase was recognising that raising awareness, fostering a sense of ownership, and providing practical tools are the most immediate and impactful starting points. Rather than addressing technical processes directly, the design focuses on creating interventions that make circularity visible, understandable and actionable in the daily work of maintenance teams.

This approach also reflects the priorities of the most engaged stakeholders, particularly the Motivated Explorers, while remaining accessible and relevant to other professional perspectives within ASAM/MAE. The aim is to activate existing curiosity, lower barriers to engagement, and build a foundation for more systemic change over time.

The next phase of the project will explore how these insights were translated into concrete design concepts and tools, based on this defined focus.

6.4 Develop

In the Develop phase of the Double Diamond model, potential solutions are explored and insights are translated into concrete design directions. During this stage, divergent thinking is employed once more, this time to generate and evaluate ideas for potential solutions rather than to explore the problem itself.

For this project, the Develop phase combined insights from theoretical and qualitative research with an iterative, creative process. The lead researcher acted as the designer, collaborating closely with NLR's maintenance professionals to ensure the emerging design concepts were relevant and practical.

The process included two key steps:
Requirement-driven ideation: generating ideas based on the prioritised design requirements.

Co-creation: collaborating with key stakeholders to refine, test, and select ideas for further development.

This approach ensured that the design phase remained closely aligned with the needs of the intended users and the practical realities of maintenance work. The following sections describe how these steps were implemented and their subsequent impact on the final design choices (Figure 18).

6.4.1 Requirement Brainstorming

The design requirements defined in Section 6.1.5 formed the basis of the ideation phase. During this phase, structured brainstorming sessions were conducted, using these requirements as a starting point. The main researcher collaborated with ChatGPT to facilitate the iterative and exploratory generation of ideas.

Each brainstorming session focused on a single requirement. This enabled the development of ideas in depth without considering all requirements simultaneously. Interestingly, many of the ideas generated during this phase

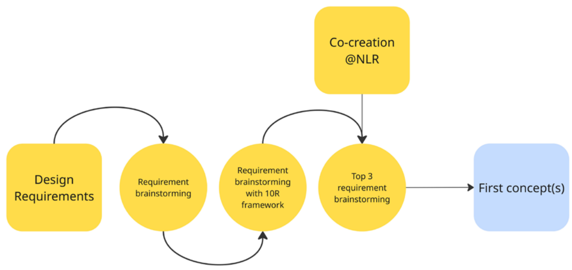


Figure 18. Ideation process driven by the design requirements.

reflecting the interconnected nature of the design challenge.

The 10R framework proved particularly valuable during this process. In a second round of brainstorming, the framework was explicitly used to guide the generation of ideas and translate abstract sustainability goals into practical actions recognisable in the context of aviation maintenance.

In total, 62 ideas were generated and documented as individual 'requirement cards' (Figure 19). These cards served as tangible inputs for the subsequent co-creation session. Although the cards were prepared as stimuli, the participants generated sufficient ideas independently during the session and did not actively use the cards to drive creativity.

6.4.2 Co-Creation

Co-creation is a collaborative design method in which designers and stakeholders work together to solve problems and come up with ideas. In this project, it was used to validate and enrich the design requirements, as well as to generate practical ideas reflecting the perspectives of maintenance professionals (Figure 20).

Based on the methodology outlined in Convivial Toolbox (Sanders & Stappers, 2012), the co-creation session involved four participants from the ASAM/MAE department. Taking place during the Develop phase, it served four main objectives:

1) To validate whether participants recognised and understood the problem statement presented in the design brief.

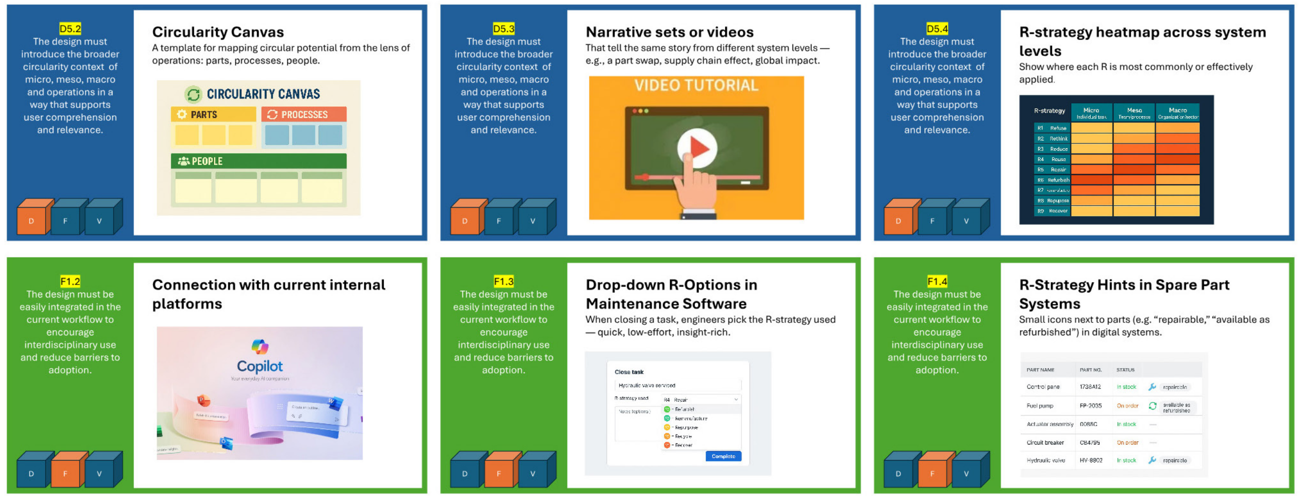


Figure 19. Six examples of the requirement cards that were created based on the ideas generated in the requirement brainstorming sessions.

Figure 20. Photograph of the co-creation session.

2) To explore which 10R strategies the participants most strongly associated with the circular economy.
3) To identify the three most relevant and urgent design requirements.
4) To generate ideas based on the selected requirements and the participants' practical experience.

Details of the co-creation session design can be found in Appendix G.

The session provided valuable insights. Most participants recognised the core problem. One participant responded: "Yes, so it's about understanding circularity? So, are you saying that you need to be aware of circularity when working on a project?" Another confirmed, "Yes, I recognise the things that are written here." This demonstrates that the participants were familiar with the topic and willing to engage with it critically.
The discussion also raised questions about responsibility and ownership: 'Is it the OEM, the maintenance company, the airline, or someone else?' This confirms that circularity is recognised as an organisational and systemic challenge as well as a technical one.

When asked which R0–R5 strategies they associate with the circular economy, most participants referred to Repair. One participant remarked: 'Repair anyway.' Another added, 'I think we do up to R5 in aviation anyway. From R6, it becomes more complicated because you need to collaborate with other industries to reuse materials.' This suggests that, although some circular practices are already integrated into maintenance operations, more advanced or collaborative strategies are difficult to implement. Some scepticism was also expressed: 'We're saying that circularity is happening and is successful, but I don't think it is. That's interesting.'

Regarding the design requirements, participants identified the following as the most important:

V5 The design must help users explore the potential added value of circularity (for future business models).

D1 The design must facilitate the use of shared, simple, and consistent terminology.

V3 The design must help identify areas where circularity creates knowledge gaps or conflicting priorities (e.g., with safety, cost, availability).

Although V5, the top-rated requirement, related to business models, this element was later excluded from the final design focus. The scope of this project is not to develop new business models, but rather to support circular thinking within the current operational context.

Several valuable ideas emerged during the session. One was the idea of introducing terminology only after telling a story to make abstract concepts more accessible. Another idea was to use visual tools to improve understanding, such as a glossary or dictionary to help navigate circularity-related terminology. Finally, the concept of a structured trade-off process with clear criteria was suggested. This could be an interesting principle to support decision-making, even if it may be too technical for direct implementation.

These insights played an important role in shaping the final design choices. The next section describes how the ideas from this session and the earlier requirement ideation were combined to select the concepts to be developed further.

6.4.3 Choosing Concepts

To select the concepts to be developed further, the ideas from the requirements brainstorming session and the co-creation session were combined and evaluated. The aim was to establish a logical sequence of ideas to support the phased strategic plan and select the most suitable concept for Phase 1, which centres on raising awareness of and promoting understanding of circularity in aviation maintenance.

First, all ideas were categorised according to the three phases defined earlier in the project. The ideas were then clustered and mapped using a feasibility and impact matrix (Figure 21). This helped to assess which ideas were practical and likely to generate a meaningful short-term impact.

For Phase 1, the focus was on making circularity visible and understandable. These included terminology exercises, visual storytelling tools, onboarding materials and interactive formats, such as chatbots and glossaries. Based on insights from the co-creation session, which emphasised the importance of storytelling and visual support, the concept of a *Circular Economy Storybook* was selected. This tool can introduce circular thinking in an accessible, relatable way that is easy to integrate into existing communication practices.

For Phase 2, the ideas aimed to support learning through practical experience. Pilots were identified as a valuable means of testing circular strategies in real maintenance contexts, generating concrete examples and lessons, and building internal momentum and ownership. Suggested pilots included developing and testing circular KPIs, lifecycle logging tools, and structured ways to track circular actions in maintenance processes. Based on this, *the Shared Pilot* concept was selected as the most suitable starting point for this phase.

For Phase 3, the focus shifts to embedding circularity directly into maintenance tools and systems. Suggested ideas include developing material passports, integrating 10R decision support into software and using structured data to inform repair, reuse and replacement decisions. Collectively, these ideas point towards the development of *a Circular Maintenance Tool*. This tool would make circular thinking part of everyday workflows, supporting

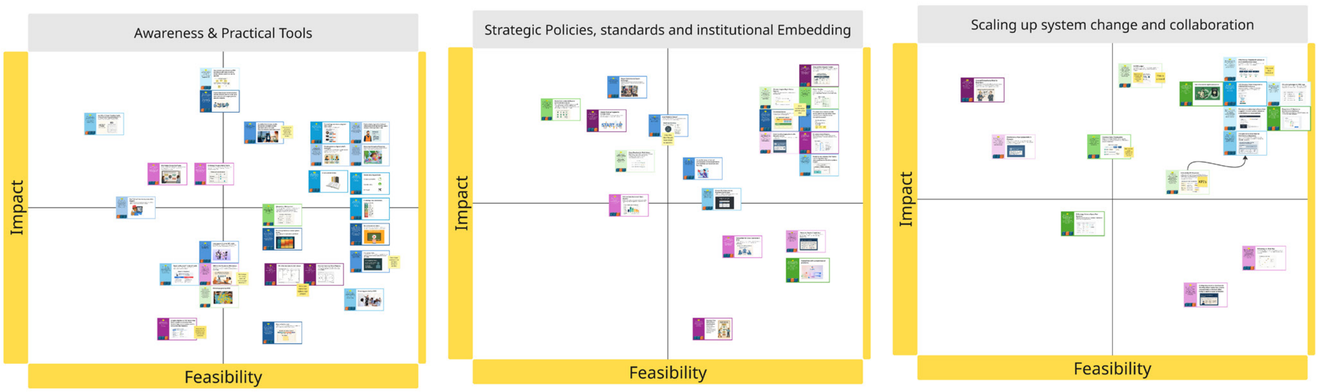


Figure 21. Per identified fase in chapter two, clustering and mapping ideas in a feasibility and impact c-box.

more systematic, data-driven circular practices across the organisation.

In summary, the following concepts have been selected for the three phases:
Phase 1 - Circular Economy Storybook
Phase 2 - Shared Pilot
Phase 3 - Circular Maintenance Tool

Together, these concepts offer a practical, phased approach to incorporating circular thinking into aviation maintenance. The Circular Economy Storybook promotes initial awareness and engagement. The Shared Pilot facilitates learning and helps to embed circularity strategically within the organisation. The Circular Maintenance Tool provides a long-term opportunity to integrate circularity directly into maintenance workflows and systems.

The subsequent chapter elaborates on the evolution of the first concept, a roadmap which incorporates all the three phases, and the concept for phase 1, the Circular Economy Storybook.

6.3.4 Intermediate Designs

Concept 1: Knowledge Creation Roadmap
Main Objective
This project's primary research question focuses on developing and embedding circular economy knowledge in aviation maintenance. The Circular Economy Knowledge Creation Roadmap was developed to address this question directly (Figure 22). It aims to structure the knowledge areas identified in the research into a logical, phased progression to support learning, application and systemic embedding over time.

The roadmap aims to guide maintenance professionals through the evolving landscape of circularity. It demonstrates that circularity is both feasible and valuable, and not an abstract or disruptive concept, thereby helping to build trust and engagement. It also provides transparency regarding impending regulatory changes and sustainability risks that the sector must address.

Concept Explanation
The Circular Economy Knowledge Creation Roadmap is self-explanatory and example-

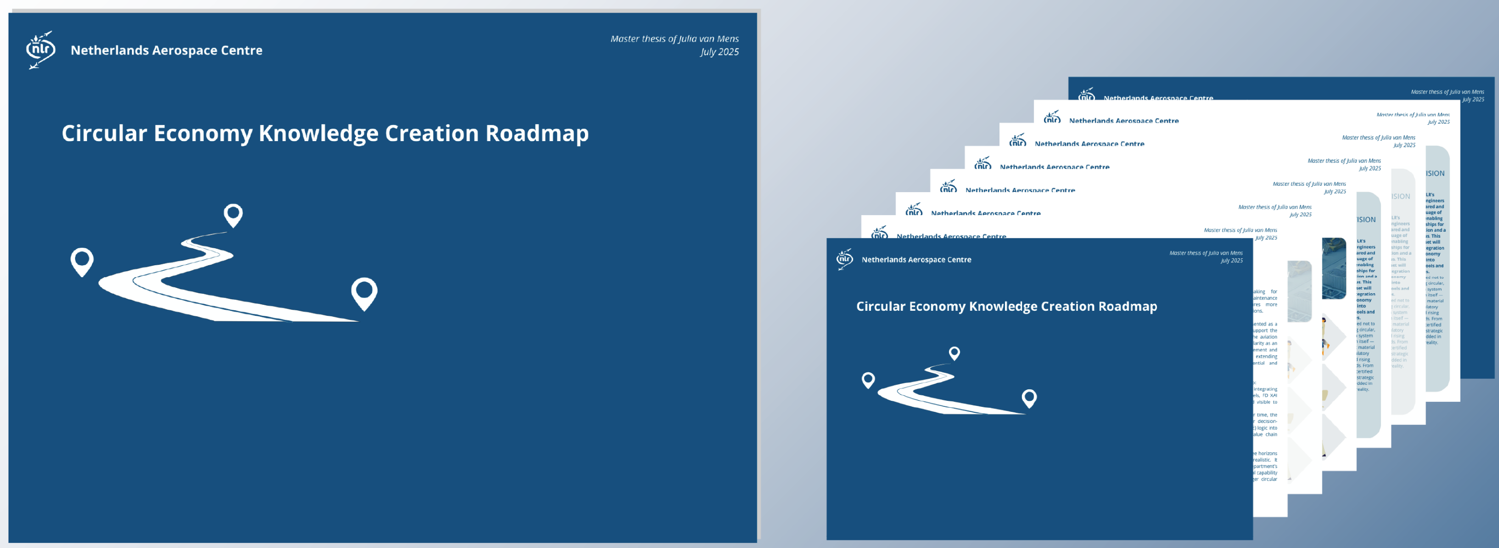


Figure 22. Per identified fase in chapter two, clustering and mapping ideas in a feasibility and impact c-box.

driven, showing how maintenance professionals can build and apply knowledge of the circular economy in their work. As part of a broader vision to transition maintenance towards a more circular approach, this roadmap focuses on gradually building knowledge over time. Addressing all four typologies, the roadmap responds to their values and concerns over a ten-year period.

