The Circular Cabin Seat

Redefining Cabin Waste: A Proof of Concept for Recycling Seat Backrests

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‘Under pressure, everything becomes liquid’

All images used in this report are sourced from KLM, unless otherwise stated.

Preface

From a young age, I have been captivated by the world of aviation and the opportunities it provides for exploration and connection. This passion for travel grew during my studies into a profound interest in how the industry can shape a sustainable future. More than a year ago, my journey took a pivotal turn when I joined the SESAME project in collaboration with Airbus, where I analyzed the environmental impact of aircraft seats from a life cycle perspective. This experience introduced me to the immense potential of circularity in aviation and allowed me to connect with KLM Engineering & Maintenance (KLM E&M) and other key industry players.

These meaningful connections opened the door to exploring the integration of circularity in the aircraft cabin, which became the foundation of this project. I would like to express my heartfelt gratitude to Sicco, whose guidance and encouragement over the past year have been instrumental in shaping my academic and professional journey. His support has allowed me to grow and aim higher, reminding me that the sky is truly the limit.

I am also deeply thankful to my academic mentor, Shahrokh, whose thoughtful guidance and constructive feedback over the past six months greatly enhanced this research.

A special thanks goes to my supervisor at KLM E&M, Linda, whose enthusiasm for innovation and belief in this project have been a constant source of motivation. Her support has been invaluable, and I look forward to continuing our collaboration as part of the KLM traineeship program.

I am grateful to my colleagues at the Tech Hub for their valuable feedback, as well as to all internal departments at KLM E&M for their support and expertise. Additionally, I extend my thanks to our external partners, including Egmond Plastic and Belgraver, for their collaboration throughout this journey.

This project reflects the power of collaboration and innovation in addressing the challenges of sustainable aviation. I hope the outcomes of this project pave the way for further research and innovation, shaping a more sustainable future for the aviation industry.

Abstract

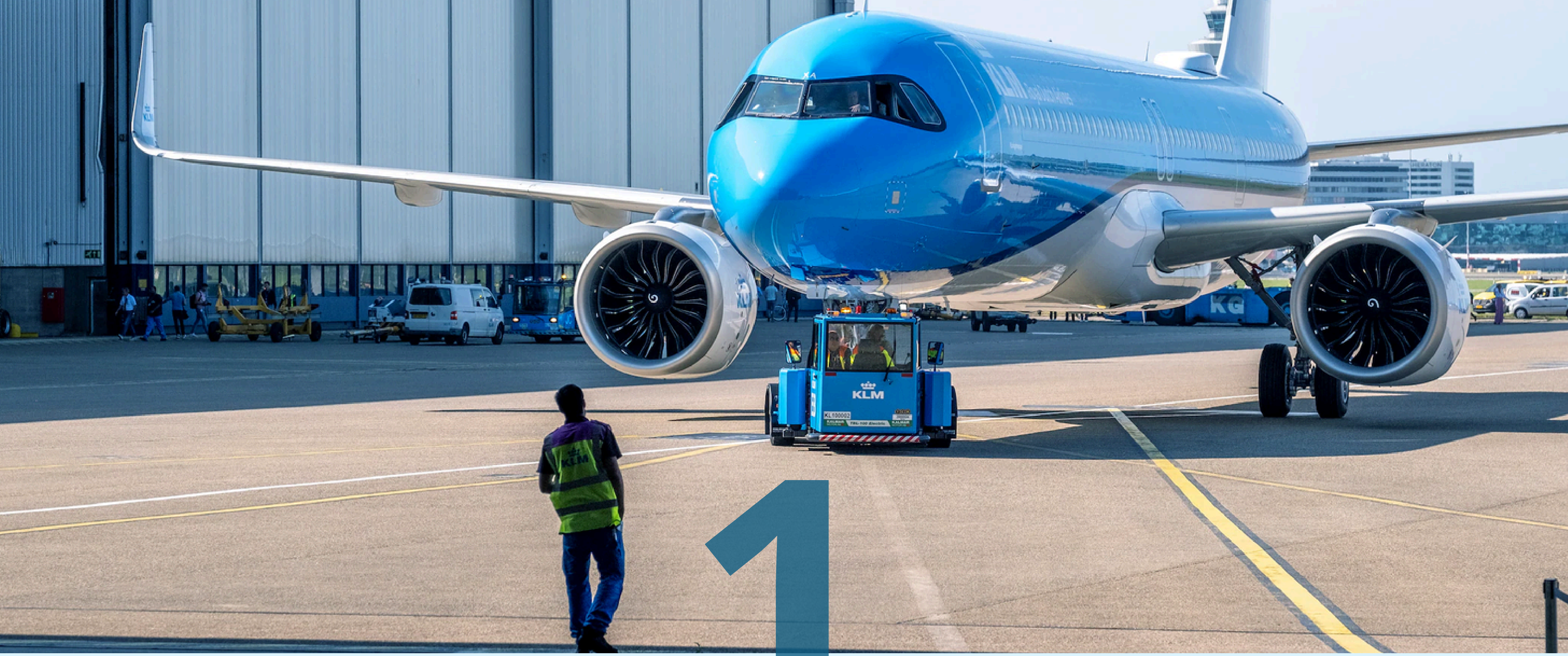
The aviation industry is at a critical crossroad, facing increasing pressure to reduce its environmental impact while managing rising operational costs. As a significant contributor to global CO2 emissions, the sector must find innovative solutions to balance sustainability with economic challenges. However, strict regulations, high material costs, and fragmented supply chains complicate efforts to drive change. This project explores how the Circular Cabin model—a framework for recycling and reusing cabin interior parts to reduce waste and extend material lifecycles—could be integrated into KLM Royal Dutch Airlines' Maintenance, Repair, and Overhaul (MRO) operations.

Cabin interior parts, particularly seats, were identified as high-potential areas for circularity due to their frequent replacement and material composition. A pilot study on seat backrests demonstrated that recycled polycarbonate can meet stringent aviation fire safety certification, representing a major milestone in advancing circular cabin practices. This breakthrough paves the way for further testing and offers a practical approach to scaling recycling practices within aviation.

To translate these findings into actionable steps, a playbook was developed to guide KLM E&M employees in embedding circularity into their operations. The playbook includes tools such as a decision tree for assessing recycling potential, a strategic roadmap for implementation, and focus areas for further research. By connecting strategic vision with practical application, the playbook provides a clear pathway for operationalizing circularity within KLM Engineering & Maintenace's (E&M) operation.

This project highlights the transformative potential of circularity in aviation. By adopting circular practices, KLM E&M can reduce material costs, enhance supply chain resilience, and create a more level playing field with Original Equipment Manufacturers (OEMs). With a commitment to the tools and insights developed in this project, KLM E&M has the opportunity to become a frontrunner in sustainable innovation, setting a powerful precedent for the industry and redefining the role of aviation in shaping a sustainable future.

Table of content



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Project Introduction

1.1 Aviation at a Crossroad

In the vast expanse of our modern world, the skies have become both a channel of connection and a canvas for technological innovation. As the aviation industry soars to new heights, the aviation industry stands at the crossroads of progress and responsibility, facing the importance of sustainable practices.

Sustainable aviation has become crucial for the industry's survival as it faces significant environmental challenges while maintaining its economic importance (Thomas & Raper, 2000). The sector contributes 2.5% of global CO_2 emissions, with projections showing 3-5% annual growth (Afonso et al., 2023). To address this, various strategies are being explored including improved operations, energy storage, propulsion systems, aerodynamics, and materials (Afonso et al., 2023).

These sustainable efforts extend beyond the aircraft to include ground operations and airport design. While technological advancements are key to achieving sustainability goals, uncertainties remain concerning the feasibility of ambitious plans, often involving complex technological and political trade-offs (Delbecq et al., 2023). In this context, sustainability is not merely an aspiration; it is a strategic necessity for the industry's future. By leading the way in sustainable practices, the aviation sector can set a powerful example for other industries, demonstrating how to effectively balance safety, environmental responsibility, and social equity (Skoyles, 2011).

1.2 KLM in Heavy Weather

This project is being carried out in close collaboration with KLM (Royal Dutch Airlines) Engineering & Maintenance. Alongside the pressure to meet new industry-wide environmental targets, KLM faces an immediate financial challenge following the turbulent period of COVID-19. In response, the airline is exploring cost-cutting measures to reduce expenditures. For KLM E&M, this has translated into three critical focus areas: People, Parts and Processes.

Though KLM has achieved record-high turnover, rising costs within the aviation sector have placed the company at a tipping point, making its continued viability increasingly challenging. These cost increases arise from various factors, including, increased Schiphol rates, passenger taxes, and elevated maintenance costs.

KLM faces the dual challenge of addressing these rising expenses while also making significant investments in a cleaner, quieter, and more fuel-efficient fleet to meet industry-wide environmental goals. A greater share of the airline's revenues is now allocated to covering these expenses, tightening its financial margin for innovation and growth.

Amid this "heavy weather," however, lies an opportunity to harness sustainable innovation as a means of overcoming these challenges. Sustainable innovation integrates long-term societal, economic, and environmental considerations, providing a framework for addressing complex global problems (Hautamäki & Oksanen, 2016). Technological innovation plays a pivotal role within this context, offering solutions to environmental challenges through the development of new products, services, and processes that optimize resource use, reduce waste, and minimize environmental impact (Hashem, 2015; Singh, 2022).

1.3 Problem Definition

Faced with increasing financial pressures and growing industry-wide environmental targets, KLM is confronted with the challenge of reducing operational costs while simultaneously investing in sustainable innovations. Achieving this balance is critical for the airline’s long-term viability, as it must continue to meet both financial and environmental goals to ensure its competitive standing in a rapidly evolving industry.

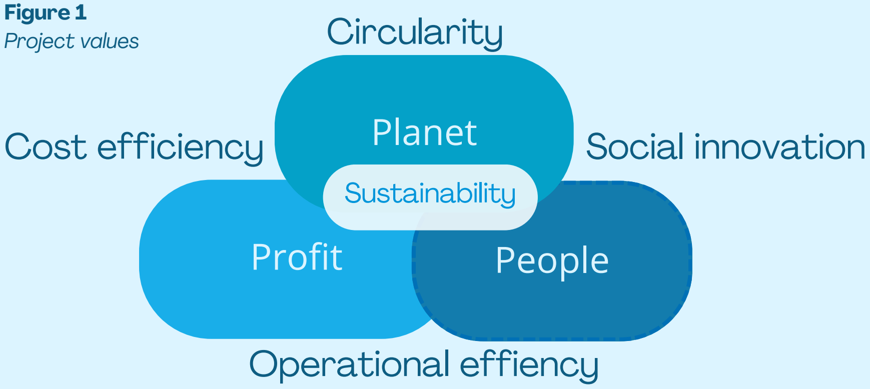
1.4 Scope

The Engineering and Maintenance department of KLM (KLM E&M), responsible for maintaining, inspecting, and repairing the fleet, faces the specific challenge of optimizing the life cycle management of cabin parts to reduce the high maintenance costs, enhance sustainability, and increase operational efficiency. A significant opportunity lies in the end-of-life stage of these parts, where strict regulations and high repair costs often result in premature scrapping (Sainte-Beuve, 2012). However, many of these parts are made from high-quality materials, offering significant potential for recycling and reuse. While this sounds promising, implementing such practices is complicated by the rigorous regulations of the aviation industry.

1.5 Research objective

The primary objective of this research is to support KLM E&M's transition toward closed-loop, circular cabin interior parts, referred to as the Circular Cabin model (explained in Section 3.3). Centred on sustainability—encompassing people, planet, and profit (see Figure 1)—the research also seeks to set a precedent for the broader aviation industry by demonstrating the effective implementation of circular practices in the maintenance, repair, and overhaul of aircraft parts. These practices aim to minimize high maintenance costs and reduce waste generated by the disposal of high-quality materials.

Figure 1
Project values



1.6 Research question

Based on the scope and research objective, the main research question for this project has been formulated as follows:

How can the circular cabin model be successfully integrated into Maintenance, Repair, and Overhaul (MRO) operations?

To comprehensively address this question, five subquestions were developed, each targeting a specific aspect of the project:

Subquestion 1: What are the key factors influencing the adoption of recycling practices for KLM aircraft cabin interior parts, considering regulatory, economic, and operational constraints?

- This subquestion investigates the barriers and enablers for integrating recycling practices, focusing on regulatory, economic, and operational aspects.

Subquestion 2: How can the recycling potential of cabin interior parts be assessed?

- This subquestion explores methods and tools for evaluating the recycling potential of cabin interior parts, considering material properties, lifecycle impact, and compatibility with MRO processes.

Subquestion 3: Which current Recaro cabin seat parts demonstrate recycling potential?

- This subquestion identifies specific Recaro (seat manufacturer) cabin seat parts to provide a focus for future research into recycling and circular design possibilities.

Subquestion 4: What is the future vision for the broader circular cabin project?

- This subquestion investigates the vision for the circular cabin project, exploring how it integrates circular principles and aligns with operational strategies.

Subquestion 5: How do the material properties of recycled cabin seat backrests change during the recycling process?

- This subquestion investigates how the recycling process affects the material properties of cabin seat backrests. It also explores how the recycling process can be set up and how certification requirements, such as fire resistance testing, can be met to ensure compliance with aviation standards.

1.7 Project Methodology

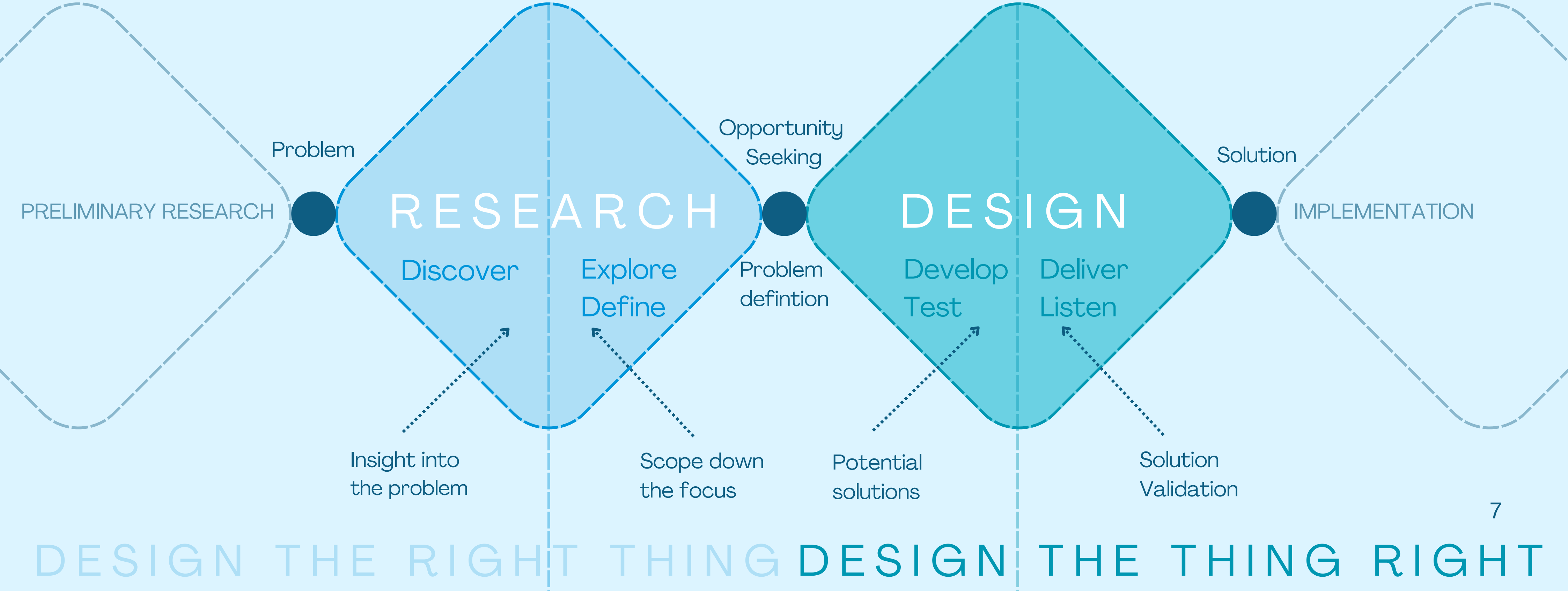
This project employs a combination of methods under the overarching framework of the Double Diamond model. The Double Diamond is a design thinking framework that emphasizes alternating phases of divergent and convergent thinking to explore problems and develop solutions (He et al., 2023). It is widely applicable across industries and focuses on iterative testing and refinement to arrive at the most effective outcomes (Design Council, n.d.), as illustrated in Figure 2.

Complementing this framework, the KISS (Keep It Simple, Stupid) design principle provided additional guidance throughout the research. Originating in aerospace design during the 1960s, this principle helped manage the increasing complexity of the project by emphasizing simplicity, integration, and logical progression.

This project is divided across the two diamonds of the Double Diamond framework. Chapters 2 to 5 focus on the first diamond, which encompasses problem exploration and understanding. Chapter 2 introduces the case, after which Chapter 3 lays the theoretical foundation through an extensive literature review, serving as a knowledge base for the subsequent stages of the project. The methods, process, and results of the subquestions are discussed in detail In Chapter 4, Methodology, and Chapter 5, Subquestions, building a comprehensive understanding of the research problem. With the results acting as the starting point of the design phase.

The second diamond is reflected in Chapter 6, The Playbook, where the design phase is fully addressed. This phase translates the insights from the first diamond into actionable outcomes, including the development of the design brief and the creation of the project's final deliverable: the playbook.

Figure 2
Double Diamond



Research
Discover

2

The Case

2.1 Introduction

This chapter introduces the case, focusing on KLM's sustainability strategy, the role of the Tech Hub in driving innovation, and the airline's position in the market. It highlights the opportunities for circular practices within cabin interiors, emphasizing cabin seats as a strategic starting point.

2.2 KLM Royal Dutch Airlines

Founded on October 7, 1919, KLM Royal Dutch Airlines is the oldest airline in the world still operating under its original name. Over the years, it has developed into a significant player in the global aviation industry. Together with its regional subsidiary KLM Cityhopper, KLM forms the core of the KLM Group, which also includes Transavia and Martinair. In 2022, KLM transported 34.1 million passengers and 621,000 tons of freight, underscoring its central role in connecting people and goods worldwide.

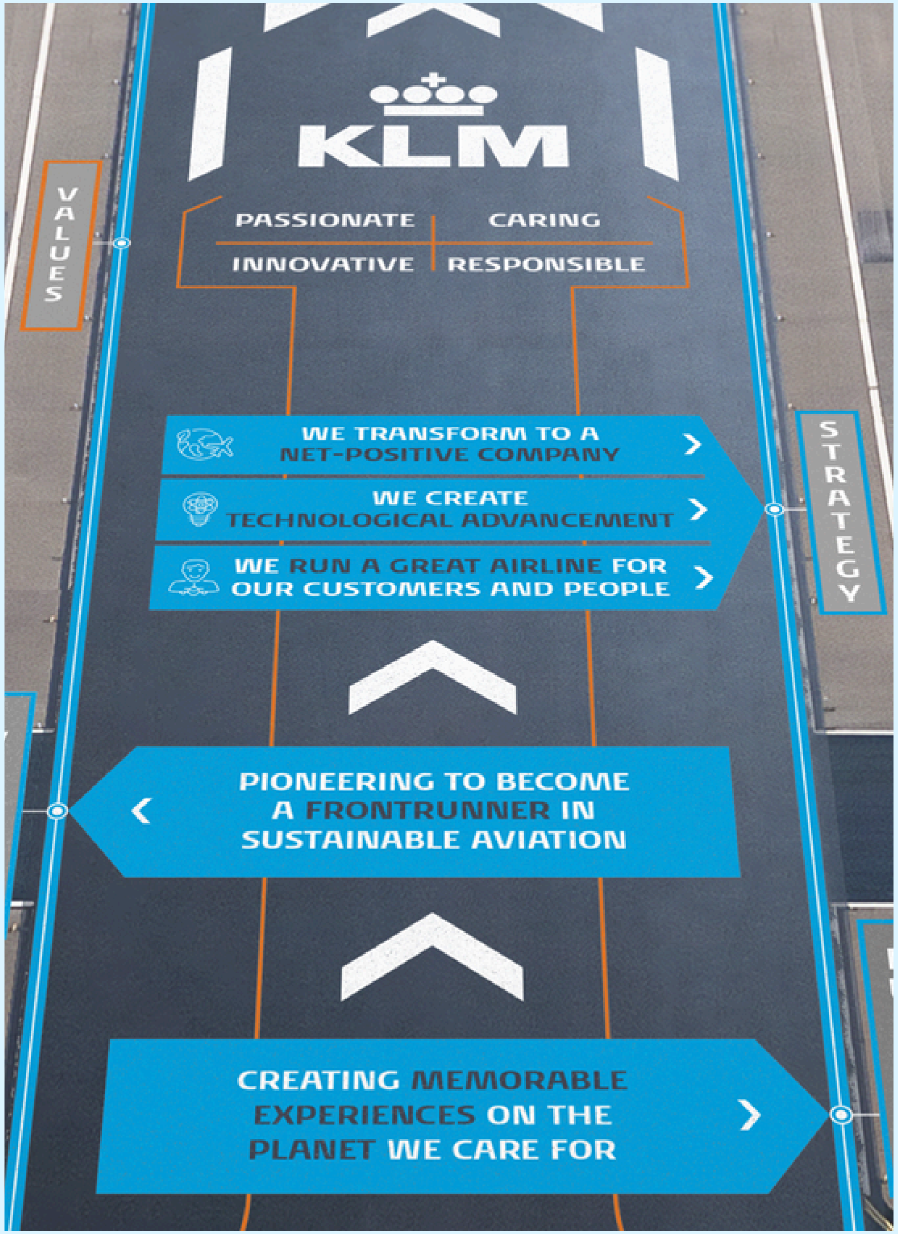
KLM has been a member of the SkyTeam Alliance since its inception, leveraging this partnership to strengthen its global network. Since its merger with Air France in 2004, KLM has shaped the European aviation landscape, focusing on innovation, collaboration, and operational efficiency.

The airline operates with a dual focus: achieving profitable growth while contributing to broader economic and social objectives. This includes a commitment to sustainable development, particularly at its hub, Amsterdam Airport Schiphol. As environmental concerns grow, KLM's sustainability strategy has become a key component of its operations and long-term vision. The next section explores how the airline integrates sustainability into its business model and the initiatives it employs to address the environmental challenges facing the aviation industry.