It outlines a shared learning journey toward a future where circularity is a normal part of maintenance thinking. Along the way, the roadmap pauses at three key stages: first, to interpret what circularity means in a maintenance context; second, to explore its practical relevance and impact; and third, to embed the lessons learned into everyday decision-making.

Chosen Format
The roadmap is developed based on both design roadmapping theory of Simonse (2024) as visualising roadmaps theory of Kerr and Phaal (2015). This format consists of choosing a frame, a structure, relationships and direction. This format was chosen because it helps to clearly show how knowledge building can evolve over time. It also allows for connecting different types of knowledge and actions in a logical flow. In this way, the roadmap does not only show what should happen, but also when and how different elements relate to each other.

A design roadmap consists of two different types of roadmaps: a strategic roadmap and a tactical roadmap. The strategic roadmap focuses on the more global planning, steps, objectives and goals of the strategy. Often in the strategic roadmap it becomes clear what the future vision is, and what are the three main steps taken to get to that future vision. In the tactical roadmap, more specific and detailed actions are written down which are necessary to achieve the goals that are laid out in the strategic roadmap.

Concept 2: Circular Economy Storybook
Main Objective
The Circular Economy Storybook aims to make the concept of circularity more accessible and relatable to aviation maintenance professionals. Through short, fictional stories inspired by everyday maintenance practice, it introduces key ideas, terms, and principles of circular thinking (Figure 23). The booklet helps to foster a sense of ownership and shared language, as well as providing an initial understanding of how maintenance activities can facilitate circular economy outcomes. Designed to spark curiosity and encourage informal learning, it lays a cultural foundation for the broader adoption of circularity across the organisation.

Concept
This booklet contains a collection of 5-minute fictional stories that explore what circularity can mean in an aviation maintenance context. The stories are written for those who are intrinsically motivated to contribute to sustainability, but may lack the structure, shared language or support to do so.

The emphasis is on sense-making: developing ownership, a common vocabulary, and a first sense of how circular principles can add value in practice. The stories aim to show that maintenance is a natural enabler of circularity, and that circular thinking can support better decisions, especially when building toward more resilient systems for the future.

Format
The Storybook is available in both printed and digital formats. It consists of an A4 booklet with an introduction and a set of short, illustrative narratives. Each story addresses a different theme or perspective related to circularity. Topics are drawn from broader research insights and may include principles such as reuse, repair, reduction, or repurposing, embedded in maintenance-related scenarios.

6.5 Deliver
The final phase of this design project involves delivering the developed tools and evaluating their usability and relevance. This phase draws on the insights, concepts and iterations from earlier stages, reflecting on how they were finalised, validated and prepared for real-world application.

Discussed in Chapter 7, a series of validation

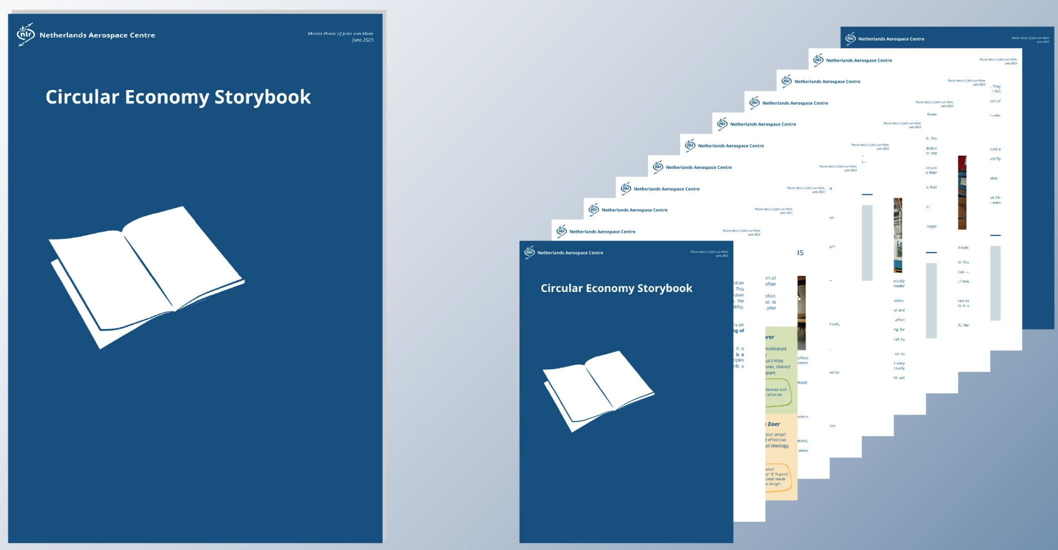


Figure 23. Per identified fase in chapter two, clustering and mapping ideas in a feasibility and impact c-box.

sessions were conducted with internal stakeholders from various departments. These sessions confirmed that the two tools developed — the CE TRACK roadmap and the SCOPE storybook — addressed the need for practical, accessible guidance on circularity in aviation maintenance. Participants responded positively to the structure, tone, and ambition of both tools. However, the feedback also highlighted areas for improvement, such as simplifying the technical language, clarifying the objectives of each roadmap phase, and strengthening the link between strategic intent and operational practice. While the storybook was valued for its engaging style and informal tone, some stories could benefit from clearer context and prompts for reflection.

The final deliverables, presented in Chapter 8, consist of two complementary tools. The CE TRACK roadmap offers a phased, value-driven structure for developing circular knowledge and embedding sustainable practices over time. The SCOPE storybook provides an accessible introduction to circular thinking through short fictional narratives designed to stimulate curiosity, reflection, and discussion. Together, these tools support structured learning and cultural awareness and are intended for use in workshops, during the onboarding process and in internal strategy discussions.

Based on these findings, a set of recommendations is presented in Section 9.4. These include embedding the tools in existing workflows, clarifying roles and responsibilities, and supporting the further development of circular tools and data usage. The recommendations also encourage NLR to view circularity as an ongoing learning process that benefits from collaboration, adaptability, and clear communication, rather than as a fixed destination.

The Deliver phase concludes the project by providing tangible tools and clear guidance on how these can evolve and contribute meaningfully to NLR's ambition create a strong foundation in circular aviation.

7

VALIDATION

This chapter outlines the validation process for the developed concepts. Rather than evaluating fully implemented tools, the purpose of the validation was to determine whether the deliverables were aligned with the needs of the target group and strategic direction. The aim was not to measure effectiveness, but to assess the deliverables' relevance, clarity, and potential for integration in the current context.

To inform this assessment, three guiding principles were adopted: desirability, feasibility, and viability. These dimensions informed both the structure of the interviews and the interpretation of the feedback. However, participants were not asked to categorise their input along these lines directly. The aim was instead to generate open-ended feedback on how the concepts were perceived, understood and potentially used in practice.

7.1 Validation Method

Six participants took part in semi-structured interviews, each lasting approximately 60 minutes. Sessions were held both online and in person. Although most participants were familiar with the project, each session began with a brief overview of the research objectives and an introduction to the validation goals.

During the interviews, participants were presented with the two core concepts: the Circular Economy Knowledge Creation Roadmap and the Circular Economy Knowledge Creation Storybook. Each concept was discussed step by step. Participants were asked to read a specific section, after which follow-up questions were asked to elicit their spontaneous impressions, clarifications and reflections. Once the concepts had been discussed in detail, broader questions were asked about their usefulness and potential implementation.

Example questions used during validation included:

- What is your general first impression?
- Which parts are clear or unclear?
- What would you add or change?
- In what setting could you imagine using this?
- What are the potential benefits or limitations?

Could this help you build or share knowledge around the circular economy?
What would be needed to make this concept work in daily practice?

These questions were designed to explore three overarching dimensions.

Desirability: Do users recognise the value of the concept? Does it address their needs and motivations?
Feasibility: Can the concept be used realistically within existing workflows or structures?
Viability: Does the concept support broader institutional goals, such as sustainability ambitions, compliance requirements, or the long-term strategy?

7.2 Validation Results

7.2.1 Circular Economy Knowledge Creation Roadmap

General Usability
The CEKC Roadmap was seen as a clear and well-designed tool for introducing circular thinking in aviation maintenance. Participants appreciated the structure, visuals, and approachable introduction. Several said it made a complex topic more accessible. However, some found the terminology abstract. Phrases like "Horizon 1" lacked clear meaning without additional context or examples. Participants suggested simplifying the language and better explaining key terms (Figure 24).

The roadmap was generally understood as a flexible guide, though some recommended making this flexibility more explicit. It should encourage reflection and adaptation, rather than suggest a fixed process.

"I like how it's structured. It helps people approach the topic gradually." – VP2

"It's practical. Despite some theoretical layers, the people using it will be hands-on. So this tone is good." – VP5

"You should really be careful with circular jargon.

Definitions matter, because across disciplines people interpret terms differently.” – VP5

Strategic Roadmap
Participants valued the long-term, phased structure. It helped show that transitioning to circularity takes time. The roadmap reassured users that full knowledge is not required at the start. However, clearer goals for each horizon were recommended. It was not always obvious what each phase aimed to achieve.

The equal size of the horizons was also seen as potentially misleading. Some suggested adding visual cues to show that early phases might require less time or fewer resources. The typologies included in the roadmap were seen as useful, but participants advised clarifying that these represent mindsets, not fixed roles. Presenting all typologies together, rather than linking one to each phase, was preferred.

Workshops or interactive sessions were suggested as effective ways to introduce the roadmap and create shared ownership.

“I liked that it shows: it’s okay not to know everything yet. That’s reassuring. It really feels like a journey.” – VP2

“Ten years feels long. Could this be shortened, or at least justified more clearly?” – VP2

“It’s not always clear what the output per phase should be. What are we actually trying to achieve in each step?” – VP3

“Those typologies are useful, but make sure it’s clear that they’re mindsets, not roles.” – VP1

Tactical Roadmap
The tactical roadmap was praised for its practical focus. Participants liked how it connected strategy to daily tasks. The visuals, icons and short descriptions helped with clarity. Still, the connection between the strategic and tactical layers could be improved. Users recommended using consistent language and themes between the two.

The future vision was appreciated but could be given more weight. A summary page linking actions to long-term outcomes was suggested. Participants also pointed out that roles and responsibilities were not clearly assigned. Editable templates could help teams define who does what and track progress.

The roadmap would benefit from built-in evaluation points. These could align with existing planning cycles and support continuous improvement.

“This part is nice and hands-on. You can really see how strategy becomes action.” – VP5

“Make sure you use the same terms between the strategic and tactical levels. Now it feels a bit disconnected.” – VP3

“Who’s doing what? That’s unclear now. Maybe editable templates would help define roles.” – VP5

“You could align this with evaluation points in existing planning cycles.” – VP4

Integration into Workflow
Participants saw strong potential for the roadmap in strategy meetings, planning sessions and cross-team collaboration. Its success would depend on how it is introduced. Regular team check-ins, ownership of actions and facilitation were seen as essential.

To broaden adoption, the roadmap should distinguish between strategic and operational actions. It should also clarify which parts are based on literature and which stem from internal research. This would help make it useful across different departments and roles.

“Workshops could help introduce this. That way, teams could create shared ownership.” – VP4

“This could work well in strategy or planning meetings – as long as someone takes ownership of it.” – VP4

“Be clear what comes from research and what is internal experience. That helps with credibility across roles.” – VP3

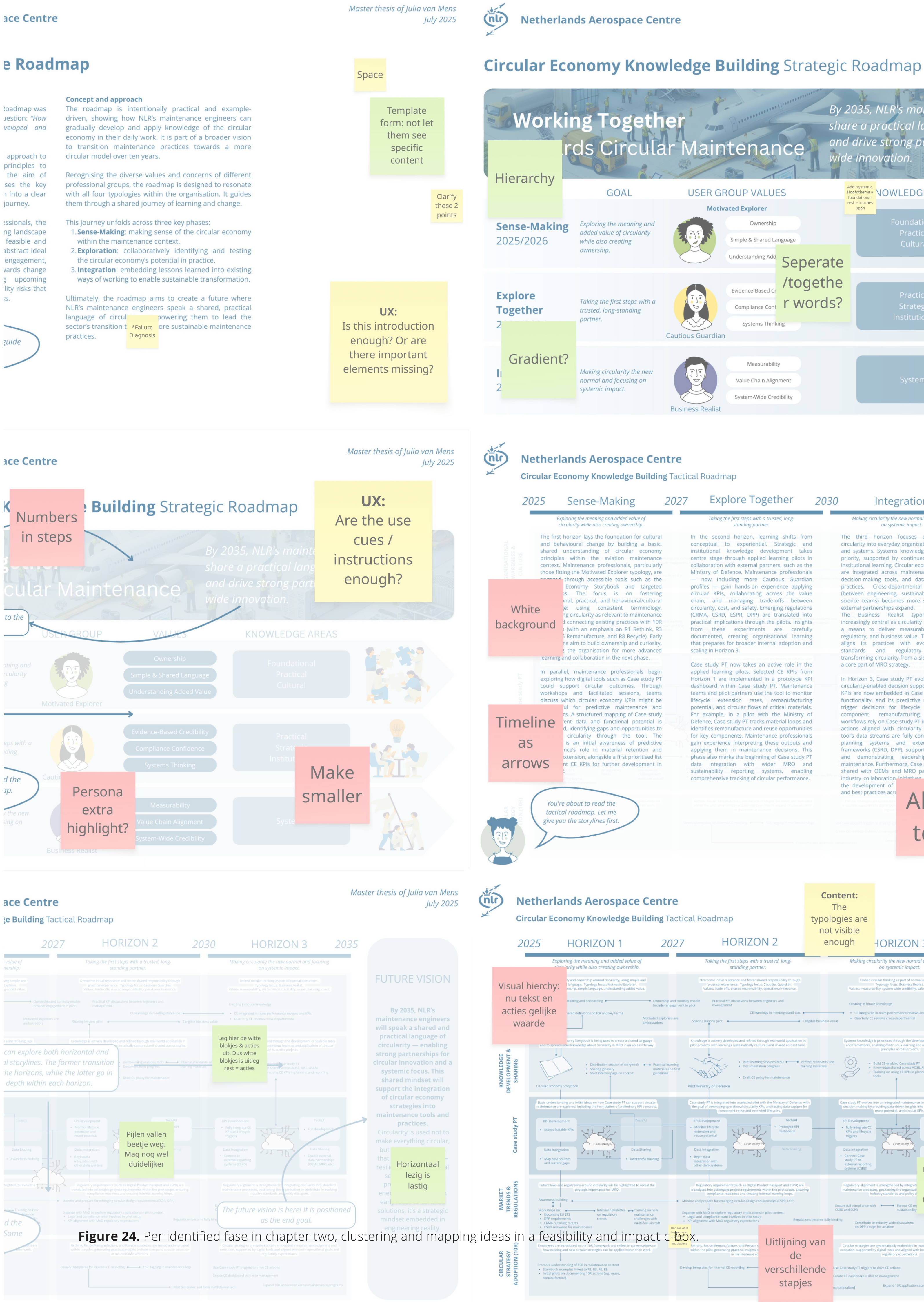


Figure 24. Per identified fase in chapter two, clustering and mapping ideas in a feasibility and impact c-box.