2.3 Sustainability at KLM

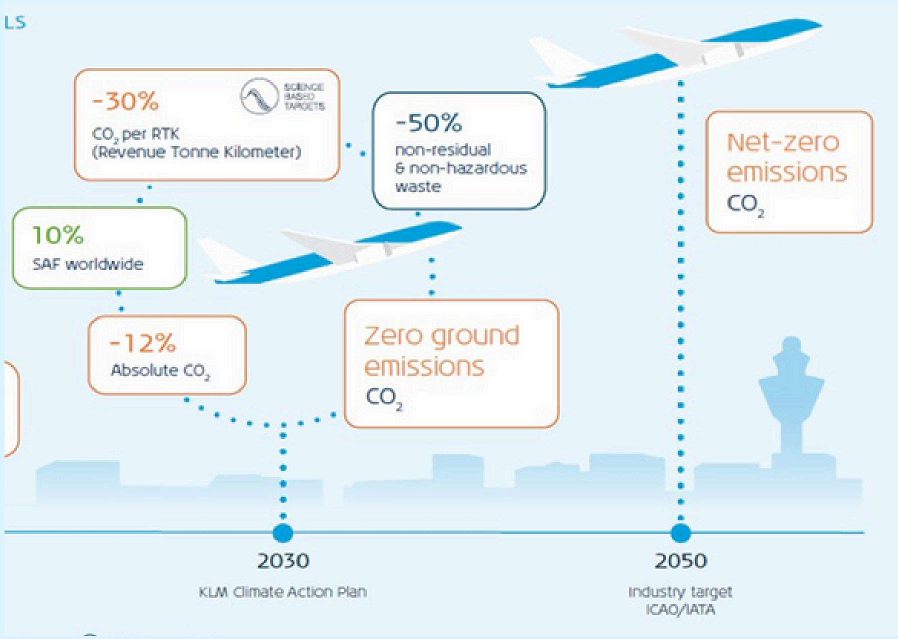
Recognising the aviation industry's commitment to achieving net zero emissions by 2050, KLM has outlined a clear sustainability vision to align its operations with this ambitious goal. Central to this vision is KLM's Sustainability Runway, a framework designed to guide the airline's efforts in reducing its environmental impact and fostering innovation in sustainable aviation. This strategy reflects KLM's aim to become a frontrunner in sustainable aviation, focusing on measures that balance environmental responsibility with operational feasibility (see Figure 3).

Figure 3
KLM Sustainability Runway



In the short term, KLM aims to achieve its 2030 sustainability targets, including a 50% reduction in waste, as illustrated in Figure 4. These efforts not only address pressing environmental challenges but also help the airline navigate ongoing industry disruptions, reinforcing its resilience and long-term viability. At the same time, KLM is working to envision the future of sustainable aviation, combining operational improvements with broader innovations in the sector.

Figure 4
KLM Sustainability Roadmap



2.4 Airbus' Cabin Vision

KLM's sustainability strategy is part of a broader industry-wide effort to achieve net zero emissions by 2050, a goal that requires collaboration with key partners such as Airbus. As one of the leading original equipment manufacturers (OEMs) in the aviation sector, Airbus plays a pivotal role in shaping the future of sustainable air travel. Airbus' Cabin Vision outlines a roadmap to transform air travel by addressing environmental challenges while maintaining passenger comfort and operational efficiency. This vision emphasizes innovative approaches such as digitalization, the use of bionic structures, and the adoption of circular design principles. By reimagining cabin design through these advancements, Airbus aims to create solutions that prioritize sustainability without compromising functionality or passenger experience. The vision also invites passengers and the wider aviation industry to join in envisioning a future of flying that balances environmental responsibility with cutting-edge design (The C-Suite—The Business Class Concept Seat, 2023).

BY 2025 TRANSPARANCY
2030 DECARBONIZATION
2035 + **CIRCULARITY**

This project is the first to contribute to Airbus' and KLM's Cabin of the Future initiative, specifically addressing the themes of the circular economy and life cycle management. As the inaugural effort under this initiative, it fosters collaboration within the industry, encouraging stakeholders to take gradual yet meaningful steps toward achieving net zero emissions. This project not only advances sustainable cabin design but also demonstrates the potential of collective action in driving the aviation sector toward a more sustainable future.

2.5 Technology Hub

This project will be conducted within KLM's Tech Hub, a central innovation platform situated in the Engineering & Maintenance (E&M) department. The Tech Hub plays a pivotal role in advancing KLM's strategic objectives, particularly in pioneering sustainable aviation. Its mission is to translate E&M's strategic goals into actionable tactical initiatives, supporting operational activities through standardized methodologies. Acting as a bridge between technological and social innovation, the Tech Hub fosters collaboration across departments and ecosystems, inspiring both internal teams and external partners to work toward shared goals.

The focus on sustainability within the Tech Hub aligns directly with the broader emissions challenges faced by the E&M department. The next section delves deeper into these emissions, highlighting their impact and the critical role of circular practices in addressing them.

2.6 Emissions Challenges at KLM E&M

In 2022, Accenture conducted an in-depth analysis of KLM's total emissions, highlighting key areas of environmental impact across its operations (Accenture, 2022). Within the Engineering & Maintenance (E&M) department, aero purchasing—the extraction and processing of raw materials—emerged as the largest category of emissions. This underscores the significant environmental footprint associated with manufacturing and procurement processes within aviation maintenance operations.

Research emphasizes that repairing rather than replacing parts is often more beneficial from both economic and environmental perspectives. However, increasing repair costs have led to a shift toward replacement practices, contributing to the growing 'throwaway society' (McCollough & Qiu, 2021). This trend poses a critical challenge for E&M, which must balance operational efficiency with sustainability goals.

The urgency to address these emissions is further heightened by the new Corporate Sustainability Reporting Directive (CSRD) regulations. Beginning with the financial year 2024, KLM will be required to comply with the CSRD, with the first reports due in 2025. This directive mandates large companies to assess risks related to human rights and environmental harm across their operations and supply chain. It also requires the implementation of mitigation policies and transparent reporting on due diligence efforts. By improving the completeness, comparability, and reliability of sustainability reporting (Baumüller & Grbenic, 2021), the CSRD adds external pressure on KLM to align its practices with stringent environmental and social standards.

The emissions challenges within E&M highlight the critical need for innovative approaches, such as those explored in this project, to reduce raw material use and adopt circular practices. These efforts not only support regulatory compliance but also position KLM to perform competitively in a market increasingly shaped by sustainability demands. The next section examines KLM's current position within the broader aviation market, analyzing how its sustainability efforts compare to industry peers and where opportunities for further progress lie.

2.7 KLM's Market Position in Sustainability

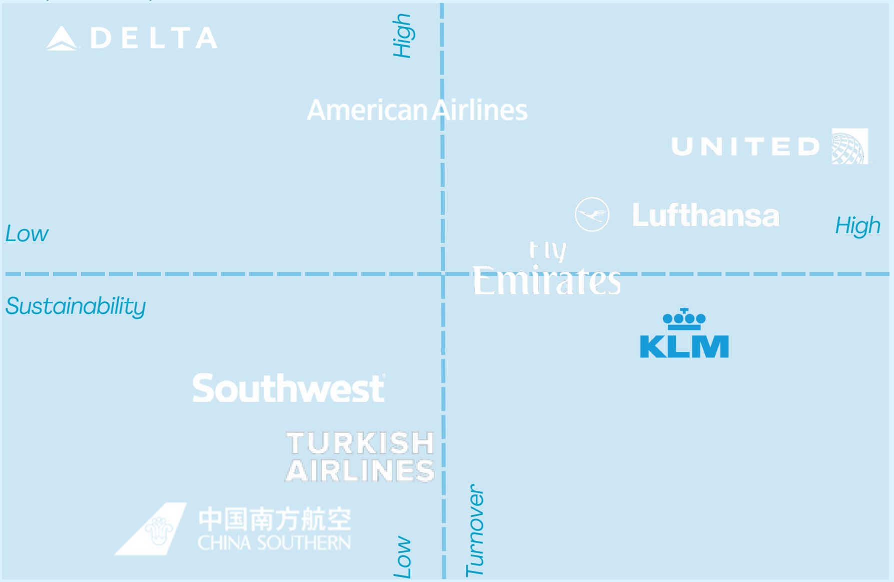
To understand KLM's position in the sustainability market, a preliminary analysis was conducted to evaluate the ten largest airlines based on their sustainability performance (see Figure 5). Airlines were ranked according to turnover (Nilson & Nilson, 2024) and sustainability scores, using multi-criteria performance models to assess financial, operational, and environmental factors (Tanrıverdi et al., 2023).

The results rank KLM third in sustainability, reflecting its efforts to reduce emissions, adopt circular practices, and align with regulations such as the Corporate Sustainability Reporting Directive (CSRD). However, the analysis also highlights opportunities for improvement, as top-ranked airlines lead with bold innovations and aggressive carbon reduction strategies (Tanrıverdi et al., 2023).

This context underscores the importance of the project in advancing KLM's sustainability strategy. By addressing emissions within E&M and adopting circular principles, KLM can enhance its competitive edge and contribute to the industry's transition toward net zero aviation.

Figure 5.

Competitor map.



2.8 Focus on Seats

Building on the challenges outlined in this chapter, the project focuses on cabin seats as a key area for advancing circularity within KLM's operations. Recycling prematurely scrapped cabin interior parts offers a significant opportunity to reduce emissions and material waste, directly supporting KLM's sustainability goals and the aviation industry's net zero ambitions.

Seats, which make up approximately 80% of an aircraft's cabin interior, are a natural focus due to their high volume, frequent use, and regular maintenance needs. Focusing on seats allows the project to address a substantial portion of the cabin's environmental impact while creating a scalable approach for circular design.

The scope is further refined to economy class seats in the rear section of the aircraft (see Figure 6). These seats are lightweight, straightforward in design, and experience high repair rates due to the large and diverse passenger base. Previous research, conducted in collaboration with KLM's Tech Hub, evaluated the lifecycle sustainability of different seat classes, identifying economy class seats as having significant potential for improvement.

2.9 Conclusion

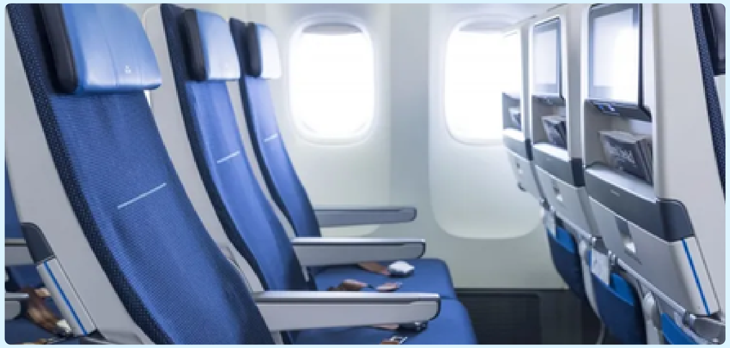
This chapter outlines the case context, highlighting KLM's sustainability efforts, its collaboration with partners like Airbus, and the opportunities within the E&M department to implement circular practices. The focus on cabin seats, supported by previous research in collaboration with the Tech Hub, demonstrates a tangible pathway for addressing emissions and material waste.

The insights from this chapter provide the operational and strategic background necessary for the project. The next chapter delves into a review of relevant literature, offering a theoretical foundation to guide the methodologies and actions explored in the later phases of the project.