7.2.2 Circular Economy Storybook

General Usability
The Storybook was well received. Participants praised its informal tone and engaging style. It made circularity more relatable, especially for those without a technical background. The fictional stories were seen as useful for sparking interest and discussion. They helped shift the view of sustainability from a compliance issue to a practical opportunity.

Some stories were viewed as too speculative. Characters changed too quickly, or their roles were unclear. This made it harder to connect with real work settings. Greater clarity around context was recommended.

"It's nice to read something like this. Much more enjoyable than ISO documents." – VP2

"The tone is great – accessible and low-threshold. That works well, especially for people without a strong technical background." – VP5

"Some stories were a bit far-fetched. That made them harder to relate to." – VP1

Story Effectiveness
The most effective stories were those grounded in everyday situations. Scenarios involving communication issues or cultural differences helped readers reflect on their own roles. Stories that showed the application of circular principles in familiar dilemmas were particularly appreciated.

Participants suggested adding reflection prompts or discussion questions after each story. A glossary or links to related roadmap phases could also improve usability.

"If a story shows a realistic dilemma and how circularity plays a role, that sticks much better." – VP2

"Miscommunication or differences in mindset – that's what people really recognize." – VP4

"I liked the story about the actuator. It made the link between self-reliance and circularity very tangible." – VP5

Application and Integration into Workflow
The Storybook was seen as a good tool for onboarding, team discussions and informal learning. It works well in shared spaces and awareness sessions. Several participants suggested adapting it for external use, such as introducing circularity to clients or partners.

To support integration, users recommended linking stories more clearly to roadmap phases or professional roles. This would help readers see how the lessons apply to their daily work.

"This would be great in shared spaces or during onboarding. It invites casual learning." – VP5

"Why not use it externally too? It could help explain circularity to clients or partners." – VP2

"You could link stories to specific roles or roadmap phases. That way people can better relate." – VP3

7.3 Conclusion of Validation

The validation confirmed that both the CEKC Roadmap and Storybook are relevant, well-received tools for supporting circularity in aviation maintenance. Participants appreciated the roadmap's clear structure and phased approach, which helped make the topic more concrete and approachable. It was seen as useful for long-term learning, planning, and alignment with strategic goals.

However, some improvements were suggested. These include clarifying the purpose of each horizon, aligning the strategic and tactical layers more clearly, and identifying responsible roles for implementation. Adding checkpoints and linking roadmap phases to a future vision would help maintain momentum and support integration into existing planning cycles.

The Storybook was praised for its informal, engaging format, which lowered the barrier to entry and encouraged reflection and discussion. Its fictional stories made circularity relatable, especially for non-technical audiences.

Participants suggested refining the clarity of some stories and adding reflection prompts or supporting tools like glossaries to enhance usability.

Both tools were seen as promising but not yet plug-and-play. Their success depends on how they are introduced, facilitated and embedded into workflows. Regular workshops, onboarding sessions and clear ownership structures were suggested to support adoption.

Together, the roadmap and storybook offer a complementary approach: one provides structure and direction, the other fosters culture and engagement. With minor refinements and the right support, both can contribute meaningfully to building circular awareness and action within the organisation.

8

FINAL DELIVERABLES

This chapter presents the final deliverables developed during the concluding stages of the design phase. While Chapter 6 introduced the core design directions, including the main objective, conceptual approach and selected formats, this chapter focuses on the detailed outcomes resulting from these decisions.

The focus shifts from the 'why' and 'how' to the 'what'. It outlines the specific content, context and practical considerations that shaped the final deliverables. These elements reflect the insights gained through earlier research, stakeholder validation and iterative development.

The following pages introduce the two final deliverables: CE TRACK and SCOPE. Together, they offer complementary strategies for developing knowledge of the circular economy within aviation maintenance. Each tool is designed to support a distinct stage of the learning process while reinforcing a shared strategic vision.

CE TRACK

8.1 CE TRACK

CE TRACK is a strategic roadmap designed to guide the phased development of knowledge of the circular economy within NLR's maintenance operations. Providing a structured overview of the key steps required to transition towards more circular practices, it addresses both cultural and organisational dimensions.

The roadmap identifies shared values, defines learning objectives and ensures that knowledge development is aligned with strategic goals. Offering a visual and narrative structure, it can be used for long-term planning, team reflection, and cross-departmental coordination. CE TRACK is a flexible framework that can evolve alongside organisational needs and priorities, rather than a fixed protocol.

8.1.1 Explainable Components

The roadmap has been designed to be self-explanatory and accessible, so it can be used without the creator's assistance. To this end, the structure incorporates several guiding elements. It opens with an introduction outlining the current challenges around circularity in aviation maintenance. This section establishes urgency and contextual relevance. It also provides a brief explanation of what a roadmap is and the rationale behind using predictive technology as a recurring case study throughout the document.

A fictional character named Jody is introduced at the beginning to further guide the reader. She acts as a narrator, helping readers to navigate key concepts. Jody introduces the four circularity typologies, explains how to read the roadmap and offers insights along the way. Her presence adds continuity, approachability and narrative cohesion to an otherwise structured document.

8.1.2 Strategic Roadmap

The strategic roadmap begins with a summary of the envisioned future state of circularity in aviation maintenance. This is followed by three coloured steps, each representing a distinct phase on the path towards this future state.

Each phase is built around a fixed structure.
A phase title and an indicative timeline
A clear goal to be achieved
A specific problem that the phase addresses
The knowledge areas emphasised in that phase
The core user values that are central to motivation and adoption

This structure supports value-driven decision-making. The 'problem to solve' is placed prominently in each phase to explain why the step matters. For instance, the initial phase, 'Sense-Making', addresses fundamental misconceptions about circularity. By making the rationale explicit, the roadmap provides stronger motivation for action and helps build internal alignment around early-stage cultural and conceptual development.

8.1.3 Tactical Roadmap

The tactical roadmap translates strategic phases into actionable dimensions and interventions. It introduces five recurring components that structure the roadmap horizontally. These represent the organisational layers and external factors that must evolve in tandem to embed circularity successfully.

Each of the five dimensions is described below:

(1) Organisational Awareness and Culture
This dimension traces how circularity becomes culturally embedded. It reflects the four typologies identified in the research and describes how shared values like ownership, language, and long-term thinking gain traction over time.

(2) Knowledge Development and Sharing
This dimension follows the structured development of knowledge areas, progressing from foundational and practical knowledge in Horizon 1, to strategic, institutional, behavioural and systems knowledge in Horizons 2 and 3. It also tracks the key learning interventions used in each phase, such as the Circular Economy Storybook, pilot projects and internal CE tooling.

(3) Predictive Technology as a Case Study
This dimension tracks how data systems evolve to support circular decision-making. It includes the development of relevant KPIs, dashboards for tracking progress, and the use of predictive technology. The emphasis is on making circularity measurable and actionable.

(4) Market Trends and Regulations
This dimension tracks relevant external developments that influence the roadmap's pace and priorities. These include regulatory frameworks such as the EU ETS, CRMA, ReFuelEU, ESPR and DPP, as well as emerging market trends in digitalisation, multi-fuel operations and advanced maintenance strategies.

(5) Circular Strategy Adoption
This dimension monitors the operational embedding of circularity in maintenance practice. It tracks the development of internal communication materials (e.g. intranet pages), the creation of circularity labels and templates, and the establishment of collaborative pilots and partnerships. The goal is to make circular thinking a visible and active part of daily maintenance work.

8.1.4 Concept in Use
The roadmap is intended as a long-term tool to guide learning, planning, and implementation. Internally, it will be used during project review sessions, onboarding processes, and cross-departmental planning meetings (Figure 25). Externally, the roadmap serves as a communication tool to illustrate NLR's vision and approach to circularity in maintenance. It encourages shared ownership and supports collaboration by providing a consistent, structured reference across stakeholder groups.

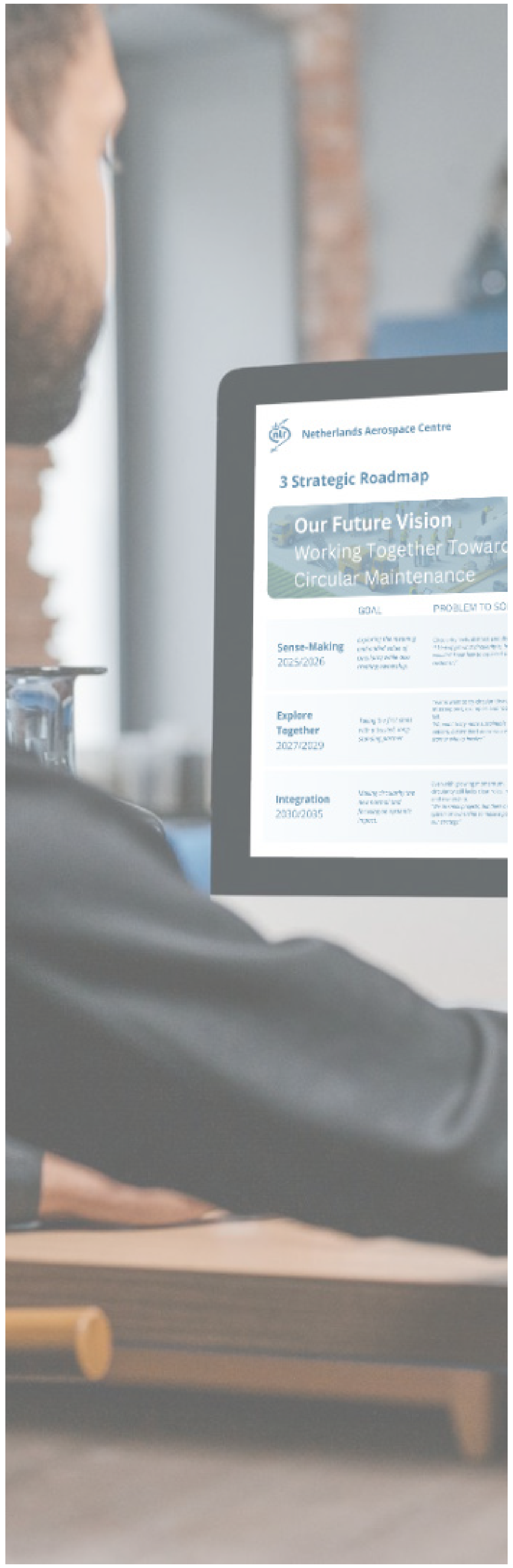
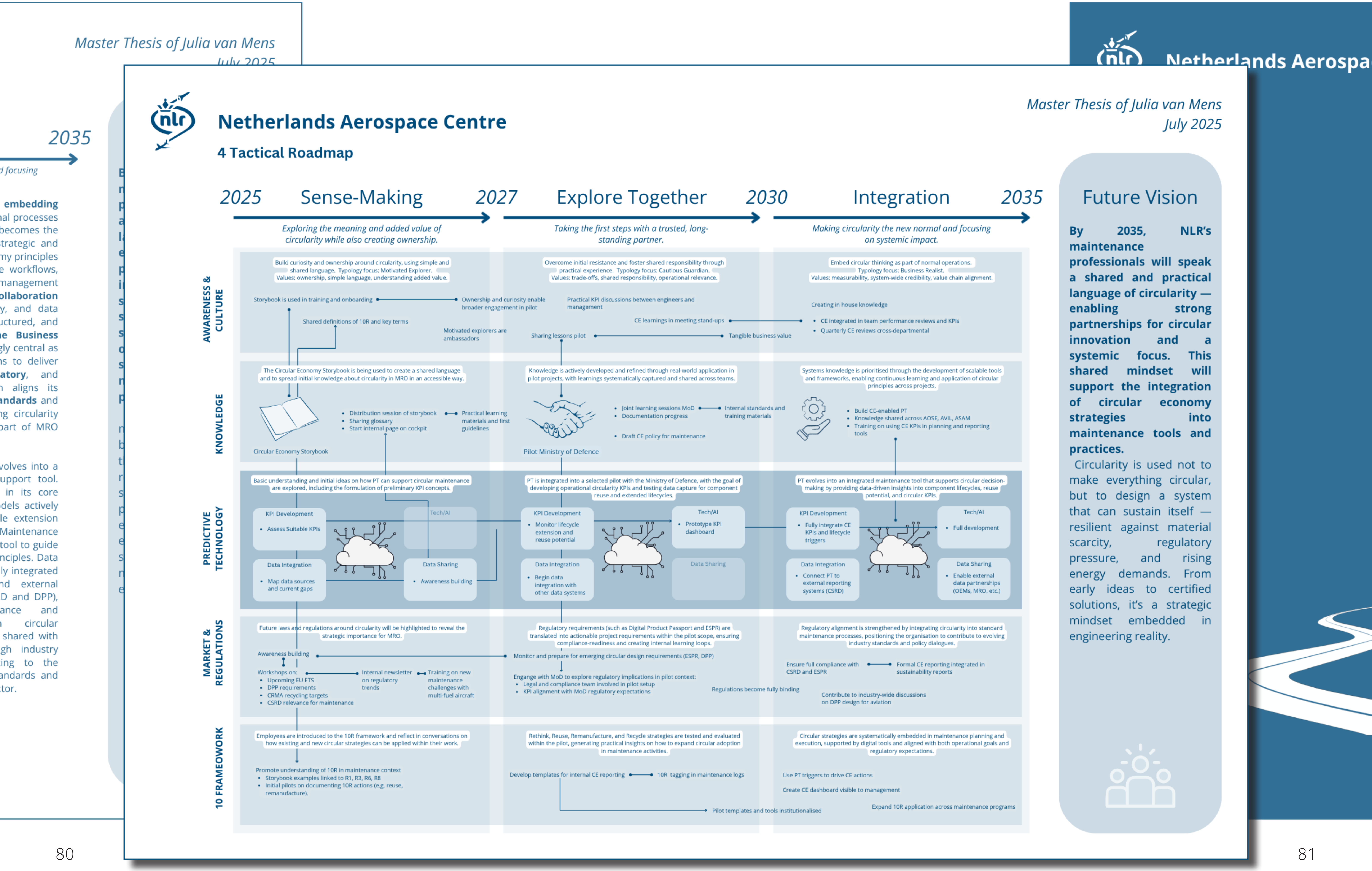


Figure 25. Mock-Ups of CE TRACK.