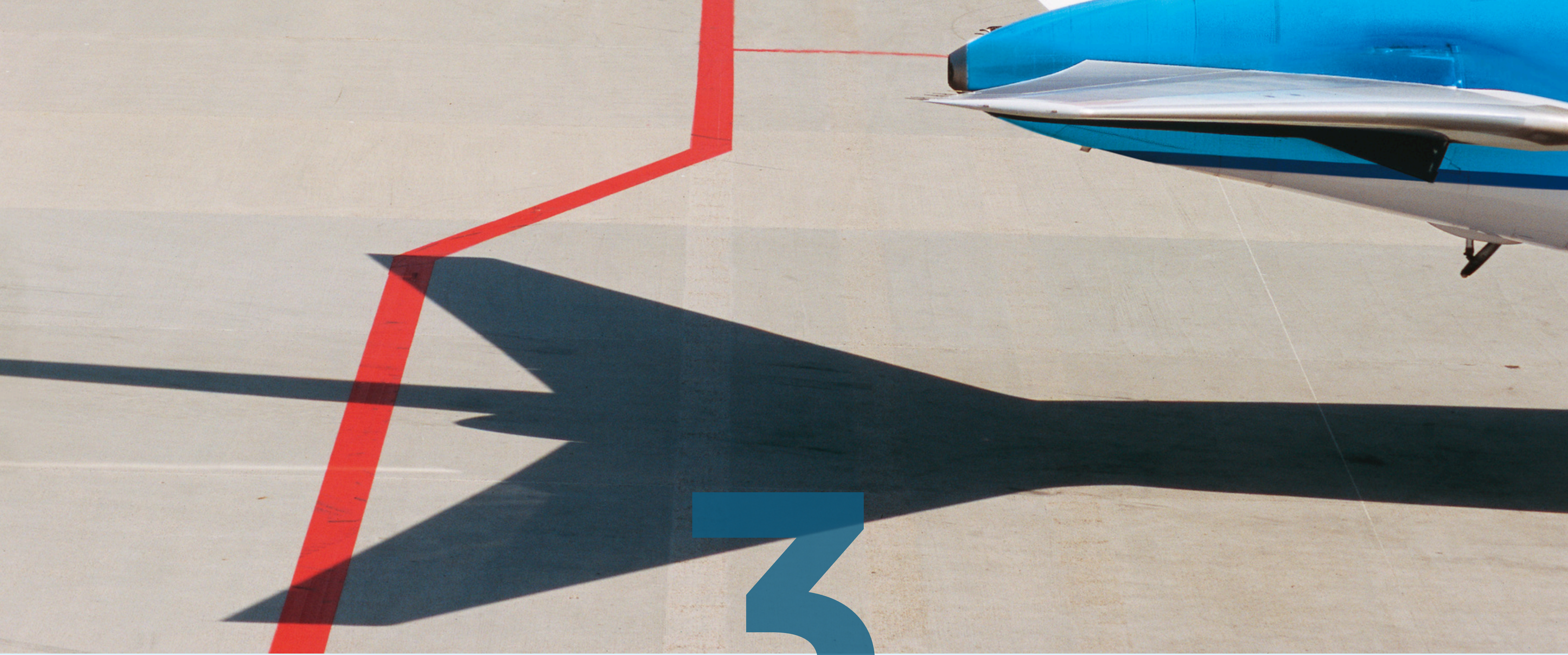
Figure 6
Overview of seats

35 business class seats

24 premium comfort seats



48 economy comfort seats
146 economy seats



3

Literature Review

3.1 Introduction

In this chapter, a detailed literature review provides a foundational understanding of the research and its context. The review begins with an overview of sustainable aviation, followed by an exploration of the circular economy as a potential solution for the environmental challenges in the aviation industry. Next, the limitations of the current business model are analyzed, and the opportunities within the aircraft dismantling and recycling market are highlighted.

3.2 Sustainable Aviation

The Nobel Prize-winning Intergovernmental Panel on Climate Change (IPCC) reports that aviation contributes around 2.5% of man-made carbon dioxide (CO_2) emissions. Although this share is relatively small, aviation emissions significantly contribute to climate change through various pollutants released at high altitudes. These emissions affect the upper troposphere and lower stratosphere, where their impact is heightened due to slower blending processes and lower temperatures (Hashmi & Manzoor, 2011). Additionally, the aviation industry's emissions are expected to grow, driven by population growth and economic factors (Hashmi, 2020). As concerns about global warming rise, several initiatives have been established to reduce the sector's footprint.

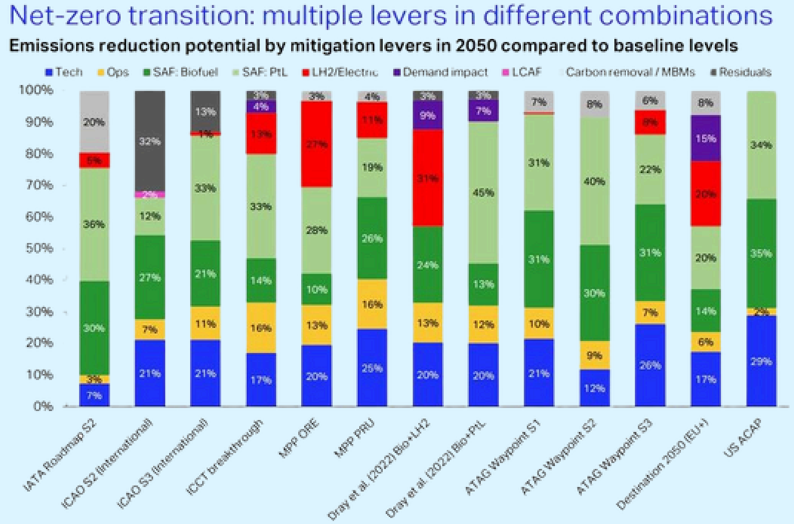
At the 77th IATA Annual General Meeting in Boston, USA, on October 4, 2021, IATA member airlines passed a resolution committing to achieve net-zero carbon emissions from their operations by 2050. This pledge aligns air transport with the objectives of the Paris Agreement, which aims to limit global warming to well below 2°C. To succeed, coordinated efforts from the entire industry—including airlines, airports, air navigation service providers, and manufacturers—along with significant government support, will be required (Our commitment to fly net zero by 2050, z.d.). This resolution has led to initiatives such as Airbus' and KLM's Cabin of the Future initiative.

Hydrogen has emerged as a promising alternative fuel, offering zero carbon emissions and potential cooling effects (Yusaf et al., 2022). However, implementing hydrogen technology faces challenges in terms of storage, cost, and infrastructure development. Moreover, sustainable aviation fuels (SAFs) offer significant potential for emissions reductions, with most SAFs reducing CO_2 emissions by 41–89% compared to conventional fuels (Song et al., 2024).

IATA analyzed the broad consensus on the transition measures available to the sector in its transition to net zero by 2050 (see Figure 7). All these mitigation levers are necessary and can be applied in various combinations. While the emissions reduction potential of each mitigation lever varies across roadmaps, all roadmaps identify Sustainable Aviation Fuel (SAF) as the largest contributor to CO_2 emissions reduction by 2050, with a median value of 53% (International Air Transport Association (IATA) et al., 2023).

Figure 7

Net zero transition



Other mitigation strategies include improving aircraft efficiency, accelerating fleet renewal, and adopting operational strategies to reduce contrail effects (Delbecq et al., 2023). However, even with these measures, aviation may only achieve a CO_2-equivalent emissions reduction of 46–69% due to non-CO_2 impacts, such as nitrogen oxides, water vapour, and contrails (Dray et al., 2022).

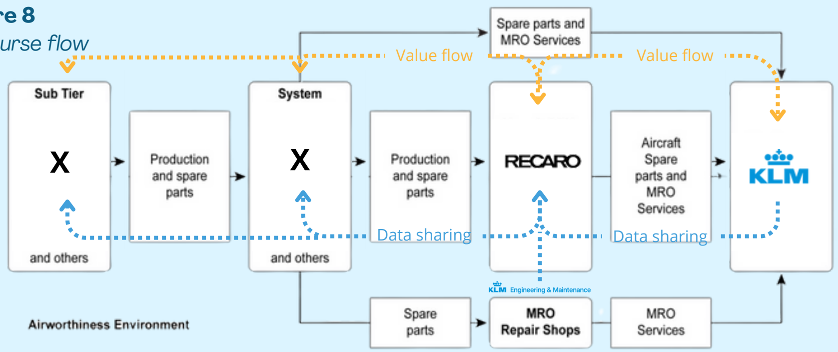
Additionally, the aircraft cabin and its operating processes have been a particular focus for manufacturers and airlines in reducing emissions (Hall et al., 2013). This emphasis arises from the high proportion of weight contributed by the cabin in a typical commercial flight (Tsai et al., 2014). Optimizations and changes in cabin layout can be implemented in existing fleets, enabling quick fuel savings for individual aircraft types as well as for entire cabin designs (Mortensen et al., 2022). These adjustments create opportunities for airlines to innovate without having to wait for fleet renewal.

3.4 Aviation Supply Chain

As the aviation industry strives for sustainability through measures like Sustainable Aviation Fuel (SAF) and operational optimizations, understanding the complexities of the supply chain becomes essential. The aviation supply chain is highly intricate, as each part of an aircraft must be certified by airworthiness authorities, which define strict requirements to guarantee safety. Due to the rigorous standards required to qualify a supplier, there is a very limited number of companies authorized to provide parts and services in the aviation industry (Rodrigues & Lavorato, 2016). This limitation leads to fewer options when selecting suppliers for new aircraft programs and results in a lack of leverage to negotiate favourable commercial conditions. Additionally, many system suppliers operate in multiple sub-tiers, making them suppliers to their competitors. This dynamic can negatively affect relationships between suppliers and, ultimately, the final customer. Figure 8 reflects this scenario, with KLM included as an example. Essentially, there are four key stakeholders in the aviation supply chain: sub-tier suppliers/system suppliers, aircraft OEMs, customers, and MRO repair shops.

Figure 8

Recourse flow



Given that the operational life of an aircraft can exceed fifty years, there is significant potential for aviation OEMs and maintenance, repair, and overhaul (MRO) companies to benefit from a collaborative product-service system (PSS) business model. This model can provide operational efficiency by supporting the product throughout its in-service life (Goncalves & Kokkolaras, 2015). A win-win partnership can be formed between MROs and OEMs by sharing data (teal line in Figure 8) to improve the quality of deliverables, such as maintenance services and product reliability. This collaboration can also increase value (orange line in Figure 8) for customers by enhancing aircraft availability.

3.3 The Circular Cabin

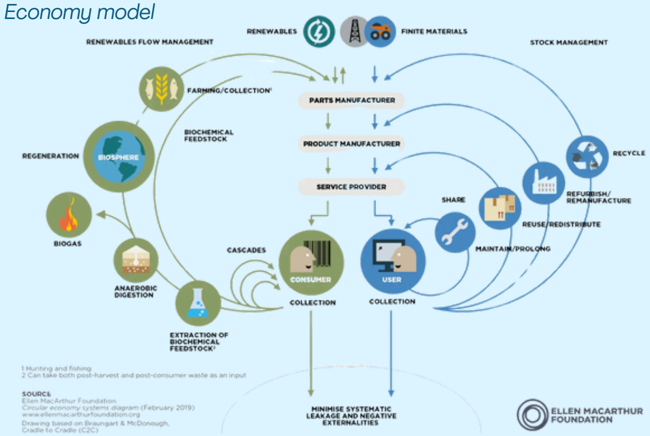
The collaborative efforts within the aviation supply chain, where stakeholders join forces to enhance efficiency and sustainability, represent an initial step in the transition from a linear model to a circular model. The Circular Economy (CE) model is designed to maximize resource use and minimize waste generation (Deutz, 2020) (see Figure 9). It is based on the 3R principles: reduce, reuse, and recycle (Heshmati, 2016).

Currently, the process of manufacturing products in our economy is linear: resources are extracted from the planet, used to create items, and then discarded as waste (Kim et al., 2021). In contrast, CE aims to eliminate waste from the outset by considering the entire life cycle of a product. Products and resources remain in circulation through composting, recycling, refurbishing, reusing, and maintaining (The Butterfly Diagram: Visualising the Circular Economy, z.d.).

CE practices offer significant potential for reducing emissions and improving sustainability across various sectors. In aviation, CE principles are being explored to convert waste into SAFs and implement waste reduction strategies (Khalifa et al., 2024). In particular, Maintenance, Repair, and Overhaul (MRO) services are increasingly adopting lean philosophy to improve efficiency and reduce waste (Sánchez & Sunmola, 2017). Waste management in aviation is a critical environmental concern, as airports generate diverse types of waste requiring sustainable disposal methods (Ravishankar & Christopher, 2022; Mehta, 2015).