Figure 26. All the pages of CE TRACK.

Figure 27. Strategic Roadmap in detail.

Figure 28. Tactical Roadmap in detail.



SCOPE

8.2 SCOPE

SCOPE is a story-based learning tool designed to raise awareness of and encourage discussion about circularity in daily maintenance practices. Consisting of a series of short, accessible narratives, it reflects common challenges, misunderstandings and opportunities related to sustainability in the workplace.

By combining fictional scenarios with real-world relevance, SCOPE encourages professionals to consider their assumptions, roles, and routines. The engaging, accessible stories are suitable for onboarding sessions, team discussions and informal learning moments. SCOPE supports a cultural shift by making circularity relatable and encouraging open interpretation and discussion.

8.2.1 Storyline Approach

The storybook was developed to support learning by providing a narrative-based format with a low threshold. At its core lies the storyline approach, a pedagogical strategy which encourages active engagement and personal reflection (Greven & Letschert, 2006). Rather than transmitting abstract knowledge, the storyline method structures learning around familiar scenarios, inviting readers to explore new perspectives through concrete situations and relatable characters. This makes it particularly effective in professional settings, where learning is often tacit and embedded in day-to-day practice.

This format was chosen deliberately. In many engineering environments, professionals often have intuitive or fragmented ideas about sustainability, yet may find it difficult to articulate or develop these ideas further. The stories are designed to create moments of recognition, mirroring the reader's own experiences and offering small 'aha' moments that invite empathy or insight. A light tone, a touch of humour and short, engaging scenes help lower the threshold for participation and spark informal conversations.

8.2.2 The Stories

Each story is written as a short, accessible narrative. While fictional, they are grounded in realistic work dynamics. Themes include:

- How maintenance can act as an enabler of circularity
- How decision-making shifts when circular principles are applied
- The importance of process thinking and long-term system value
- Common misunderstandings between different roles, generations or professional perspectives
- Realistic barriers and potential opportunities when applying circular thinking in maintenance

Rather than providing answers, the stories aim to raise questions. They reflect common dilemmas and misunderstandings, helping teams explore how circular thinking might apply to their own context.

8.2.3 Concept In Use

The storybook is used in onboarding processes, internal awareness campaigns, and innovation-related workshops. It is available in both digital and printed form, and shared in communal spaces to encourage informal engagement (Figure 29). Selected stories are also used as conversation starters in team meetings, particularly when circularity is a relevant topic. This allows the stories to function as a light and accessible entry point into complex or unfamiliar ideas.

Figure 29. Mock-ups of SCOPE.

Introduction

In this circular economy storybook, multiple **5 to 10-minute stories** can be found on what circularity and the circular economy is, in an aviation maintenance context. This booklet is part of a bigger vision to move maintenance towards a circular direction and has a focus on **'Sense-Making'**. This booklet is especially made for you, the **motivated explorer**. You are intrinsically motivated to contribute to sustainablity, but often lack the right structure, shared language or support.

Sense-making means that around the topic of the circular economy, the focus is on creating **ownership**, a **simple and shared language** and a first **understanding of the added value** of the circular economy and its principles.

In this booklet you can find realistic stories, in which specific terms are used. It is almost like you learn while you do. Uhm read. It shows that **maintenance is a natural enabler** of the circular economy and that the circular economy principles can be helpful in **decision-making**. Especially since we want to work towards a **robust system** in the future.

Netherlands Aerospace Centre
Master thesis of Julia van Mens
July 2025

Story 1

10R | CE Terminology and Definitions | Jargon

Wait.. Does refurbish mean the same as overhaul?

The morning sun filtered through the glass walls of the NLR project room. Sanne placed two coffees on the table and dropped into a chair opposite Bram. Between them lay a freshly printed document: “10R Strategies for Circular Economy.”
Bram raised an eyebrow. “Ten of them? I thought there were maybe three.”
Sanne smiled. “Apparently, there are levels. Like a ladder—from smartest to least ideal.”
He leaned in, finger following the words as he read aloud: “Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, Recover.”
“Catchy,” he said. “Still sounds a bit... abstract.”
“Let’s see,” said Sanne, "Shall we just walk through it together?"

Refuse
Bram frowned. “So we just say no to buying stuff?”
“In aviation?” Sanne shrugged. “Maybe more like: don’t accept default assumptions. Like, why replace that part every six months if failure data doesn’t support it?”
“Fair point,” he nodded. “It’s more strategic refusal.”

Rethink
“This one’s familiar,” Sanne said. “Remember our digital job card project last year? That was rethink. Changing how we plan inspections—not just digitizing paper.”
“Yeah,” Bram agreed. “We turned four steps into one. Less handling, fewer errors. Rethink isn’t about throwing things out—it’s about seeing them differently.”

Figure 30. Stories of SCOPE.

Reduce
"Material use?" Bram guessed. "Or reducing interventions?"
"Both," said Sanne. "If you only open up what's needed, and do it at the right time—you're not just saving effort. You're avoiding wear-and-tear from over-maintenance."
He smiled. "That sounds like something you'd say in a report."

Reuse
"Now this one's trickier," Sanne admitted. "When do we trust a part enough to reuse it?"
"If the history's rock solid," Bram said. "And if we've scanned it, checked it, logged everything… then sure. But it needs transparency."
They both glanced at the RFID tags lying in a tray on the table.

Repair
"Bread and butter," Bram said. "We live here."
Sanne grinned. "Yes, but repair has become undervalued. Everyone wants new—because it's safer? Faster? But if we structure the repair process better, it can be both circular and reliable."

Refurbish
They paused.
"Okay," said Bram, "this is the one I always stumble on."
"Me too," said Sanne. "Is refurbish just a fancy word for overhaul?"
"Could be," he said. "In our world, overhaul means full teardown, clean-up, replacing wear parts—signed off and certified again."
"But refurbish might not go that far," she mused. "Maybe it's less about function, more about appearance. Or just restoring usability."
"So overhaul is… somewhere between refurbish and remanufacture?"
She nodded. "Possibly. But I'd love a side-by-side chart."

Remanufacture
"Now we're talking rebuild," Bram said. "New life. Same bones."
"With improvements," Sanne added. "Think: design tweaks, upgraded materials. Still certified, still safe, but smarter."

Repurpose
"Creative territory," she smiled. "Not easy in aviation."
"Still," said Bram, "I've seen decommissioned engine parts turned into training tools. That counts, right?"
"It does. We're just not used to calling it that."

Recycle
"Material recovery," Bram said. "Better than landfill. But honestly, if it reaches this point, we missed an opportunity earlier."
Sanne nodded. "It's the 'too late' option."

Recover
"Energy from waste," she read.
He frowned. "Do we even…?"
"Not really. But it's useful to know where the ladder ends."

They sat back, letting it sink in.
"It's funny," Sanne said. "We've been doing circular work for years. Just never called it that."
"And never saw the whole system," Bram added. "I used to think circularity was about recycling bins and green logos."

"But now it's about smarter choices," she said. "It's maintenance thinking—with a long-term lens."
He held up the page. "So next time someone asks me about circularity, I can say: we already do it—we're just getting better at naming it."

The End

Summary Explanation Box Circular Economy Terminology

In this story you read about …

Story 2

Responsibility | Decision-Making | Regulations | Internalizing Risks

Is That Really Our Responsibility?

Back in the project room, Nina reopened the draft report. It was solid, data-rich and technically watertight. But it was also clinical. It said nothing about circularity, nothing about the broader implications of automating inspections.

She glanced at a recent published article on cockpit on important sustainability regulations in aviation.

- 2025 – CSRD: Full ESG disclosure begins. All tooling and services must show environmental and social impact.
- 2026 – EU ETS: Aviation loses free emissions allowances. Carbon costs will directly affect maintenance economics.
- 2025 – CRMA: Raw material use must be documented, traceable, and justified — including for inspection equipment.
- ReFuelEU Aviation: Mandates SAF usage, but requires full chain transparency — from aircraft to tools that determine aircraft status.

Nina sat back. “We’ve been building GERDA for productivity. But in this context, not reporting on its impact could be seen as a blind spot. Or worse — a missed responsibility.”
Daan nodded. “Imagine a shop reusing more parts because GERDA catches repairable damage early enough. Or imagine inspection data supporting reuse certification — something KLM can actually report under CSRD.”
“And the tooling itself,” she added. “What sensors we use, where they come from — CRMA will demand we know that. Even the robot’s materials could be questioned.”

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July 2025

“And if GERDA allows airlines to reduce unscheduled removals,” Daan continued, “that’s fewer maintenance-related emissions. That’s EU ETS compliance support, indirectly.”
They looked at each other.
“We never planned for this,” he said. “But maybe we should start.”

They sat in silence for a moment. Outside, someone was powering down the adjacent test bench. The lights flickered, then stilled.
“I think we’ve been framing this the wrong way,” Nina said. “We always ask: what does the regulation require from us? But maybe we should ask: what kind of organisation do we want to be in this landscape?”
“You mean… taking responsibility before it’s assigned?”
“Yes,” she said. “Because when KLM submits their CSRD report in 2028, they’ll need to explain not just their emissions, but their entire supply chain logic—including the tools and decisions they base their maintenance strategy on.”
“And that includes us.”
She nodded. “We don’t manufacture airplanes. We don’t fly them. But we shape the systems that others rely on to prove they're sustainable.”
Daan stood up, drained the last of his coffee, and smiled.

“You know,” he said, “I used to think this was someone else’s job. Like—let compliance deal with it.”
Nina smiled back. “I used to think the same.”
He paused at the door. “Should we add a section to the report? About circularity potential?”
“I already started,” she said, clicking open a new page.
GERDA continued scanning in the background — quiet, precise, and now, part of something larger than just efficiency.

The End

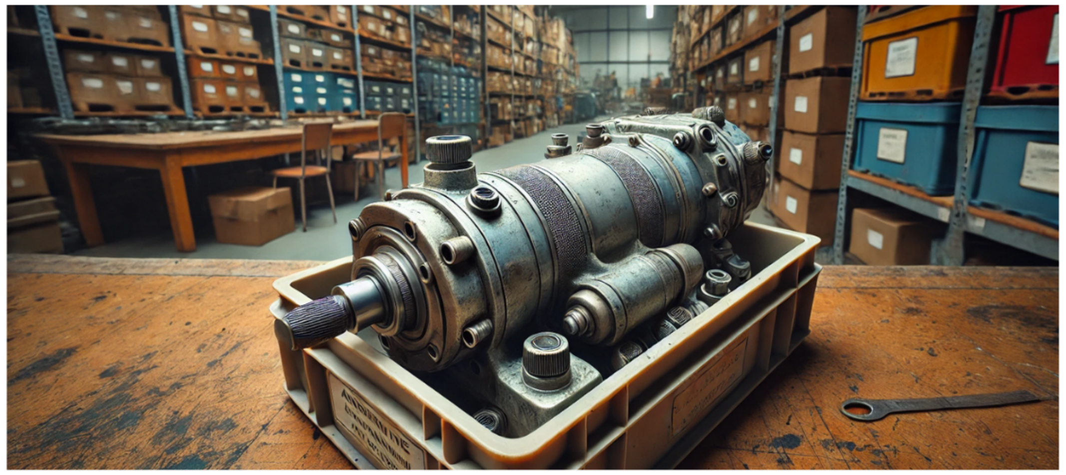
Summary Explanation Box Regulations and Responsibilities

In this story you read about ...

Story 3

Ministry of Defence | System & Process | Measurability | Component Level

The Last of Its Kind



A story told by a retired actuator

They pulled me out on a Wednesday. I remember the chill of the hangar floor, the hiss of hydraulic fluid, and the quiet muttering of the tech who tagged me.
“Out of spec,” he said. “End of life.”
That’s what the red tag means: your mission’s over. You don’t go back in. You don’t get repaired. You get stored, stripped, or scrapped.
For thirty-seven years I did my job. Left flap, outer actuator. You wouldn't notice me unless I failed — which I didn’t. I extended. I retracted. I hissed. I held. I flew.
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Then, the thresholds changed. Not because I broke, but because the rules moved. And suddenly, I was obsolete.

I was shelved.
Crate 28, Section G, under a retired fuel pump and a disassembled radome scanner. I listened to stories from parts that had seen wars, monsoons, desert heat. We swapped tales like old pilots in a bar. And we waited.
But I wasn’t ready to be forgotten.

One day, someone opened the crate. She wore a navy-blue jacket with a patch that said NLR. Her name was Eva.
She ran her scanner over my serial. Frowned. Checked the tag. Frowned again.
“Still under fatigue threshold,” she said.
“But no traceability after 2012,” said the technician.

“Doesn’t mean it’s useless,” Eva replied.
Interesting. Most people see red tags and walk away. But she didn’t. She saw potential.

The next day, I was on a bench. Cleaned, scanned, tested. They didn’t just check if I moved. They looked at how I moved. The delay, the smoothness, the thermal response. They used lasers. I felt important again.
Then came Tom — a Defence guy. Broad shoulders. Greasy gloves. He looked at me like I was part of the family.
“Actuator like this?” he said. “They don’t make ’em like this anymore.”
He and Eva talked. A lot. About reuse protocols. Field certification. Something called the Circular Readiness Framework.
“It’s not about the part,” Eva said. “It’s about the process.”
“We need systems,” she added, “not heroic fixes.”
Still, I liked Tom. He wasn’t afraid of heroic fixes.

They didn’t throw me away.
Instead, they made me part of a pilot. Not a flight test, but a test of something bigger: could we build a process where parts like me don’t get wasted just because the system isn’t flexible enough?
I got a second tag — blue this time. I was recertified for limited use in non-critical systems. I would fly again — maybe not at 35,000 feet, but in a simulator rig, or a test bench. Still moving. Still useful.
And this time, every move would be logged.
I’m still just an actuator. I extend. I retract.
But now, I’m also a symbol. Not because I’m special — but because I’m not. I’m ordinary. Replaceable.
And still — I was worth saving.

Epilogue (from Eva’s notes)
The pilot showed that legacy components, when properly tested and certified, can extend asset life and reduce waste. This isn’t about nostalgia. It’s about designing systems that recognize value — even when it comes from the past.

The End

Summary Explanation Box Second Life of Components

In this story you read about ...

9

DISCUSSION AND CONCLUSION

This chapter reflects on the project's findings and design outcomes. It considers the areas in which meaningful progress has been made, the challenges that remain and how these insights can inform the future development of circular knowledge within aviation maintenance.

9.1 Discussion

9.1.1 Interpreting Results

This project examined ways in which knowledge of the circular economy can be developed and embedded in the field of aviation maintenance. The findings generally support the theoretical framework, which suggests that the adoption of circularity is influenced by factors at micro, meso, and macro levels. However, the research revealed that the micro level, encompassing culture, language and daily routines, plays an even more pivotal role than anticipated.

Although literature often emphasises the importance of regulation, technology and cross-sector coordination, this study indicates that the adoption of circularity frequently begins with minor shifts in mindset and operational framing. These early signals are essential for later scaling up. Without a foundational understanding and a sense of ownership among professionals, broader strategic ambitions are unlikely to take root effectively. While the layered framework remains useful, a gradual approach starting from within the organisation appears more practical and realistic.

The findings also challenge the idea that a lack of tools or innovation is the main obstacle. Many professionals expressed curiosity and interest in circular practices. However, this topic is not always visible in daily work and there are no clear entry points for engagement. This mirrors literature findings on the gap between abstract sustainability strategies and their translation into practice. There is a need not only for better tools, but also for improved framing that aligns with operational realities.

The roadmap and storybook were developed to address this. Participants found them helpful in initiating discussion and raising awareness, but they also noted that the terminology and structure could still be improved. This reinforces earlier insights about the difficulty of communicating circularity in an accessible way. It also highlights the potential of design methods to bridge the gap between strategic intent and professional practice.

Another insight concerns the role of maintenance itself. Although it is central to reuse, repair and extending the lifecycle, maintenance is not always recognised as a strategic enabler of circularity. The aim of this project was to strengthen this perspective, and initial feedback suggests that reframing maintenance in this way offers clear potential for future development.

9.1.2 Implications

The outcomes of this project provide guidance on future circularity efforts in aviation maintenance.

Firstly, the results emphasise that circular strategies are most effective when based on existing values, such as safety, efficiency and performance. If circularity is introduced only through high-level narratives or general sustainability messaging, there is a risk that it will be perceived as abstract or disconnected. Aligning circularity with operational priorities increases the likelihood of engagement and long-term adoption.

Secondly, although change is needed at all levels, particular attention should be given to the micro level. Organisational culture, shared language and internal coordination were identified as essential foundations. Without a common understanding within teams, larger ambitions relating to regulation or supply chain collaboration are less likely to succeed. Therefore, strengthening internal clarity and ownership is a crucial starting point.

Thirdly, the findings suggest that maintenance could play a more strategic role in enabling circularity. By integrating circular thinking into planning, diagnostics and resource management, maintenance professionals can contribute directly to more sustainable outcomes. Realising this potential requires institutional support and the explicit recognition of maintenance as a site of innovation.

The project also reinforces the idea that human and behavioural factors must be part of any successful transition. Professionals emphasised the importance of practical relevance, clarity, and a sense of involvement. Tools and strategies will only be effective if they resonate with people's daily work and identities. Therefore, knowledge-building efforts must be embedded in existing routines and framed in accessible ways.

Finally, the research suggests that a more coordinated internal approach would have a broader impact. NLR has already taken steps towards integrating sustainability across its programmes. Further alignment, shared language and cross-role collaboration, building on this momentum, can strengthen NLR's ability to meet external expectations and respond to future challenges. Rather than indicating a lack of progress, the findings highlight the potential to consolidate existing initiatives and establish a long-term position as a leader in circular aviation maintenance.

9.2 Limitations

This project explores how knowledge of the CE can be developed and applied in a maintenance context. However, a few limitations should be acknowledged.

Firstly, the scope was intentionally limited to one department as a starting point for exploration. While the outcomes are promising, they do not yet reflect the full range of expertise or activities across the organisation as a whole. Future work could expand this focus to include more departments to strengthen alignment and exchange further.

Secondly, the research approach was qualitative and exploratory. The findings are based on in-depth interviews and co-creation activities, which provide depth but not statistical generalisability. The roadmap and storybook should be viewed as adaptable frameworks rather than fixed models.

Thirdly, the project emphasised cultural and knowledge development over technical innovation. Although the organisation has a core strength in technical expertise, this project focused on creating the conditions in which circular thinking can be understood, discussed and applied. Further work could explore how this thinking can be translated into engineering or system-level solutions.

Finally, while the roadmap builds on current trends, the aviation sector is dynamic. Changes in regulation, technology, or market demands could influence the future direction of circularity initiatives. Ongoing reflection and updates will be required to ensure continued relevance.

Despite these limitations, the project provides a solid basis for future work. It provides tools and structures that can support learning, collaboration, and circular innovation across teams.

9.3 Conclusion

The aim of this project was to explore how NLR could develop and apply knowledge of the circular economy in order to support more circular maintenance practices. This goal was addressed through research and design, resulting in two main outputs: a roadmap, CE TRACK, and SCOPE, a fictional storybook.

The former outlines a phased approach to building knowledge over time, while the latter supports informal learning and cultural engagement. Together, these outputs provide a practical basis for incorporating circular thinking into daily practice and long-term planning.

The first research sub-question examined current understandings of circularity in maintenance. The findings show that, although circularity is recognised as important, it has not yet been embedded in daily decision-making processes. The topic is often framed in terms of efficiency or technical optimisation, and there is a clear need for a shared vocabulary and sense of ownership across roles.

The second sub-question focused on the types of knowledge required to support circularity. Six knowledge areas were identified, with foundational and practical knowledge being deemed the most urgent. Gaps were noted in strategic thinking, systems understanding, and cross-team collaboration. Strengthening internal alignment and encouraging exchange between departments will be essential for closing these gaps.

The third sub-question explored how circular knowledge can be developed and implemented in practice. A phased approach was considered both realistic and necessary. The roadmap will provide structure and direction, and the storybook will facilitate dialogue. However, successful integration will require leadership support, stronger collaboration across departments, and alignment with existing workflows.

In summary, the project shows that knowledge of the circular economy can be developed through structured, creative approaches tailored to the organisation's context. With further refinement and active implementation, these tools could establish NLR as a contributor to circular innovation in aviation maintenance.

9.4 Recommendations

This section outlines recommendations for the further development and implementation of the final two deliverables, CE TRACK and SCOPE, as well as broader strategic considerations to support circularity within NLR's aviation maintenance activities.

9.4.1 Recommendations for the Deliverables: CE TRACK and SCOPE

Together, CE TRACK and SCOPE form the basis for internal learning and cross-functional dialogue on circularity. Their long-term value depends on careful implementation and ongoing development. Both tools should therefore remain flexible and modular. Editable templates will enable teams to allocate responsibilities, track progress and customise content to align with evolving workflows. Initial workshops or onboarding sessions are recommended to accompany implementation and foster relevance and shared ownership.

During validation, participants appreciated the accessible format and engaging tone of the tools. However, some noted that abstract language or rigid framing could present challenges. Key terms, particularly those related to typologies and roadmap phases, should be clarified. Typologies should be presented as dynamic ways of thinking, rather than as static identities. It is important to make clear that all perspectives are relevant throughout each phase. Emphasising collective engagement will support the inclusive and effective use of the tools.

The example of predictive technology should clearly be presented as a hypothetical case rather than a technical output of this project. While its inclusion illustrates how digital tools could support circularity, further research is needed to identify relevant indicators, assess data availability, and determine how such technologies can be adapted for circular purposes. Future versions of CE TRACK could benefit from more detailed guidance on exploring this transformation process within specific projects.

In order to remain relevant, CE TRACK and SCOPE must be kept up to date. A small coordination group could update the content to reflect new pilot outcomes, strategic developments, or regulatory shifts. The storybook (SCOPE) is particularly well-suited to supporting informal learning and could be used internally or externally to introduce the concept of circularity in an accessible way. Further reinforcing their impact could be achieved by strengthening the connection between SCOPE and the roadmap, for example by linking individual stories to specific phases or challenges in CE TRACK.

9.4.2 Broader Organisational Recommendations for NLR

At an organisational level, there is an opportunity to strengthen the coordination and mutual reinforcement of existing sustainability efforts. While several departments already work on related topics, a clearer shared vision and increased collaboration could amplify the impact of these efforts. CE TRACK could support this alignment, particularly if project leads and managers were encouraged to consider circular opportunities in the early stages of project development.

In terms of external positioning, maintenance could be presented more prominently as a core enabler of circular aviation. Highlighting internal knowledge and pilot efforts through targeted communication, demonstrations, or cross-departmental showcases could foster engagement across the sector and create opportunities for new partnerships.

The validation also underscored the value of experimentation. Circular strategies often remain high-level in the early stages. Structured pilot projects could explore topics such as lifecycle prediction, component reuse, and cross-departmental coordination. These pilots would also help to clarify responsibilities and collaboration structures. While CE TRACK outlines key actions, further development could include concrete examples of task distribution and interaction between different roles.

Planning across time horizons also warrants attention. While the ten-year scope of CE TRACK supports long-term thinking, breaking this down into more specific time segments could help to translate strategy into short-term actions. Aligning these segments with policy goals, such as the Climate Neutral 2050 target or Fit for 55, could support strategic coherence and increase momentum.

NLR is well placed to help establish new standards for circular maintenance. Rather than focusing on individual tools, the organisation could establish best practices and knowledge frameworks to guide future development in this field. This would require closer alignment with regulatory frameworks, market needs, and internal capabilities.

In addition to strengthening internal alignment and visibility, NLR could explore more actively how specific circular economy trends may apply to aviation maintenance. Frameworks such as the 10R model or the use of material passports present concrete starting points for experimentation. For instance, initiating small-scale pilots that explore product-level circular opportunities, or using the 10R framework as a lens during early project stages, could help translate abstract concepts into practical insights.

Furthermore, there is value in identifying existing research agendas at both national and European levels. NLR may wish to position itself more strategically in response to these agendas, contributing to broader sectoral goals while also shaping the development of circular standards in MRO. Taking on this role would not only demonstrate leadership but also create pathways for future collaborations and innovation.

9.5 Contributions

9.5.1 Theoretical Contributions

This project makes several contributions to the academic understanding of circularity within the field of aviation maintenance.

First, it extends existing theoretical frameworks by showing that the adoption of circularity depends on a combination of technical, organisational and behavioural factors. The research highlights how these factors influence each other over time, and how they can enable or hinder progress. The inclusion of cultural aspects such as mindset, motivation and shared language confirms that circularity is not only a technical challenge but also a social and institutional one.

Second, the project offers new insights into how the 10R framework can be applied within a complex and highly regulated setting. The findings illustrate which circular strategies are already in use, which show promise, and which face practical or systemic barriers. This adds nuance to existing theories that often assume a more open or flexible implementation environment.
Third, the project introduces a practical knowledge development framework that suggests pacing and sequencing are critical to long-term adoption. It shows that organisations benefit from phased approaches when building new capabilities, especially when working with emerging or unfamiliar concepts.

Finally, the theoretical framework developed during the project is supported by empirical findings. This combination of design and data strengthens its validity and demonstrates that circular strategies can be shaped through structured reflection and applied research. The project also shows that theoretical concepts can serve as a foundation for designing new tools and processes that support sustainable transformation.

9.5.2 Practical Contributions

This project also makes a number of practical contributions that are directly relevant to the aviation maintenance sector and to NLR's internal strategy.

The Roadmap and Storybook provide concrete tools to support internal learning and collaboration. Both were developed to fit the needs of professionals working in maintenance, engineering and project planning. They are designed to open conversations about circularity, help create a shared vocabulary and support gradual knowledge building across teams.

The project also reframes the role of MRO as a key contributor to circular aviation. Rather than viewing maintenance as a reactive process, the project shows how it can actively support value retention, component reuse and life extension. This perspective strengthens the strategic importance of maintenance in sustainability discussions.

By applying the 10R framework in an aviation setting, the project highlights which circular strategies are already feasible and where further development is needed. It also demonstrates how a phased approach to knowledge creation can help organisations move forward, even in contexts that are constrained by safety standards and legacy systems.

Finally, the project shows how design methods such as storytelling and roadmapping can help organisations deal with complex transitions. These formats made abstract ideas more relatable, supported engagement among technical professionals and helped participants reflect on their own role in change processes. The result is a set of tools that can guide both immediate action and long-term development in circular aviation.

9.6 Personal Reflection

This project has been a valuable learning experience, both professionally and personally. I have gained new insights into how change occurs in highly regulated and technically complex sectors such as aviation. One of the key things I learned is that sustainability transitions require time and must be introduced carefully. In sectors where safety and compliance are paramount, pushing for change in a provocative manner often provokes resistance. A better approach is to use language and examples that fit the world of the professionals you are speaking to. Many people were open to learning about new developments as long as they were introduced in a way that respected their expertise and day-to-day realities.

Another thing I noticed was the strong culture of collaboration in the aviation sector. Many sustainability efforts are carried out in partnerships across different organisations. This is something that could be adopted by other sectors. At the same time, however, I also became aware that collaboration does not automatically lead to real impact. Some projects seem to exist mainly to demonstrate activity without actually achieving much in practice.

Coming into this project, I was highly motivated to promote sustainability. Initially, it was therefore frustrating to see that not everyone shared the same sense of urgency. It took me a while to realise that this is simply part of working in a large, diverse organisation. Not every individual or team will be equally committed to sustainability goals. I learned to focus on those who were curious and open to discussion instead of being discouraged by more sceptical or hesitant voices.

One of the most important insights I have gained from this project is that cultural change in large organisations is, by its very nature, slow. With over 800 employees, it is unrealistic to expect new ideas to spread quickly or evenly. Change often starts in informal networks instead, and ideas take time to grow. I have learned to appreciate this slower, curiosity-driven approach to innovation. It is more effective to present sustainability as an opportunity than as an obligation. Allowing people to explore sustainability in ways that align with their interests and skills has proven to be a much more productive approach.

Over the course of the project, I also developed new academic and professional skills. I developed a theoretical framework from scratch and applied it to a real-world context. If I had had more time, I would have liked to delve deeper into how sustainability could be made measurable. I would have explored KPIs more thoroughly and organised additional focus sessions within the organisation. It would also have been valuable to speak with more people in the industry to understand the demand for circular economy approaches. I would also have liked to talk to regulatory bodies to gain insight into what standardisation might be required and their vision for achieving a carbon-neutral aviation sector by 2050.

Personally, I learnt a lot from this thesis project. I had to work independently for six months, make my own decisions and develop a basic understanding of a completely new sector. I also had to manage the relationship with the client, which taught me a great deal about communication and managing expectations. I improved slightly in my ability to ask for help when needed, although I still have room for improvement in this area.

Overall, this thesis project has given me more confidence in my ability to handle complex challenges. It showed me that, even in unfamiliar and demanding situations, it is possible to contribute meaningfully by staying curious, open and flexible.

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APPENDIX

APPENDIX A: LDE for Sustainability Thesis Lab Green Skies

GREEN SKIES

LDE THESIS LAB

INTERDISCIPLINARY THESIS LAB 2024-2025

Universiteit Leiden
TUDelft
Erasmus Universiteit Rotterdam

Green Skies Thesis Lab

In 2025, a group of nine Masters students and five Bachelor students from Leiden University, Erasmus University Rotterdam, Delft University of Technology and InHolland University of Applied Sciences joined the Green Skies Thesis Lab. The Lab was organized by the Leiden-Delft-Erasmus Centre for Sustainability together with three case holders in the aerospace sector: Collins aerospace, AETHOS and NLR. During five months, the students conducted research and confronted their findings during interdisciplinary sessions to answer the challenge set by the case holders: "How can design, technological innovation, new business models and legislation help the aerospace industry reduce its impact on the environment?". This catalogue summarizes their results and recommendations.