Figure 9

Circular Economy model



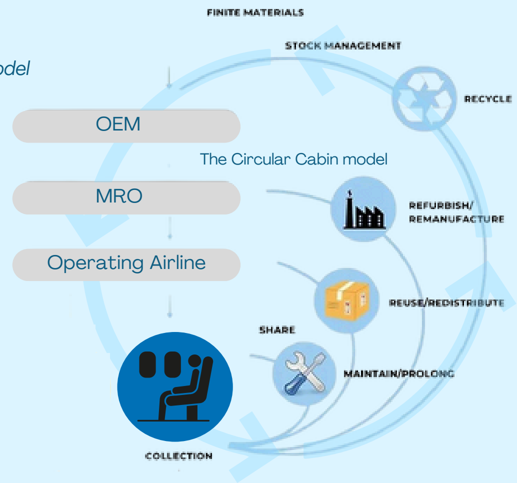
When looking at the automotive industry, the Circular Economy (CE) is emerging as a crucial sustainability paradigm (Aguilar Esteva et al., 2020). The automotive industry has developed networks for reusing, refurbishing, remanufacturing, recycling, and recovering parts from end-of-life vehicles (Catană et al., 2022). Government legislation and participation from original equipment manufacturers and automobile companies play a critical role in driving the industry toward sustainability, despite growing consumption (Patel & Singh, 2022).

The implementation of circular cabin parts in the aviation industry offers significant potential to decrease the amount of waste generated during MRO practices. However, challenges remain in scaling CE practices, including technological readiness, economic viability, and the need for more effective policies and research on emissions quotas and consumption patterns (Khalifa et al., 2024).

To address these challenges, the CE model is applied to the aviation MRO supply chain, serving as the foundational framework for this project (see Figure 10). This model integrates CE principles to establish a closed-loop material flow for the aircraft cabin. The Circular Cabin model focuses on maintaining, reusing, refurbishing, and recycling cabin interior parts to create a sustainable system. While maintaining, reusing, and refurbishing are already practised within the allowed operational limits, recycling has not yet been integrated into KLM E&M's processes. This presents an opportunity to explore and implement recycling as the initial step in this project. Future phases will focus on redesigning cabin parts to enhance their repairability and recyclability, further advancing the Circular Cabin model.

Figure 10

The Circular Cabin model



3.5 Market Potential

Airbus (OEM) anticipates significant growth in the market for aircraft dismantling and recycling over the next 20 years. The OEM expects that the used serviceable material generated will help ease the supply chain challenges currently affecting the industry, including parts shortages, high parts prices, and aircraft delivery delays. However, the industry faces obstacles, such as the lack of a robust market for recycled materials and the need for clear regulations (Maaß & Scholz, 2021). To address these issues, experts recommend enforcing global recycling standards and investing in research and development for composite recycling technologies (Scheelhaase et al., 2022).

During a media briefing on September 18, 2024, where Airbus presented its 2024-43 Global Services Forecast, the OEM predicted that the dismantling and recycling market will experience a 7.5% annual growth rate over the next 20 years. Nearly 19,000 older-generation aircraft are expected to be replaced, generating approximately $52 billion in used serviceable material (Airbus Amber, 2024). According to Amaya Rodriguez Gonzalez, VP of Aftermarket Strategy at Airbus, approximately 92% of an aircraft's weight can currently be recycled, and 30% of that weight can be converted into used serviceable material. This highlights the immense opportunities within this market (Airbus Amber, 2024).

3.6 Conclusion

This chapter demonstrates that collaboration within the supply chain, the application of the circular cabin model, and the growth of the aircraft recycling market collectively present a significant opportunity for KLM to reduce costs and enhance sustainability. By fostering stronger partnerships, KLM can create a collaborative ecosystem that increases the availability of recycled materials and streamlines processes.

The Circular Cabin model provides a clear framework for transitioning from a linear approach to a closed-loop system. This enables KLM to recover valuable resources, reduce dependency on virgin materials, and minimize waste. Furthermore, the anticipated growth in the recycling market offers a tangible financial incentive to invest in recycling cabin interior parts, supporting both economic and environmental goals. The next chapter focuses on the methodologies used to address the subquestions, outlining actionable steps for integrating these opportunities into KLM's operations.

Research
Explore
Define

Design
Develop
Test

4 Methodology

4.1 Introduction

This chapter outlines the methodology used to address the main research question by detailing the research approach and methods employed. Each subquestion is paired with specific methodologies, including literature research, fieldwork, expert consultations, and practical testing. These approaches are described to provide a clear understanding of how the research was conducted and how they support the analysis presented in the subsequent chapter.

4.2 Methodology

To answer the central research question—"How can the circular cabin model be successfully integrated into Maintenance, Repair, and Overhaul (MRO) operations?"—a series of subquestions were developed to systematically address specific aspects of the overarching challenge. Each subquestion was explored using a tailored methodological approach, combining literature review, fieldwork, expert consultation, and practical testing. These methods ensured that the findings were grounded in both theoretical frameworks and practical insights. The methodologies applied to each subquestion are as follows:

Subquestion 1: What are the key factors influencing the adoption of recycling practices for KLM aircraft cabin interior parts, considering regulatory, economic, and operational constraints?

- This subquestion was addressed through literature research to identify key factors discussed in academic and industry sources. Field research was conducted to validate and expand upon these factors with real-world insights specific to KLM's operations.

Subquestion 2: How can the recycling potential of cabin interior parts be assessed?

- To answer this subquestion, a combination of literature research and field research was employed. Practical insights from a pilot project and consultations with experts across various departments in E&M were integral to the process. Additionally, validation sessions were conducted to ensure that the simplified knowledge frameworks applied in the research were accurate and comprehensive.

Subquestion 3: Which current Recaro cabin seat parts demonstrate recycling potential?

- This subquestion was explored through field research, involving collaboration with various internal and external stakeholders to identify potential parts for recycling. Complementary desk research was conducted to analyze and substantiate the assumptions regarding the potential of these parts based on available data.

Subquestion 4: What is the vision for the broader circular cabin project?

- A simplified design road mapping method was used to outline a future vision for the Circular Cabin project. This method provided clear steps for implementation while ensuring alignment with broader circular economy objectives.

Subquestion 5: How do the material properties of recycled cabin seat backrests change during the recycling process?

- This subquestion was addressed through field research and practical testing with partners like Egmond Plastic and Belgraver. The recycling process and fire resistance were evaluated to ensure compliance with aviation standards.

4.3 Conclusion

The methodology employed in this research was designed to systematically address the subquestions and, ultimately, the main research question. A combination of literature research, fieldwork, expert consultations, and practical testing ensured a comprehensive approach, allowing for both theoretical insights and practical validation.

Each subquestion was explored using methods tailored to its specific focus, ranging from identifying adoption factors and assessing recycling potential to conducting practical recycling tests on cabin seat backrests and evaluating certification processes.

In the following chapter, the research process and the answers to these subquestions are elaborated. Together, these findings will be synthesized to provide a clear and actionable response to the main research question, offering a pathway for integrating the circular cabin model into MRO operations effectively.

5

Subquestions

5.1 Introduction

This chapter outlines the process and results of the subquestions addressed in this project. Each section is dedicated to detailing the methods employed, the research conducted, and the insights gained. Key outcomes of this chapter include an overview of the main factors that influence the recycling process, a decision tree, a vision roadmap, a list of potential cabin interior parts for recycling, and a proof of concept.

5.2 Subquestion 1

Introduction

In this section, the method and research used to address subquestion 1, "What are the main factors influencing the adoption of recycling practices for KLM aircraft cabin interior parts, considering regulatory, economic, and operational constraints?" will be elaborated, culminating in the overview of the main factors as the final result.

Method

To address this subquestion, a combination of literature research and expert interviews within KLM's Engineering & Maintenance (E&M) ecosystem was employed. The literature provided insights into regulatory, economic, and operational factors, which were validated and refined through practical discussions to ensure alignment with KLM's specific context.

Research

<u>Step 1: Deep dive into literature</u>

The process began with a focused review of existing literature to build a solid foundation of knowledge on recycling processes in aviation. This deep dive aimed to identify key challenges, frameworks, and opportunities related to recycling cabin interior parts. The findings from this research are discussed in detail on the following pages and serve as the basis for the next step.

<u>Step 2: Validation and refinement with the internal ecosystem</u>

The insights from the literature were then validated and refined through brief expert interviews from KLM's internal ecosystem (Appendix 1: Project Ecosystem). This step ensured the relevance of the findings to the specific context of KLM's Engineering & Maintenance (E&M) operations. Additionally, the interviews provided supplementary insights that enriched the understanding of the factors influencing the recycling process. These added insights are highlighted in the overview on page X, with further details of the interview process documented in Appendix 5: Interview Main Factors.

Focused literature review:

This focused literature review examines the recyclability of parts and the constraints posed by regulatory, economic, operational, and social factors. Each section builds on the understanding that successful recycling practices require a balance between technical feasibility and broader considerations such as safety, economic viability, and sustainability goals. At the heart of these practices lies the recyclability of individual parts, forming the foundation for circular systems. From this starting point, the review explores how regulations, economics, supply chain dynamics, and social innovation influence the potential for implementing recycling processes.

Recyclability of the part

The recyclability of a part is determined during its design phase, as design decisions influence how effectively materials can be processed and reused. This forms the foundation for circular practices, making recyclability a crucial starting point for this review. The recyclability index provides a structured way to evaluate a part's potential for recycling (Rp) through three key factors (Martínez Leal et al., 2020):

$$R_p = \frac{C_m + D_m + R_m}{n_{al}}$$

- Compatibility of Materials (Cm): Ensures materials can be recycled together without degrading their properties, preserving the quality of recycled outputs.
- Diversity of Materials (Dm): A higher diversity of materials complicates separation and processing, while simpler material compositions enhance recycling efficiency.
- Recyclability of Materials (Rm): Measures the amount of material recovered and its purity, which are critical for maintaining value in recycled products.

These factors, compatibility, diversity, and recyclability, provide a practical framework for evaluating design decisions. This focus on design forms a critical link to the regulatory and safety requirements that guide material use.

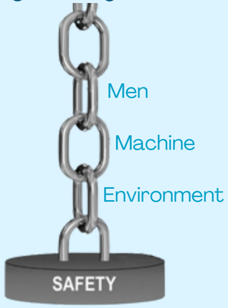
Regulations & Flight Safety

The aviation industry is highly regulated, with stringent standards ensuring that all parts meet safety requirements. These regulations are directly tied to the recyclability of parts, as changes in material composition or design during the recycling process must comply with airworthiness standards. This interplay highlights the importance of integrating safety and recycling considerations early in the design phase.

Flight safety depends on three interdependent factors: the person, the environment, and the machine (see Figure 11). A failure in any of these links can lead to an accident, emphasizing the need for robust safety measures (De Florio, 2016). Airworthiness standards eliminate or mitigate risks by setting strict requirements for aircraft parts. Modifications to parts must undergo rigorous approval processes, classified as minor or major changes depending on their impact. This classification determines the level of oversight required, with major modifications demanding extensive verification (De Florio, 2016).

Figure 11

Flight Safety



There are two types of changes to aircraft parts: minor and major. Minor changes, which have no appreciable effects on mass, balance, structural strength, reliability, or operational characteristics, can often be approved directly by an organization with Design Organization Approval (DOA) without additional oversight from authorities. Major changes, on the other hand, require comprehensive verification and direct approval from authorities like the European Aviation Safety Agency (EASA) or the Federal Aviation Administration (FAA) due to their potential impact on safety (De Florio, 2016).