Case holders

AETHOS is a foundation that stands for sustainable solutions for the end-of-life of aircrafts. Aethos supports research into the recycling of aircraft materials. It also supports the professional network that is currently tackling the challenge of recycling parts of aircraft and makes companies aware of the latest research outcomes.

NLR is the connecting link between science, industry and government for the aerospace sector. It supports the sector by developing and applying advanced technologies for innovative products and applications. NLR aims to make aerospace more sustainable, safer, more efficient and more effective.

COLLINS AEROSPACE is one of the world's largest suppliers of aerospace and defense products. From aircraft nose to tail and from the battlespace to deep space, Collins collaborates with customers and partners across markets and disciplines to develop pioneering technologies for the sector.

LDE Centre for Sustainability

LDE Centre for Sustainability aims to accelerate a deeper and broader understanding of sustainability and stimulates collaboration between LDE-universities, applied universities, industries, governments an citizens initiatives. The Centre empowers students, researchers and professionals to develop new knowledge and skills for the transition towards a sustainable society.

Executive summary

The diverse focus areas of the Green Skies Lab within the field of sustainable aviation included feasibility of sustainability aviation fuel (SAF), airport sustainability, importance of maintenance as an enabler for the circular economy, loss and damage financing through the aviation sector, legitimacy of sustainability efforts and the end-of-life solutions for aircraft.

The collaborative effort involved stakeholder engagement through roundtable discussions, field visits, panel discussions, and expert consultations. Through these engaging methods, the research output enabled key insights for stimulating sustainable growth of the industry, increased customer involvement, improved methods of measuring sustainability, new innovations, and the economic viability of proposed reforms and changes. The combined research output from the participants provided in this catalogue is linked to these focus areas.

The eventual research outcomes suggest the need for openness within the industry and greater need for collaboration between stakeholders. There also needs to be more emphasis on academic engagement by the industry. Greater accountability and transparency are urged to ensure outcomes which are truly sustainable. Organizations like the Centre for Sustainability can become a crucial network to realize the sustainability goals of aviation. There is great importance in inter-disciplinary and cross-industrial collaboration to achieve sustainable goals in an industry that is difficult to decarbonize.

Green Skies Lab Program

During five months, from February to July 2025, the students of the Green Skies Lab participated to 11 interactive sessions with the Lab case holders and other industry professionals in the aviation sector. Via workshops, lectures and visits, the students gained insights into the real-world challenges of making aviation more sustainable. The Lab Program also provided a platform for inter and transdisciplinary exchanges between the students, during which connections between the various research topics and disciplines were sought. This progressively led to the formulation of the combined recommendations for the sector provided in this catalogue.

Workshops

The Thesis Lab commenced on February 5, 2025, with an introductory session attended by students, coordinators, and case holders from the various LDE Thesis Labs. The students then took part in interactive team-building activities and learned about their individual Lab's objectives and stakeholder expectations. The day ended with a workshop using the EnROADS climate simulator, during which separate teams, playing the roles of relevant stakeholders, considered several systemic climate solutions that would allow a temperature increase of only 1.5 degrees by 2100.

The second plenary pressure-cooker session was held on April 2, utilizing the LEGO SERIOUS PLAY methodology to creatively analyze sustainability challenges in the aviation sector. The students collaboratively built the envisioned future for aviation and identified potential innovations in the industry (as seen in the photos). The workshop concluded with reflections on shared insights and the formulation of questions for subsequent Round Table discussions.

During a science communication workshop, the students practiced audience-centric messaging and effective dissemination of scientific findings. At the last pre-final presentation event, the students gathered with other labs to discuss their final results and integrate them into a cohesive presentation. These workshops facilitated the organization of the final event with industry stakeholders, during which the students presented the final product of the Green Skies Lab.

Interactive Sessions

One of the most interesting aspects of the Lab for the students was the opportunity to participate in interactive sessions with the Lab case holders and other industry experts. These sessions encouraged dialogue between students and professionals, providing valuable opportunities to learn from their experiences and perspectives.

During the Lab kick-off, five core research questions were defined with the active input of the Lab case holders. Their involvement helped to refine and expand the scope of the

questions, making them more meaningful and relevant. Later, halfway through the Lab program, a Round Table was organized with the Lab case holders and external stakeholders, offered insights into how the case holders' perspectives aligned with wider industry developments. Topics covered included Sustainable Aviation Fuel (SAF), responsibility within the sector, certification, reuse and repair, and the role of multiple fuel types in the future of aviation.

Other sessions focused on broader themes, such as the future of aviation, degrowth, and legal sustainability issues. As an original equipment manufacturer, Airbus presented its outlook on aviation growth, including an expected global demand for 43,420 new passenger and freighter aircraft over the next ten years. The company linked this growth to rising GDP per capita, increasing passenger numbers, and the delayed retirement of older aircraft due to the impact of the pandemic. A lecture on degrowth from a TU Delft researcher sparked critical discussion on whether sustainable aviation can coexist with continued economic growth. These sessions, including the one on law and regulations from the International Institute of Air and Space Law in Leiden, added depth, context, and credibility to the theses developed by the students in the Lab and to the insights they shared.

Site Visits

During the Lab, the students visited several aerospace facilities, which improved their understanding of the connection between theory, research, and real-world applications. These visits brought the sector to life, offering an up-close view of the tools, technologies, and people shaping the future of aviation.

At the TU Delft Aerospace Structures and Materials lab, the students observed a wide range of tools and testing machines. It was inspiring for them to see fellow students working on their theses and projects. The rocket development and the small hydrogen-powered aircraft were particularly fascinating. These projects demonstrated how students contribute directly to sustainable innovation in aviation.

The students also visited SAM XL (Smart Advanced Manufacturing XL), an advanced manufacturing center focused on automating production processes in the aerospace industry. The visit demonstrated how robotics and smart technologies are being developed for large-scale industrial use. The facility was filled with high-tech machines and industrial robots, many of which were in an advanced stage of development. SAM XL connects TU Delft faculties with the manufacturing industry and suppliers. It develops software and hardware to enhance the intelligence, flexibility, and connectivity of industrial robots. The center also provides training for students and professionals to enhance their digital and technical abilities.

The visit to AELS (Aircraft End-of-Life Solutions), an aircraft recycling company in the Netherlands, offered the students a unique perspective on the aviation sector. During this visit, they examined what happens when aircraft are taken out of service. The

Interview Guide - Circular Takeoff

Project: The Circular Takeoff for NLR: Reimagining Maintenance Repair and Overhaul Management
Researcher: Julia van Mens (TU Delft)

Main research question

What knowledge framework for managing CE principles does NLR need in its services to support MRO customers in a green aviation future?

Sub questions

1. How does the current knowledge framework for current services looks like?
2. How does NLR currently support MRO customers regarding sustainability?
3. What are the key CE principles relevant to aviation aviation (MRO), and how are they currently implemented in the sector?
4. What CE-related challenges do MRO customers face, and how can NLR structure its knowledge to support them?
5. (What does a "green aviation future" mean for the MRO sector, (and how can NLR align its strategy accordingly?)

Checklist for start

- Private room
- Printed consent form + pen
- Printed questions
- Audio recording device
- Laptop for notes
- Snacks and drinks

Introductory Text

- Thank you for your time!
- Signing the consent form and asking permission to record audio
    - Risk of the study
    - Minimize the risk
        - Anonymization process. This involves the removal of any personal identifiers such as names, contact information, or other details
        - Original audio recordings of interviews will be erased immediately after transcription
        - participation is entirely voluntary, and you can withdraw or interrupt at any time.
- Start audio recording
- This interview will be semi-structured. This means it is an open conversation, but it will be at the base of some main questions.
- There are no wrong or right answers
- → "This research started out, since there is a global target to become net zero in 2050. And all sectors should work towards this goal. One of the strategies or ways to get there

is the circular economy. Within the circular economy it is important to move from a linear perspective, to a circular one, where we hopefully never use non-renewable energy anymore and where we reduce and eliminate waste. Within aviation there are several horses we are betting on, for instance hydrogen and SAF's. Sustainable Aviation Fuels. But, other processes might also need to change. That is where Arjan Derks also saw some similarities between MRO, so the maintenance of aircrafts, and repairing. Which is one of the strategies behind the circular economy.

- So my job is to investigate what the future is of MRO within sustainability and circularity.
- During this interview I will use circularity and sustainability a bit mixed. This is because sustainability is a more broadly adopted term, and some people do not understand circulraity yet. But you can specify always towards circularity if you are open for that.
- The structure of todays interview:
    - **Micro-level (company)**: Implementation of CE principles within MRO organizations, focusing on internal processes, maintenance strategies, and business model innovation.
    - **Meso Level (industry)**: Collaboration across the aviation sector, including supply chain integration, cross-industry partnerships and shared circular infrastructure.
    - **Macro Level (regulation & policy)**: The role of governments, regulatory frameworks, and international policies in shaping the adoption of circular strategies in aviation MRO.
- You can interrupt at any time if you wish.
- Do you have any questions or comments on this?
- Make clear how much time it will take → until what time do we have?
- Good to go!

Theme 1: Personal information

1. Non circular:
    a. Can you describe your role within the organization?
    b. For me to get a better understanding of what you do, could you give 1 example of a recent client or a project and walk me through the steps of it? From start to finish.
2. Circular:
    a. What is your understanding of the circular economy?
3. What is your connection to MRO/ASAM?

Theme 2: Micro level: Company

1. What role does sustainability currently play in your work or decision-making?
2. What are the biggest challenges in improving efficiency, reducing waste, or optimizing resources in Aviation (MRO)?
3. Are there any areas where reusing materials, extending product life, or reducing waste could make sense for your operations? Why or why not?
4. What are factors that influence decision-making on sustainability?

Theme 3: Meso level: Industry

1. How do you collaborate with other companies and organisations on sustainability or efficiency projects?
2. Are there challenges in sharing data, resources, or best practices between companies and organisations?
3. Do you see opportunities for joint efforts (e.g., shared logistics, component refurbishment) to improve sustainability in Aviation MRO?
4. Are there currently any interesting collaborations around the topic of sustainability in your work? Which ones would you highlight as the most important and valuable?

Theme 4: Macro level: Policy and Regulation

1. How do policies, regulations and safety now shape your work?
2. Are there financial incentives or business drivers that could make sustainability or circular practices more attractive?
3. What do you think will drive the biggest change in Aviation (MRO) over the next 10 years; new technology, regulation, customer demand, or something else?

Theory (introduction section of literature review was send before interview)

1. Looking at this 10R framework, which strategies do you think are already happening in Aviation (MRO), even if they aren't labeled as circular?
2. Based on this 10R framework, if (Aviation) MRO were to experiment with one of these strategies, what would be a good starting point, and what would be needed to make it work?

Final

If NLR could lead a major sustainability initiative in aviation, what do you think it should focus on? Could you explain this within an NLR broad perspective, but maybe also for MRO specific?

Checklist for closure

- Do we miss important topics?
- **Do you have feedback for me? What did you think of the interview?**
- Do you have other people that would be interesting for me to talk to?
- Is there any follow-up after the interview?
- Thanking the participant
- !!! Hand on the door phenomenon!!!

List of generic probes (optional)

- Nodding
- 'Yes'
- 'That is interesting' - when you want participants to really talk more about this specific topic

APPENDIX C: Consent Form

You are being invited to participate in a research study titled “The Circular Takeoff for NLR: Reimagining Maintenance, Repair and Overhaul Maintenance Management”. This study is being done by Julia van Mens from the TU Delft as part of a graduation thesis in cooperation with the Netherlands Aerospace Centre (NLR).

The purpose of this research study, which will take approximately 60 minutes to complete, is to examine the current state of knowledge regarding the implementation of circular economy principles within NLR and how this knowledge can be applied to help Dutch MRO customers. The data will be used for the final thesis report and presentation of the corresponding researcher, after which the report will be available in the repository of the TU Delft and the archive of NLR. We will ask you to participate in a conversation using a semi-structured interview approach to answer questions on the topics of circular economy and maintenance, repair and overhaul. In addition, a knowledge implementation framework developed during this thesis will be discussed and feedback and input will be requested.

As with any online activity, there is always a risk of data breach. To the best of our ability, your responses in this study will be kept confidential and anonymized to reduce the risk of re-identification.

- Anonymization is a priority in this study. No personally identifiable information (PII), such as names, will be linked to responses.
- Audio recordings will be used for transcription purposes only and will be permanently deleted after transcription.
- All responses will be anonymized during analysis, and results will be reported in an aggregated format to prevent indirect identification.
- Data will be securely stored exclusively on the private OneDrive TU Delft workspace of the corresponding researcher, with access strictly limited to the supervisory team.
- Any direct quotes will be anonymized and generalized before inclusion in publications. If there is a potential risk of identification, participants will be given the opportunity to review and approve before inclusion.

As part of TU Delft's commitment to Open Science, fully anonymized research data may be archived in the TU Delft repository for future academic research. However, no personally identifiable or commercially sensitive information will be included in publicly available datasets.

Your participation in this study is completely voluntary and you may withdraw at any time up to two weeks after your interview by contacting the researcher. You are free to skip any questions if you do not wish to answer them. After the specified withdrawal period, anonymized data that has already been included in the analysis cannot be removed.

Julia van Mens

(Corresponding Researcher)

Shahrokh Nikou

(Responsible Researcher)

PLEASE TICK THE APPROPRIATE BOXES	Yes	No
A: GENERAL AGREEMENT – RESEARCH GOALS, PARTICPANT TASKS AND VOLUNTARY PARTICIPATION		
1. I have read and understood the study information dated 01/03/2025, or it has been read to me. I have been able to ask questions about the study and my questions have been answered to my satisfaction.	☐	☐
2. I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions and I can withdraw from the study at any time, without having to give a reason.	☐	☐
3. I understand that taking part in the study involves: • This research captures information through semi-structured interviews with participants from the Netherlands Aerospace Centre (NLR) and other stakeholders in the Dutch MRO sector. Interviews will be audio-recorded to ensure accuracy and will be transcribed into text. No video recordings will be made. • The audio recordings will be used solely for transcription purposes and will be permanently deleted after transcription is completed. Transcripts will be fully anonymized, removing any personally identifiable information (PII) such as names, job titles, or company-specific references. • Notes may also be taken during the interviews to support analysis. All collected data will be securely stored on the private OneDrive TU Delft workspace of the corresponding researcher. Findings will be presented in an aggregated format to minimize the risk of re-identification.	☐	☐
4. I understand that the study will end on the 14th of July, the day of the presentation of the thesis.	☐	☐
B: POTENTIAL RISKS OF PARTICIPATING (INCLUDING DATA PROTECTION)		
5. I understand that taking part in the study involves the following risks: • Potential professional discomfort – Participants may feel uncomfortable discussing their organization’s knowledge gaps or challenges related to circular economy implementation. • Cognitive effort and time commitment – The interview may require participants to reflect on complex topics, which could be mentally demanding. • Perceived pressure to participate – Since participants are recruited through professional networks, they might feel obligated to take part. I understand that these will be mitigated by: • Voluntary participation – Participants will be informed that participation is entirely optional, and they may withdraw at any time without consequences. • Anonymization – No personal or company-identifying details will be included in reports, reducing potential reputational concerns. • Flexibility in scheduling – Interviews will be scheduled at participants’ convenience to minimize disruption to their work. • Right to skip questions – Participants can choose not to answer any questions that make them uncomfortable.	☐	☐

PLEASE TICK THE APPROPRIATE BOXES	Yes	No
6. I understand that taking part in the study also involves collecting specific personally identifiable information (PII) and associated personally identifiable research data (PIRD), with the potential risk of my identity being revealed. • Collected PII: Participants' names and email addresses will be collected solely for administrative purposes, such as scheduling interviews and obtaining informed consent. This information will not be linked to research findings. • Collected PIRD: Professional opinions, perspectives on circular economy (CE) implementation, and insights into MRO sector challenges will be collected during interviews. • Given that the aviation industry, particularly in sustainability and MRO, is relatively small, there is a risk of indirect identification based on job role, expertise, or industry-specific details.	☐	☐
7. I understand that the following steps will be taken to minimise the threat of a data breach, and protect my identity in the event of such a breach: Mitigation Measures: • Anonymization: Names, specific job titles, and company identifiers will be removed from transcripts. • Semi-aggregated Reporting: Findings will, be presented in summary form, with the exception of anonymized quotes. • Participant Review: If direct quotes are used, participants will have the opportunity to review and approve them before inclusion in the final report. • Secure Data Storage: All personal data will be securely stored and deleted after the project is completed, following TU Delft's data management policies.	☐	☐
8. I understand that personal information collected about me that can identify me, such as my name or where I live, will not be shared beyond the supervisory team.	☐	☐
9. I understand that the (identifiable) personal data I provide will be destroyed before the end of this graduation thesis (14-07-2025).	☐	☐
C: RESEARCH PUBLICATION, DISSEMINATION AND APPLICATION		
10. I understand that after the research study, the de-identified information I provide will be used for the following purposes: • Master's thesis repository – The final report will be publicly available in the TU Delft repository as part of Open Science initiatives. • NLR internal archive – The final report will also be stored in NLR's internal archive, where it may be used for strategic planning, policy development, and internal knowledge management related to circular economy and MRO practices.	☐	☐
11. I agree that my responses, views or other input can be quoted anonymously in research outputs.	☐	☐

Signatures

__________________________ _________________________ ________

Name of participant [printed] Signature Date

I, as researcher, have accurately read out the information sheet to the potential participant and, to the best of my ability, ensured that the participant understands to what they are freely consenting.

________________________ __________________ ________

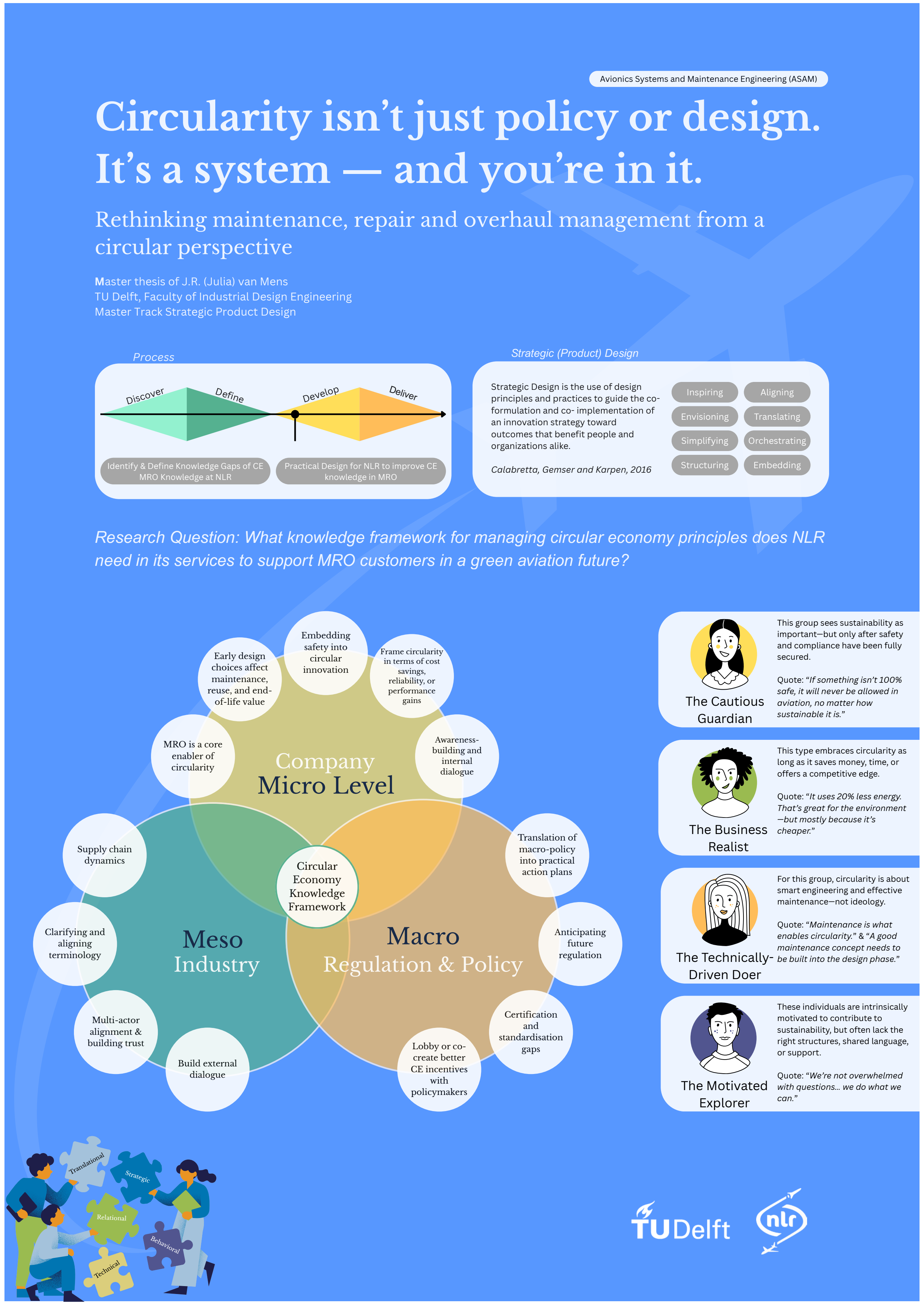
J.R. van Mens Signature Date

Study contact details for further information:

Julia van Mens

j.r.vanmens@student.tudelft.nl

APPENDIX D: Midterm Internship Poster Presentation NLR



APPENDIX E: Requirement Brainstorming Cards

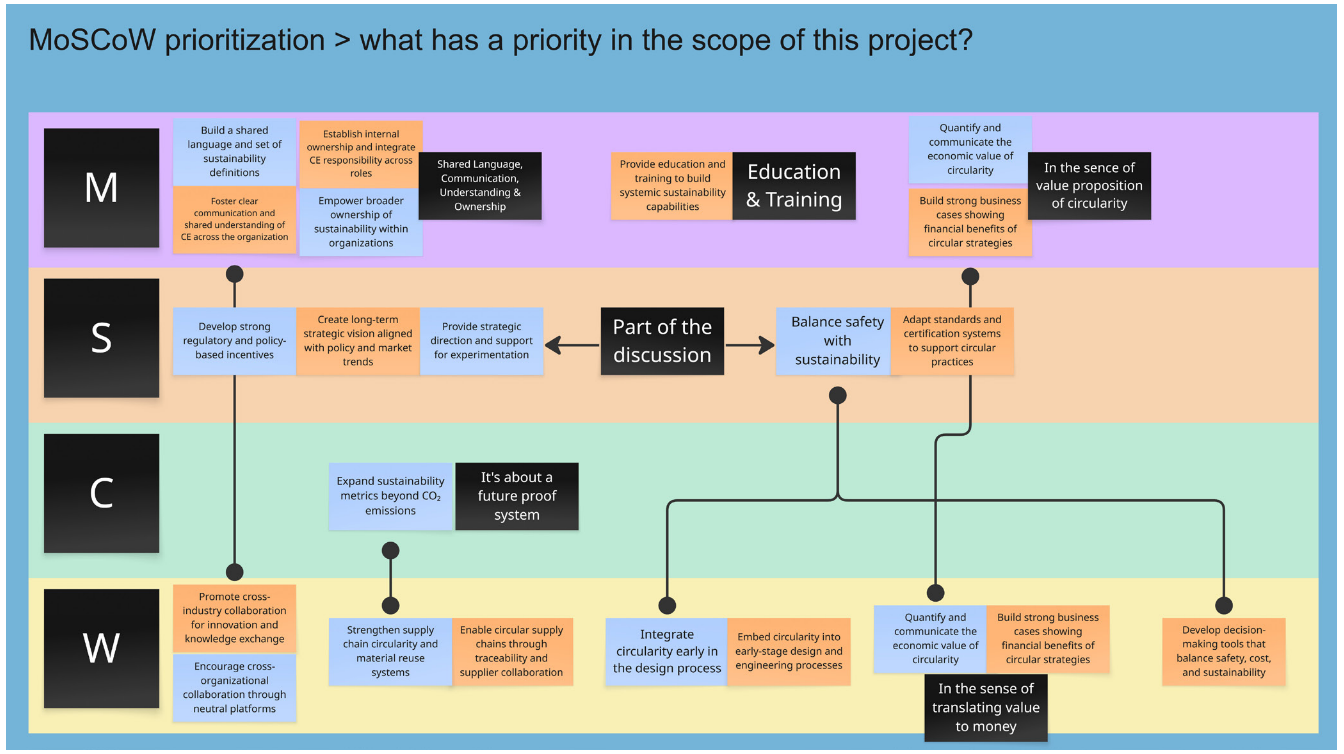
APPENDIX F: MoSCoW Prioritisation

Needs, based on the themes

- Integrate circularity early in the design process
- Balance safety with sustainability
- Quantify and communicate the economic value of circularity
- Develop strong regulatory and policy-based incentives
- Strengthen supply chain circularity and material reuse systems
- Encourage cross-organizational collaboration through neutral platforms
- Build a shared language and set of sustainability definitions
- Empower broader ownership of sustainability within organizations
- Expand sustainability metrics beyond CO_2 emissions
- Provide strategic direction and support for experimentation

Needs, based on theoretical framework

- Embed circularity into early-stage design and engineering processes
- Develop decision-making tools that balance safety, cost, and sustainability
- Build strong business cases showing financial benefits of circular strategies
- Establish internal ownership and integrate CE responsibility across roles
- Foster clear communication and shared understanding of CE across the organization
- Create long-term strategic vision aligned with policy and market trends
- Adapt standards and certification systems to support circular practices
- Enable circular supply chains through traceability and supplier collaboration
- Promote cross-industry collaboration for innovation and knowledge exchange
- Provide education and training to build systemic sustainability capabilities



Co-creation - Preparation Assignment

For the master thesis of Julia van Mens

Hi there! Good to hear that you will be joining the co-creation session on circularity this upcoming Wednesday. To have a smooth session, I would like to ask two things of you:

1) Read this document with a small piece on circularity theory.
2) Answer the question that you find at the end of this document.

If you have questions beforehand, please do not hesitate to contact me (j.r.vanmens@student.tudelft.nl).

Assignment 1

When trying to understand circularity and the circular economy, it is important to find definitions on the different terms. For the session I would like you to read the definitions on circularity, the circular economy and sustainability. **Please highlight what you might not understand, and also the things that you think are nicely defined. Also, do you prefer the generic definitions or the MRO specific ones?**

Generic Definitions

The Circular Economy = The circular economy is a model of production and consumption designed to retain value within the economic system. It involves conserving natural resources, designing products for recyclability, shifting consumer behavior, and adopting sustainable business models (Kumar et al., 2023).

- Core principles: reduce, reuse, recycle.
- Primary goal: shift from the linear "take-make-dispose" model toward a closed-loop system where materials are reused and reintegrated (Ghazanfari, 2023).

Circularity = Circularity refers to the capacity of a system (such as a company or supply chain) to preserve resources, minimize waste, and recirculate materials into the economy. It is a core component of the circular economy but can be applied independently at the organizational or sectoral level (Ulyanenko & Savchenko, 2024).

- Measures how effectively circular principles are applied.
- Focuses on internal operations, external interactions, and long-term integration in sustainability strategies.

Sustainability = Sustainability is a strategic approach aimed at fostering economic development without harming the environment or social structures. It seeks a balance between ecological protection, economic progress, and social equity (Ghazanfari, 2023).

- The three pillars: ecological, economic, and social.
- Often aligned with the United Nations Sustainable Development Goals (SDGs).

MRO Definitions

The Circular Economy = A sustainable development initiative aimed at reducing the linear material and energy throughput of societal production-consumption systems. It does so by applying material cycles, renewable and cascade-type energy flows, and fostering collaboration among producers, consumers, and societal actors in sustainable practices. — Adapted from Korhonen et al. (2018).

- This definition is selected as most applicable to aviation MRO due to its attention to:
  - Systems thinking (micro–meso–macro levels),
  - Regulatory and operational constraints, and
  - Sector-specific adaptation needs in a highly technical industry.

Circularity = Circularity refers to the ability of systems—particularly in production and maintenance environments—to retain resources in use by minimizing waste, extending product lifecycles, and enabling reuse, remanufacturing, and recycling. — Synthesized from Gräßler & Pottebaum (2021), Ferreira & Gonçalves (2021), and Potting et al. (2017).

- It functions as a performance metric of how well an organization or sector applies CE principles.
- Circularity in MRO manifests through:
  - Remanufacturing (e.g., turbine blades),
  - Predictive maintenance,
  - Additive repair (e.g., Directed Energy Deposition),
  - Material tracking (e.g., digital twins, material passports).

Sustainability = the integration of environmental, economic, and social objectives into decision-making and operations to ensure long-term viability without depleting natural or human capital. — Synthesized from Saade et al. (2025), Markatos & Pantelakis (2023), and Bruce & Spinardi (2018)

- Sustainability within the aviation MRO context must consider:
  - Environmental impact (e.g., carbon footprint of maintenance),
  - Economic feasibility (e.g., cost-efficiency of remanufacturing),
  - Social inclusion (e.g., workforce development, policy alignment).

Assignment 2

Please answer the following question in a few sentences:

Have you ever done or seen something in your work that - consciously or unconsciously - contributes to circularity? Think about reusing something, saving material, smarter maintenance, less waste or something designed with the future in mind.

APPENDIX H: Use of AI

Use of AI

Various AI tools were used to support the research and writing process in this project. Rather than generating original content, their role was primarily to assist with improving clarity, structuring information and exploring ideas.