The recycling process often introduces material and design changes, requiring parts to meet these airworthiness standards through certification. Achieving certification for recycled parts is complex and costly, as adjustments must be carefully assessed to ensure compliance with safety regulations, with an emphasis on fire safety (Xie et al., 2019). This regulatory framework highlights the critical balance between meeting safety standards and enabling efficient recycling, a challenge that directly connects to the financial implications of the process, explored in the next section.

Economic Viability

Economic viability is a key determinant of whether recycling cabin interior parts is feasible, particularly in light of KLM's financial challenges. Recycling offers potential cost savings by reducing resource consumption, landfill use, and environmental contamination (Asmatulu et al., 2013). It can also serve as a strategic supply source for manufacturers, enabling higher production quantities and profits (Raz & Souza, 2018). Studies suggest that recycling can often be more cost-effective than waste disposal, further supporting its economic potential (Bogert et al., 1993).

A major cost factor in recycling is the certification of recycled parts. Certification is essential for ensuring flight safety but is both complex and expensive, adding financial pressure to recycling efforts. This process is particularly costly for major design changes, which require extensive verification and direct approval from authorities (Xie et al., 2019).

Recycling becomes more economically viable in a closed-loop system, where secondary materials are returned to the original OEM, avoiding additional production costs such as creating new moulds for parts (Souza, 2012).. However, if recycled materials are diverted to alternative production routes, investment costs rise significantly, reducing feasibility. Strong partnerships with OEMs are crucial for optimizing costs and maintaining efficiency (Van Loon & Van Wassenhove, 2017).

Part availability further complicates recycling's economic feasibility. Low-demand parts, while critical for aircraft functionality, are often in short supply due to supplier reluctance to produce them, creating operational and financial challenges (Chenoweth et al., 2010). Grounded aircraft caused by missing parts can result in substantial financial losses, with potential savings from improved spare parts management estimated at $10–50 billion annually (McDonald, 2012).

The costs incurred from grounded aircraft due to part shortages often outweigh recycling and production costs in a closed-loop system. By stabilizing supply chains, closed-loop recycling can help alleviate material shortages, reduce stress on supply chains, and lower overall material costs (Xie et al., 2019). This economic perspective aligns closely with the operational and supply chain considerations discussed in the following sections.

Supply chain, Tech readiness & Partnership

As discussed earlier, the supply chain for aircraft parts faces pressure from material shortages and the unpredictability of low-demand components. To address this, the recycling process must be more efficient than the original supply chain and grounded in strong partnerships. Recycling complicates the supply chain, as it relies on a consistent flow of secondary materials. For a circular, closed-loop process to succeed, the supply chain must be prepared to handle both the technology and the frequent material flow required (Lapko et al., 2018).

The literature shows that closed-loop recycling of polymeric parts is possible, offering the potential for remanufacturing certified parts (Hyvärinen et al., 2023). However, challenges remain, including the lack of a mature market for recycled materials and the increasing use of composite materials in modern aircraft, which are more difficult to recycle (Maaß & Scholz, 2021). Despite these obstacles, the aircraft recycling industry is growing, with new recycling plants being established and best practices being developed (Maaß & Scholz, 2021).

Operational Considerations

Operational unpredictability poses a significant challenge to recycling cabin interior parts. Establishing a closed-loop system requires a consistent and sufficient flow of materials, which is difficult to achieve due to variability in repair needs.

Demand for spare parts in aircraft maintenance is highly variable, reducing confidence in forecasting models and negatively impacting aircraft availability. This variability also complicates repair pipelines, influenced by factors such as the number of previous repairs and the time since the last repair (MacLean et al., 2005). Repair shops face uncertainty in their capacity and the materials required for repairs, adding to the complexity of planning (Driessen et al., 2013).

Routine maintenance checks, ranging from short preflight inspections to detailed examinations, provide opportunities to collect recyclable materials. These checks, typically categorized as light maintenance (A-checks) or heavy maintenance (C-checks), see heavier checks producing a greater volume of scrapped or repairable parts (Deng & Santos, 2021). However, the phased collection of parts through these routine checks means it takes time to accumulate enough material for recycling, directly affecting the process.

Additionally, aircraft cabin modifications represent a significant aspect of the aviation industry, encompassing changes such as cabin redesigns, freighter conversions, and VIP completions. Over the next 20 years, an estimated 38,000 cabin redesigns are projected, highlighting a substantial opportunity to collect parts in significant volumes (M. Niță & Scholz, 2011). Aligning recycling efforts with these planned modifications offers a promising way to increase material availability and efficiency.

This alignment not only mitigates material variability but also supports broader sustainability goals and public perception efforts. These factors, tied to Corporate Social Responsibility (CSR), are explored in the next section.

Public Perception, CSR & Sustainability goals

Public perception, Corporate Social Responsibility (CSR), and sustainability goals significantly influence the extent of a company's sustainability practices. These factors directly impact the level of effort a company is willing to invest in recycling cabin interior parts.

The degree of a manufacturer's social responsibility plays a critical role in recycling activities, with an optimal threshold for maximizing the benefits of CSR practices (Modak et al., 2019). In closed-loop supply chains, CSR behaviour by manufacturers can enhance consumer surplus and system profitability, though it may reduce the efficiency of government subsidies (Wang et al., 2021). Overall, CSR initiatives, including recycling efforts, are pivotal in shaping consumer perceptions, optimizing business operations, and driving environmental sustainability.

Recent studies have investigated pathways to achieving the aviation industry's goal of net zero emissions by 2050. Key strategies include advancements in aircraft technology and operational efficiency, which could reduce emissions by up to 30% (Bergero et al., 2023).

The largest reductions, however, are expected to come from sustainable aviation fuels (SAF) (Jensen et al., 2023). Despite these advancements, the sector may still need to actively remove CO_2 from the atmosphere to counterbalance non-CO_2 forcing effects (Bergero et al., 2023). Even with these measures, aviation's CO_2-equivalent emissions are projected to decrease by only 46–69%, emphasizing the necessity for additional actions to address non-CO_2 impacts (Dray et al., 2022).

Social innovation

Social innovation is a critical factor in implementing new recycling processes within the aviation industry. Open social innovation projects, led by multifunctional teams, foster sustainable value creation and growth in aeronautics (Allal-Chérif et al., 2022). Social capital, derived from interpersonal relationships, plays a pivotal role in driving radical innovation. Strong departmental ties, competence-based trust, and tacit knowledge are essential for fostering creative and innovative thinking (Emre, 2012).

The aviation industry is undergoing three interrelated categories of change: technological, social, and process changes. Together, these drive sustainable transformations at a macro level across the sector (Wing & Cloutier, 2023). However, high workload pressures among aviation maintenance personnel remain a significant concern for aircraft safety. Studies indicate that stress, fatigue, and workload pressure can adversely affect maintenance performance, increasing the risk of errors (Santos & Melício, 2019; Dias et al., 2019).

For this project, the focus is on process change, as implementing the recycling process at KLM E&M will directly impact existing workflows. Given the already high workload levels, the adaptability and success of the recycling process will depend on its ability to minimize additional workload burdens.

Conclusion of focused literature review

The focused literature review identifies the key factors influencing the recycling of cabin interior parts in aviation. Recyclability, driven by material compatibility and design, forms the foundation for circular practices, while regulatory requirements, such as fire safety and certification, ensure airworthiness despite adding complexity.

Economic viability depends on managing certification costs and improving supply chain efficiency. Strong partnerships and local recycling infrastructure are also critical for success. Operational challenges, such as high workloads and inconsistent part availability, emphasize the importance of streamlined processes. Additionally, public perception, CSR, and social innovation drive adoption aligning recycling efforts with broader sustainability goals.

In the next section, these insights are refined through expert interviews, prioritizing the key factors necessary for effective recycling implementation.

Overview of total main factors

1. Recyclability of the Part

The recyclability of a part is largely determined by its design. The recyclability index highlights three critical factors: compatibility of materials, diversity of materials, and recyclability of materials (Martínez Leal et al., 2020). Material compatibility ensures that combined materials retain their properties during recycling while reducing material diversity, which simplifies the process. High recyclability of materials improves recovery rates and purity, making parts suitable for circular practices.

- Interview Insight: Understanding whether material properties change during recycling is crucial. One participant emphasized, "If the recycled material is identical to the original, it avoids additional certification. Otherwise, fire safety and batch consistency must be ensured" (Interview 6).

2. Regulations & Flight Safety

In aviation, strict certification regulations ensure flight safety and airworthiness. Any design changes, including recycled materials, must comply with EASA or FAA standards, often requiring extensive testing and approval (De Florio, 2016). Fire safety remains the most critical certification aspect for cabin interior parts.

- Interview Insight: Participants highlighted fire safety as the most important consideration for material approval, stating, "Material must be flame retardant and maintain structural integrity over its lifespan." (Interview 8).

3. Economic Viability

The feasibility of recycling depends on economic factors, including return on investment and certification costs. Recycling reduces environmental impact while potentially lowering material costs through closed-loop processes (Asmatulu et al., 2013). However, high certification expenses and fluctuating part demand pose challenges.

- Interview Insight: Interviewees noted the importance of cost management, stressing that "the financial business case will ultimately determine whether recycling is adopted" (Interview 3).

4. Supply Chain, Technology Readiness & Partnerships

Efficient supply chains and strong partnerships are essential for implementing closed-loop systems. Recycling infrastructure near KLM can reduce costs and improve logistics, but the readiness of these systems varies (Maaß & Scholz, 2021). Additionally, OEMs hold significant influence over material usage and recycling practices.

- Interview Insight: One participant noted, “OEMs prioritize their profit models, but airline pressure could drive more sustainable practices” (Interview 5). Another emphasized the importance of nearby recycling facilities, saying, “Local recycling capabilities are key for efficient operations” (Interview 1).

5. Operational Considerations

The unpredictable flow of cabin parts, driven by maintenance schedules and varying repair needs, complicates recycling. Maintenance planning requires consistent material availability for closed-loop systems (MacLean et al., 2005).

- Interview Insight: Workload was highlighted as a major concern. “High workloads leave little capacity for additional tasks like material separation, making process simplicity critical” (Interview 2).

6. Public Perception, CSR & Sustainability Goals

Sustainability efforts in aviation are increasingly shaped by public perception and CSR initiatives. Recycling aligns with net zero goals, enhancing a company’s reputation and consumer trust (Modak et al., 2019).

7. Social Innovation

Implementing recycling processes relies on employee involvement and social innovation. Collaborative efforts across teams enhance creative problem-solving and process efficiency (Allal-Chérif et al., 2022).

- Interview Insight: “Knowledge and behaviour of employees are critical to success; proper training is essential to ensure recycling effectiveness” (Interview 1).

Conclusion

The overview presented is the result of insights gathered from the literature review and expert interviews, offering a detailed understanding of the main factors influencing the recycling process. The literature provided a robust theoretical foundation, identifying critical elements such as material compatibility, regulatory requirements, and economic feasibility. The expert interviews complemented this with operational insights, highlighting practical challenges and opportunities within the aviation industry. Together, these findings form a comprehensive basis for addressing the next subquestion: how to assess the recycling potential of cabin interior parts, which will be explored in the following chapter.

5.3 Subquestion 2

Introduction

In this section, the method and research used to address subquestion 2, "How do you assess the recycling potential of cabin parts?" will be elaborated, culminating in the decision tree as the final result.

Method

This subquestion was explored through a combination of theoretical and practical research. Literature provided a framework for evaluating recyclability, which was complemented by fieldwork insights from pilot projects and expert consultations. Validation sessions ensured the findings were accurate and applicable to real-world operations.

Research

Step 1: Literature Review

The literature review, explained in section 5.2, provides the basic knowledge needed to assess the recyclability of a part. It summarizes existing research, standards, and guidelines on how to evaluate materials and their recyclability. This step serves as the foundation for understanding the key concepts and criteria that will be applied in the practical part of the research.

Step 2: Field Research

In the second step, field research is used to gather practical insights. This research is based on the pilot study (see section 5.6 and the Visit appendices). The fieldwork helps connect the theoretical knowledge from the literature to real-world practices. It focuses on gathering firsthand information from industry experts, observing recycling processes, and understanding the specific challenges involved in recycling cabin interior parts.

By combining the knowledge from both the literature review and the field research, a set of practical questions is developed. These questions will help evaluate the recyclability of cabin interior parts, looking at factors such as material type, ease of disassembly, contamination risks, and environmental impact.

IStep 3. Question Overview

Needed to start: Part Number, Part name, Part visual

To begin, it's important to gather the part number, name, and a visual representation of the part. This information is essential for ensuring the process runs smoothly, as it clearly identifies the exact part being assessed.

The part number can usually be found directly on the part itself and can also be cross-referenced in SAP or the part's manual. (Source: Pilot experience)

Is there a relatively high number of repairs in combination with high costs?

To determine whether a part is worth recycling, its usage frequency and associated costs must be evaluated. Currently, a part is considered viable for repair if it is used or repaired at least 10 times a year and costs over 1000 euros (Source: Repair Lab). For lower-cost parts, such as plastic parts, repairs are only considered if the recycling process is cheaper than producing a new part. This evaluation relies on data from SAP systems, which provide insights into repair frequency and costs, as well as input from Salvation and Warranty teams, mechanics, and Scrap Plaza. This approach ensures that repairs are both cost-effective and practical.

Is the part scrapped when disassembled from the aircraft?

Only parts that are scrapped are eligible for recycling. Parts that can still be repaired or are covered by warranty are not eligible, as they can either be restored to working condition or replaced under warranty terms. Recycling is reserved for parts deemed beyond repair or reuse. (Source: Salvation & Warranty)

Is there a modification on the agenda for this part or a consistent flow of repair?

A successful recycling process requires either a large batch or a consistent flow of materials. Recycling becomes impractical with small quantities, as manufacturers often have minimum batch size requirements, and the costs associated with machinery and processing outweigh the benefits for smaller volumes. (Source: Pilot experience)

Does the part consist of multiple materials?

For a part to be suitable for recycling, its design should be simple and ideally made from a single material (Martínez Leal et al., 2020). If the part is composed of multiple materials, additional steps are required to separate them, as KLM staff typically do not have the capacity to perform this task. In such cases, external support, such as social workshops, may be utilized for material separation.

Is the material recyclable?

The next step is to determine whether the material is recyclable. This begins by identifying the specific material used, which can be done through consultations with engineering teams and the OEM.

Once identified, the material's recyclability is analyzed in collaboration with industry experts to assess its suitability for recycling processes. (Source: Pilot experience)

Is the OEM interested in setting up a closed-loop system?
Contact the OEM to explore their interest in establishing a partnership for a closed-loop recycling system. If the OEM is not interested, proceed to collaborate with a third-party supplier to develop an effective recycling system instead. (Source: Pilot experience)

These questions will lead to the following end options:

- Due to economic, logistical, and material factors, this part is not in scope for KLM to recycle at this point.
- Play into the planned modification or consistent flow and set up a partnership with an OEM Set up part collection with Scrap Plaza.
- Play into the planned modification or consistent flow and set up a partnership with an OEM Set up part collection with Scrap Plaza

<u>Step 4. Design of the process tree</u>
As the decision tree should be shareable throughout all E&M departments, it should be easy to understand. Therefore, the decision tree is made from the KISS design principle. The process is simplified as much as possible, utilizing simple language with a clear, appealing look and feel in KLM colours.

<u>Step 5. Testing</u>
To test the result, the decision tree was tested with colleagues to see if they could easily understand the process without prior knowledge. Some adjustments in language were made. The decision tree was also discussed inside the ecosystem with experts to test the accuracy of the simplified knowledge. No discrepancies were found by the experts.

Result
The complete decision tree is presented in Appendix 14 : Decision tree.

Conclusion
The decision tree developed in this project offers KLM E&M a practical tool for evaluating the recyclability of cabin interior parts. By combining insights from literature, field research, and validation within KLM E&M’s internal ecosystem, this tool provides a clear, structured pathway to assess each cabin interior part’s recycling potential. The resulting questions guide users through key considerations, such as cost-effectiveness, material composition, and repair frequency. Enabling KLM E&M to make informed decisions about which parts can feasibly be recycled. With its simple design and clear language, the decision tree is intended for easy application across E&M departments, supporting the project's goals of fostering interdepartmental knowledge sharing.

5.4 Subquestion 3

Introduction

In this section, the method and research used to address subquestion 3, 'Which current Recaro cabin seat parts demonstrate recycling potential?' will be elaborated, culminating in a visual overview as the final result.

Method

The methods for this subquestion combined field research and desk research. Scrapped parts were analyzed during site visits, while maintenance data was used to substantiate observations. Collaborations with manufacturers added further insight into material suitability for recycling.

Research

Step 1: Salvation & Warranty

The process began with a visit to the Salvation & Warranty department to gather information. Scrapped parts were analyzed, and discussions with part handlers provided insights into which cabin parts were most frequently scrapped. This field research resulted in the initial identification of parts with recycling potential. (See Appendix 7: Visit to Salvation & Warranty.)

Step 2: Aircraft Analysis During Checks

Further identification of parts was carried out in collaboration with mechanics during scheduled A and C checks. Mechanics shared their experience regarding cabin parts that often break or require replacement. Aircraft in Hangar 11 were inspected, and frequently damaged parts were added to the list. (See Appendix 9: Visit to Hangar 11.)

Step 3: Data Analysis

To support the findings, data analysis was conducted. Part numbers identified during field research were located in maintenance manuals and then cross-referenced in SAP (data program of KLM). This provided data on repair frequency and part costs, adding a data-driven layer to the initial observations.

Step 4: Collaboration with Recaro

Material information for the identified parts was collected in collaboration with Recaro. This data is essential for recycling parts into secondary materials. Additionally, material groups were created to enable more efficient collection and processing.

Step 5: Additional data

Eventually, stock planning helped in finding most of the missing data. It also provided meaningful insights into some constructions used, for example, to clean the seat covers. However, not all data could be found. The number of used backrests, for instance, could not be determined because these parts go through the repair shop and are not officially scrapped, which made it difficult to track.

Result

From the Excel overview, a visual overview was created to present the most insightful information. This overview is presented in Appendix 13: Overview of Recaro seat parts.

Conclusion

The goal of this section was to identify cabin interior parts with significant recycling potential by analyzing their usage patterns and associated costs. Although data limitations prevented a fully comprehensive analysis, key insights were gained for parts from the Recaro seat. A visual representation was created to showcase the most relevant data, revealing the estimated annual purchasing costs for four key plastic economy seat parts.

These findings highlight the substantial financial significance of these four relatively small parts. Given their limited scope, the total costs associated with all seat parts across the fleet are likely to be far greater, underscoring the potential for significant cost savings through recycling initiatives. However, challenges in accessing and consolidating data remain a barrier to further analysis.

5.5 Subquestion 4

Introduction

In this section, the method and research used to address subquestion 4, "What is the future vision for the broader circular cabin project?' will be elaborated, culminating in the strategic roadmap as the final result.

Method

This subquestion was addressed through a strategic roadmapping approach. Stakeholder input guided the development of a long-term vision for circularity, while phased steps were outlined to ensure actionable and practical implementation.

Research

<u>Step 1: Future Vision</u>

The design process starts with crafting a forward-looking vision that clearly articulates the ultimate goal of the Circular Cabin project. This vision positions KLM as a leader in sustainability and innovation, aiming to set a new industry standard for circular cabin interior parts. The future vision establishes KLM's role in adopting a fully closed-loop system, where every cabin part is designed with end-of-life recycling in mind. This vision serves as the guiding principle for all subsequent steps in the roadmap, ensuring that every decision and action is aligned with the long-term objective of circularity.

<u>Step 2: Horizon 0 – Current Status (2024)</u>

The first horizon, "Current Status," focuses on evaluating KLM's existing operations. The design of this horizon aims to establish a comprehensive understanding of the current state, specifically how cabin parts are disposed of when damaged beyond repair. This phase highlights key challenges, including the siloed organisational structure, regulatory constraints, and lack of collaboration, which hinder innovation. By recognising these barriers early on, the roadmap creates a foundation for change. The goal in Horizon 0 is to foster greater awareness of sustainability practices and lay the groundwork for transforming KLM E&M into a more collaborative and innovative environment.

<u>Step 3: Horizon 1 – Take-Off (2024-2025)</u>

Horizon 1 marks the beginning of the Circular Cabin project, laying the foundation for future growth. The design of this horizon is centred around establishing a collaborative ecosystem that connects stakeholders from various departments within KLM. By focusing on breaking down the siloed structure and encouraging knowledge sharing, this phase sets the stage for innovation and the successful adaptation of circular practices. The main objective of Horizon 1 is to transition from isolated, individual efforts to a more unified and cooperative approach. This collaborative network will play a crucial role in building the project's long-term success. During this phase, a small-scale pilot is conducted to explore the practical applications of recycling cabin interior parts, preparing the project for the next stage.

<u>Step 4: Horizon 2 – Pilot (2025-2026)</u>

In Horizon 2, the focus shifts to conducting a substantive pilot to test the feasibility of recycling cabin interior parts. The design of this phase revolves around collaboration with key partners, such as seat OEM Recaro, to further develop a proof of concept. This pilot is critical in evaluating the quality and performance of recycled materials for the full material certification. The aim is to explore how these materials can be integrated into future cabin designs, even if they are not yet fully certified for use. A significant milestone of this horizon is the first Cabin Roundtable meeting, where stakeholders across KLM will discuss potential applications for cabin recycling practices. Horizon 2 aims to demonstrate the viability of circular cabin parts, scale the ecosystem, and lay the groundwork for scaling these solutions in the future.

<u>Step 5: Horizon 3 – Scaling Up (2026-2027)</u>

Horizon 3 focuses on expanding the pilot project and scaling up the Circular Cabin initiative. The design of this horizon involves broadening the scope of recycled materials from just seats to include other cabin parts, such as headphones, lifejackets, and carpets. Where the certification of new parts with recycled material is crucial. This phase will also see the expansion of the collaborative ecosystem, incorporating a wider range of stakeholders, including additional OEMs and suppliers. The goal is to foster a larger, more diverse network capable of solving the challenges associated with implementing circularity across the aviation industry. By the end of Horizon 3, the project will be closer to full-scale implementation, setting the foundation for long-term sustainability and industry-wide impact.

Step 6: Horizon 4 – Closed Loop Parts (2028+)

The final horizon envisions KLM E&M at the forefront of sustainable aviation. In this phase, the design focuses on refining the circular cabin system to enable a fully closed-loop recycling process for cabin interior parts. By 2028 and beyond, the goal is to establish a robust, operational system where all cabin parts are designed with end-of-life recycling in mind, making it possible to recycle, refurbish, and reuse parts across KLM's fleet. The collaborative ecosystem continues to grow, enabling the certification and integration of circular parts into future aircraft, supported by evolving regulatory frameworks. Horizon 4 represents the culmination of the Circular Cabin project, where KLM achieves its vision of a fully circular cabin interior system.

Result

The result, the strategic roadmap, is presented in Appendix 16: Strategic roadmap

Conclusion

The strategic roadmap provides a structured approach for KLM to achieve the project's goal of implementing the circular cabin model. Starting with the current status of cabin part disposal and advancing through each horizon, the roadmap outlines the necessary steps to establish a closed-loop recycling system in partnership with OEMs. By conducting exploratory pilots, validating a proof of concept, and building toward a fully integrated closed-loop process, KLM is set to lead the industry in sustainable cabin practices. This roadmap not only outlines actionable steps but also lays the groundwork for expanding collaborations with OEMs, levelling the supply chain's playing field, and reinforcing KLM's commitment to innovation and sustainability in aviation.