During the writing process:

- *DeepL* was used to translate text between Dutch and English and to improve the quality of English phrasing. The DeepL output was used almost unchanged after review.
- *ChatGPT* was used to make the text more concise and improve its clarity and flow. While the tool supported the rewriting and refining of my own writing, it did not generate thesis content independently.

During the literature review phase:

- *NotebookLM* supported literature review activities. It was used to summarise papers, extract relevant information on specific topics and organise content from multiple sources. The tool was useful for providing quick overviews and for locating specific information within papers. However, I critically reviewed and reworked all outputs to ensure accuracy and coherence.

In the project and design phase:

- *ChatGPT* was used as a creative and reflective partner. It contributed to requirement brainstorming by generating initial ideas and helping to refine concepts through iterative dialogue. This included exploring alternative names, formats, and framing. While these exchanges supported the development of design outcomes, they were always supplemented with critical evaluation and manual editing.

Reflections on the use of AI

Advantages:

- The chat history function in ChatGPT proved valuable in tracing the development of ideas and decisions, serving as a digital notebook of sorts.
- AI tools supported the rapid retrieval of information, provided quick overviews of topics and proved effective as sparring partners during the ideation process.

Constraints:

- ChatGPT struggled to handle multiple documents simultaneously and often generated errors when working with larger sets of files (even with the Plus version).
- During the literature review, AI-generated summaries were often too generic and occasionally inaccurate. This required careful cross-checking and often additional effort to ensure the quality of the review.
- ChatGPT's citation handling was unreliable and unsuitable for academic standards, particularly in the literature review, so all citations were handled manually.

In summary, AI tools were used to improve efficiency and creativity during the research process while ensuring that the final outputs remained under full human control and judgement.

APPENDIX I: Project Brief

DESIGN FOR our future

TU Delft

Personal Project Brief – IDE Master Graduation Project

Name student Julia van Mens **Student number** 4,861,752

PROJECT TITLE, INTRODUCTION, PROBLEM DEFINITION and ASSIGNMENT
Complete all fields, keep information clear, specific and concise

Project title The Circular Takeoff for NLR: Reimagining Maintenance Repair and Overhaul Management

Please state the title of your graduation project (above). Keep the title compact and simple. Do not use abbreviations. The remainder of this document allows you to define and clarify your graduation project.

Introduction

Describe the context of your project here; What is the domain in which your project takes place? Who are the main stakeholders and what interests are at stake? Describe the opportunities (and limitations) in this domain to better serve the stakeholder interests. (max 250 words)

The aviation industry, including maintenance, repair and overhaul (MRO), must align with circular economy principles to achieve net-zero environmental impact by 2050 (European Economic and Social Committee, 2020). The circular economy (CE) emphasizes the reuse, repair, refurbishment, and recycling of materials (Ellen MacArthur Foundation). In aviation, this includes dismantling retired aircraft for parts refurbishment and resale, reducing waste and maximizing resource use. This shift promotes efficiency, competitiveness and new business models. However, challenges remain in making CE profitable, navigating regulations, scaling solutions, and overcoming resistance to change.

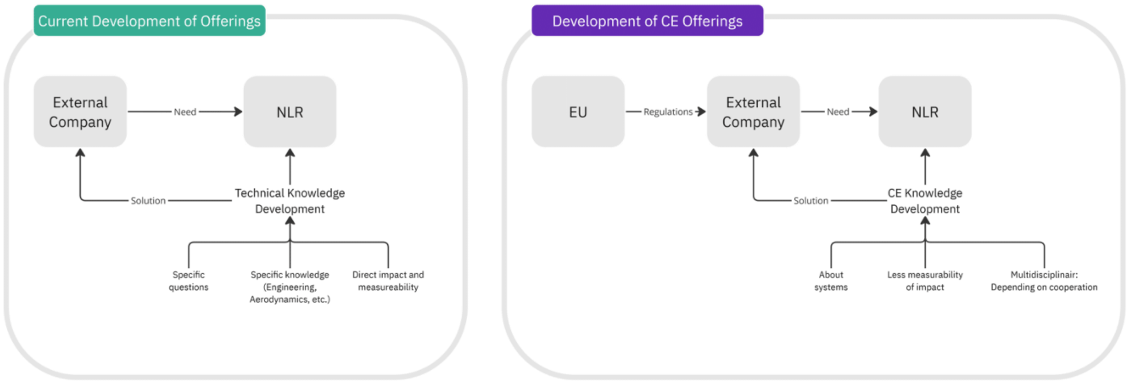
This graduation project is assigned by the Avionics Systems & Maintenance Engineering (ASAM) department of the Netherlands Aerospace Centre (NLR) and is connected to the LDE Centre for Sustainabilities lab 'Green Skies'. This project is within the domain of Circular Aviation and it focuses on maintenance management within aviation MRO.

NLR is a research centre that bridges fundamental research and practical applications, developing technology solutions for external clients. With new regulations, customer demands are now driven by compliance, and solutions are evolving from a technology-based approach to a more systemic, multidisciplinary one (Figure 1). The challenge is to determine the knowledge required to implement CE principles in MRO, while also considering financial drivers due to the industry's focus on cost and efficiency (Figure 2).

Stakeholders within NLR, such as business managers, research engineers and application engineers, aim to position NLR as a leader in aircraft maintenance, fleet renewal and sustainable materials (NLR Strategy Plan 2022-2025). In the Dutch MRO sector, companies such as KLM, Fokker and Kayak are focused on maintaining aircraft availability at minimum cost while integrating circular strategies to meet new sustainability regulations.

➔ *space available for images / figures on next page*

introduction (continued): space for images



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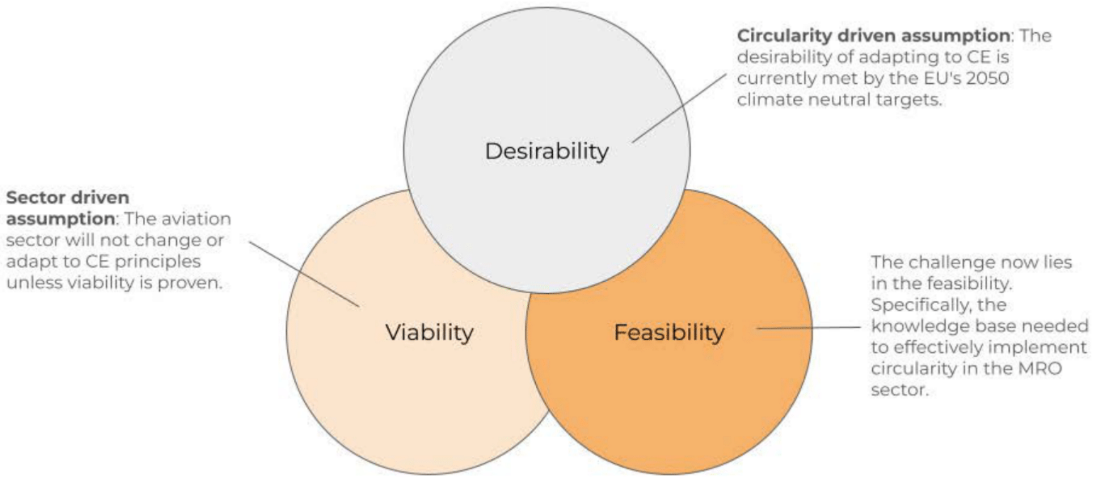

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Problem Definition

What problem do you want to solve in the context described in the introduction, and within the available time frame of 100 working days? (= Master Graduation Project of 30 EC). What opportunities do you see to create added value for the described stakeholders? Substantiate your choice.
(max 200 words)

The problem at hand is that NLR currently lacks a structured understanding of how the MRO sector perceives and applies Circular Economy (CE) principles. Despite NLR's strong engineering capabilities, there is no internal expertise or structured knowledge on CE, which limits NLR's ability to help clients navigate the circular transition. This underscores the company objective to understand what all the CE buzzwords mean and what kind of change the CE is. In addition, the Aviation sector is conservative, efficiency-driven and lacks consistent terminology, making it difficult to bridge the gap between technical innovation and practical implementation of CE principles.

An opportunity exists in the form of Life Cycle Assessment (LCA), which has already identified the MRO components with the greatest environmental impact (Rahn et al., 2024). This insight can serve as a starting point for understanding where the most significant improvements can be made in future MRO management and help NLR focus on the most impactful areas. By structuring CE management knowledge and focusing on these high-impact areas, NLR can better support MRO stakeholders in transitioning to a circular economy while aligning with the financial and operational priorities of the sector. This structured approach will ultimately help NLR position itself as a key player in advancing circularity within the aviation industry.

Assignment

This is the most important part of the project brief because it will give a clear direction of what you are heading for. Formulate an assignment to yourself regarding what you expect to deliver as result at the end of your project. (1 sentence) As you graduate as an industrial design engineer, your assignment will start with a verb (Design/Investigate/Validate/Create), and you may use the green text format:

Investigate the current knowledge structure of NLR around the management of Circular Economy principles to develop a more structured and applicable knowledge framework, aimed at enabling the ASAM department of NLR to effectively support the Dutch MRO sector in transitioning towards Circular Economy principles.

Then explain your project approach to carrying out your graduation project and what research and design methods you plan to use to generate your design solution (max 150 words)

Existing research on circular economy (CE) in aviation explores different strategies, including top-down, bottom-up and mixed approaches (Ghisellini & Ulgiati, 2020) and the application of the ReSOLVE framework to aerospace (Dias et al., 2022). This project builds on these findings by applying the double diamond design approach to answer the main research question: "What knowledge framework for managing CE principles does NLR need in its services to support MRO customers in a green aviation future?"

The first diamond involves a systematic literature review of current CE management strategies and semi-structured interviews to assess NLR's knowledge landscape. This helps to identify the most relevant frameworks for NLR. In the second diamond, the research focuses on contextualizing this knowledge within MRO operations through interviews and co-design sessions to assess feasibility and industry alignment.

In addition, eleven sessions within the LDE Center for Sustainability program foster multidisciplinary collaboration with stakeholders from NLR, Collins, and AETHOS, providing early validation and reinforcement of the research findings.

Project planning and key moments

To make visible how you plan to spend your time, you must make a planning for the full project. You are advised to use a Gantt chart format to show the different phases of your project, deliverables you have in mind, meetings and in-between deadlines. Keep in mind that all activities should fit within the given run time of 100 working days. Your planning should include a ***kick-off meeting****,* ***mid-term evaluation meeting****,* ***green light meeting*** *and* ***graduation ceremony****. Please indicate periods of part-time activities and/or periods of not spending time on your graduation project, if any (for instance because of holidays or parallel course activities).*

Make sure to attach the full plan to this project brief.
The four key moment dates must be filled in below

Kick off meeting	11 feb 2025
Mid-term evaluation	7 apr 2025
Green light meeting	13 juni 2025
Graduation ceremony	14 juli 2025

In exceptional cases (part of) the Graduation Project may need to be scheduled part-time. Indicate here if such applies to your project

Part of project scheduled part-time	
For how many project weeks	
Number of project days per week	

Comments:

Motivation and personal ambitions

Explain why you wish to start this project, what competencies you want to prove or develop (e.g. competencies acquired in your MSc programme, electives, extra-curricular activities or other).

Optionally, describe whether you have some personal learning ambitions which you explicitly want to address in this project, on top of the learning objectives of the Graduation Project itself. You might think of e.g. acquiring in depth knowledge on a specific subject, broadening your competencies or experimenting with a specific tool or methodology. Personal learning ambitions are limited to a maximum number of five.
(200 words max)

I am driven to understand the (psychological) factors that influence sustainable change at the corporate level and how these factors affect a company's position in its sector. I am particularly interested in demonstrating that sustainability can be both effective and profitable. This project offers the opportunity to work in a multidisciplinary environment, to work with a new sector where there are few designers, and to bring a fresh perspective to NLR.

I want to develop emerging design skills in using computational and AI tools such as Linguistic Inquiry and Word Count (LIWC) and AI stakeholders to analyze drivers of change. I also want to improve my ability to create quick visualizations to bridge the gap between designers and non-designers, and to navigate the complexities of multi-stakeholder problems and contradictions.

Personally, I I want to strive for low-stress completion by focusing on progress rather than perfection and accepting that mistakes are part of the process. I want to work with clear goals and a method, not randomly. I want to believe in myself as a designer and maintain professionalism in my work. Above all, I want to do things that excite me.

#09 Green Aviation Management Expectations : making Maintenance, Repair and Overhaul more circular

How to prepare for the management and execution of maintenance in a green aviation future?

Problem statement:
In the current system of aviation, Maintenance, Repair and Overhaul (MRO) play an important role in guaranteeing Continued Airworthiness, as a precondition for safe aviation operations. Not only does this mean that significant means are spent on maintenance within aviation, but also that the aviation industry aims to organize maintenance in such a way that it is needed as little as possible and that it can be done as quickly as possible, leading to a high availability of aircraft (Kinnison and Siddiqui, 2013).These circumstances have shaped the current MRO industry and MRO landscape within the wider aviation industry. However, the aviation industry as a whole, including the MRO industry, needs to transition towards an approach more in line with Circular Economy principles leading to a neutral environmental impact by 2050 (European Economic and Social Committee, 2020). At the same time, the strong MRO industry might already relate to certain principles underlying the circular economy. However, the current mode of thinking of the Aviation MRO industry might not see the connection that may exist between their work and Circularity. This research is intended to shine a light on this relationship and build knowledge for the way forwards.

Research question(s):
In what way does the current status of the Aviation MRO industry and their activities relate to Circular Economy practices for the Aviation Industry?

- What are the conceptual connections between the activities of the Aviation MRO industry and Circular Economy Strategies? How strong are these connections?
- What are the current knowledge gaps for the Aviation MRO industry with regards to Circular Economy principles and/or practices?
- In what ways should current Aviation MRO industry strategies evolve to cover the knowledge gaps between current and Circular Economy strategies?

Expected type of work:
Literature analysis, gap analysis, interviews with professionals, exploratory research.

Available data/reports or other relevant information sources for the assignment:

- THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE. (2020, March 11). A new Circular Economy Action Plan. EUR-Lex – Access to European Union law. https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=COM:2020:98:FIN
- Rupcic, L., Pierrat, E., Saavedra-Rubio, K., Thonemann, N., Ogugua, C., & Laurent, A. (2023). Environmental impacts in the civil aviation sector: Current state and guidance. Transportation Research Part D Transport and Environment, 119, 103717. https://doi.org/10.1016/j.trd.2023.103717
- Kinnison, H. A., & Siddiqui, T. (2013). Aviation Maintenance Management. Aviation Maintenance Management, (Second Edition). Retrieved from https://commons.erau.edu/publication/1538

Other remarks:
Preference for regular contact moments with the student, Preference for design included in (final) outcome

Commisionairs details:
Organization / Department: NLR / Avionics Systems & Maintenance Engineering (ASAM)
Name(s): Arjan Derks
Email(s): arjan.derks@nlr.nl

17

Strategic Product Design

July, 2025