5.6 Subquestion 5

Introduction

In this section, the method and research used to address subquestion 5, "How do the material properties of recycled cabin interior parts change during the recycling process?" will be elaborated, culminating in an executed pilot and proposition.

Method

This subquestion involved field research and material testing in collaboration with industry partners. The recycling process was analyzed to evaluate changes in fire resistance and compliance with aviation standards, ensuring the feasibility of using recycled materials.

Research

Step 1: Set up the ecosystem

Through analyzing the current journey of a cabin part through the E&M department, contact was made in different departments of the internal ecosystem (Appendix 1). The journey of a part through E&M is showcased in Appendix 6: Cabin part journey. See the visit Appendices for an elaborate description of all site visits. Besides analyzing the processes in the departments in regard to the repair/disposal of parts, the identification of potential parts to recycle was initiated. This was done by utilizing the expertise of the employees in the departments.

Step 2: Part identification

Two departments were crucial in the identification of potential parts. Checkpoint Charly/Salvation and Warranty and Hangar 11 (Appendix 7 Visit: Salvation & Warranty, Appendix 9 Visit: Hangar 11). The contacts that were made early on helped in further identifying potential parts. This was done by analyzing the waste at Checkpoint Chalry and analyzing the broken parts inside aircraft (777-200/300, 787-900/1000, A330-200/300). From this analysis, the focus shifted towards plastic seat armrests. The potential was analyzed by material (estimation), number of repairs (estimation), cost (estimation), and design.

Step 3: Benchmark with manufacturers

After the first potential parts were identified, a meeting with Belgraver, Spiral, and Egmond Plastic was held to benchmark the possibility of processing the material. It was concluded that the materials could be processed. A partnership was settled with Egmond Plastic and Belgraver. For this, a batch of 10 kg material was needed.

Step 4: Part analysis

To further analyze the potential of the parts, research was done on the number of repairs, the costs of the part, and the exact materials. The cabin academy could provide the 2000-page manual of the Recaro seats to find the names and correct part numbers while also hinting that the backrests could also be of potential. Cabin Engineering helped to get insight into the exact material and set up contact with Recaro. Through stock planning, insight into the amount of repairs was gained.

Step 5: Part Collection & Opportunity Sourcing

After this, the collection of the armrest needed to be set up. While doing this, in collaboration with Salvatio & Warranty, several pallets with scrapped and unused backrests were found. Offering the opportunity to utilize these for the pilot.

Step 6: Legal & Shipping

To ship the parts out of Schiphol-Oost legally, the legal department was contacted. Additionally, the shipping went through the Parts Trading department, which repairs and sells scrapped engine materials. There was a delay due to high shipping costs, but eventually, the employees of Parts Trading delivered the batch themselves.

Step 7: Processing of the parts

Following the delivery of the backrests, a site visit was conducted at Egmond Plastic to discuss the next steps in processing the materials. Further details regarding this visit are provided in Appendix 2. During this visit, the backrests underwent a manual cleaning process, which included the removal and separation of additional plastic parts embedded within the backrests. Subsequently, the cleaned backrests were shredded, accumulating approximately 10 kilograms of granulate material, which was injection moulded into test plates.

During the shredding of the first batch of backrests, black material was identified within the granulate. This material was separated manually in order to continue. Cabin Engineering later confirmed that the black material originated from a repair method utilized by KLM. Specifically, thermoplastic material is added to the corners of the backrests to address cracks, a practice applied across multiple plastic parts. This repair method is a critical factor to consider when assessing the recyclability of a part.

Step 8 Testing of the material

To analyze whether the material properties changed during the recycling process, a test was conducted in collaboration with Belgraver. Details of this visit can be found in Appendix 3. During the test, the plates were evaluated for their "flammability resistance" properties. The results demonstrated excellent performance across all three criteria: no burning material dripped for five seconds, the burning length did not exceed twenty centimetres, and the flame self-extinguished within fifteen seconds. The full certification reports can be found in Appendix 12.

To fully certify the material on fire resistance, additional tests on smoke, heat release and toxicity were conducted at the test lab of Aeroworks. The results demonstrated that the recycled material passed all tests in the parameters of polycarbonate. Resulting in fully certified fire-resistant recycled material. The visit, details about the tests and the corresponding certification reports are showcased in Appendix 4: Visit Aeroworks. An overview of the total recycling process is visualized on the following page.

Step 9 Proposition

To preserve the integrity of the material, the decision was made to avoid repurposing it for other applications and instead focus on reintegrating it into the aircraft, ideally as the same part. This aligns with the broader objective of achieving closed-loop recycling for cabin parts. While repurposing the material could reduce waste that is currently discarded, limited resources and time necessitate prioritizing working towards the goal of closed-loop systems.

Additionally, a proposition is made for KLM on how the supply chain of a closed loop backrest would take form. Details of this proposition can be found in Appendix 14: Closed loop backrest model proposition.

Result

The material's properties remained unchanged when tested for fire resistance, indicating that it meets the certification requirements for fire resistance. This pilot serves as a minimal viable proof of concept, demonstrating that it is possible to recycle the backrests and minimally certify the material in terms of fire resistance.

Conclusion

This pilot marks a significant first step in evaluating the feasibility of recycling backrests and has successfully established a network of stakeholders to support future developments. The results confirm that recycling backrests while maintaining full fire resistance (flammability, toxicity, heat release and smoke release) certification is achievable, providing a minimal viable proof of concept.

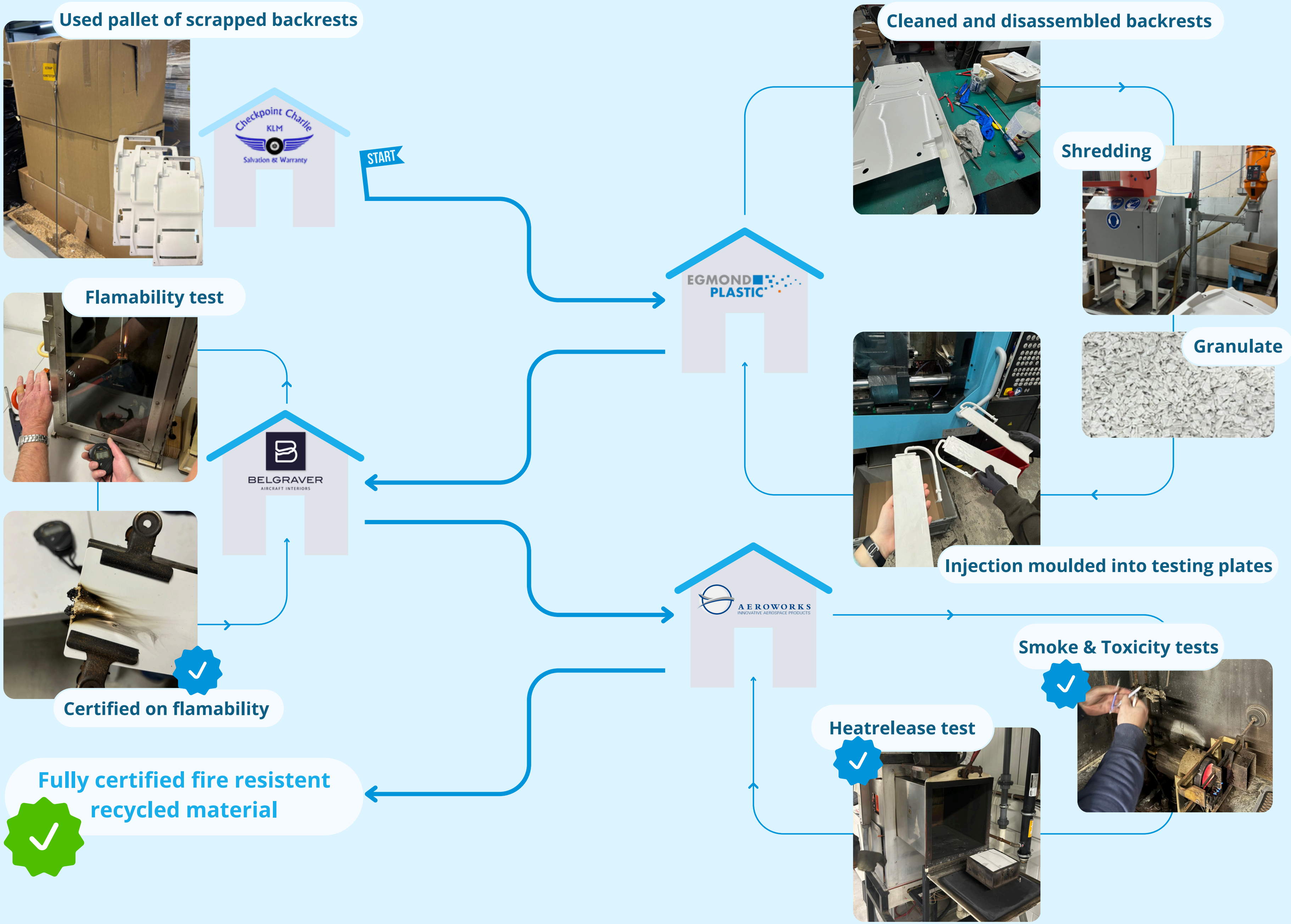
As discussed in the literature review the fire resistance certification is the most crucial certification. The polycarbonate material fully complies with fire safety requirements, therefore it represents a significant step towards certification, and the material could be quickly approved for use in certain applications. However, for critical or structural components, additional testing (mechanical performance, environmental and ageing and chemical resistance) may be required depending on the specific application, the FAA/EASA and the OEM. To further certify and test the material and work towards implementation of a seat part in flight a further pilot in collaboration with the OEM, in this case Recaro, is proposed.

A critical insight from this pilot is the tangible possibility of implementing a closed-loop recycling process. Through collaboration with partners such as Belgraver and Egmond Plastic, it has become evident that recycled materials can be reintegrated into the same part, bringing the vision of circular backrests closer to reality. This streamlined approach provides a clear pathway for achieving both sustainability and potential cost and supply chain efficiency.

Nevertheless, attention must also be given to the embedded materials used for mounting and repairs, as these significantly affect the recyclability of backrests. Further research is necessary to understand and mitigate the impact of these additional materials on the recycling process
.

The primary challenge to scaling this process is not the certification of recycled materials but advocating for changes in OEM requirements to allow the use of 100% recycled/non-virgin materials in aircraft parts. Addressing this barrier will be essential to achieving a fully circular cabin model. By leveraging the insights and partnerships established through this pilot, KLM can take a pivotal role in advancing sustainable practices and shaping the future of circular aviation.

Pilot process



5.7 Conclusion

This chapter systematically addresses the challenges and solutions for adopting recycling practices for KLM's aircraft cabin interiors. By exploring key subquestions, it provides insights into the feasibility, opportunities, and constraints of implementing a circular cabin model, ultimately paving the way for the design brief elaborated in the next chapter.

The adoption of recycling practices for KLM cabin interior parts is influenced by several factors, including regulatory requirements, economic feasibility, and operational constraints. Certification costs, return on investment, and the unpredictability of part demand complicate efforts to establish a steady recycling flow. However, public perception, Corporate Social Responsibility (CSR), and sustainability goals have become driving forces for implementing circular practices. These align with advancements in recycling technology, which hold promise for reducing emissions and improving material efficiency. Collaboration within the aviation industry remains critical to overcoming these challenges and achieving long-term sustainability.

To evaluate the recycling potential of cabin interior parts, a decision tree was developed. This tool integrates insights from literature, field research, and internal validation to provide a structured framework for assessing recyclability. By guiding users through considerations such as material composition, cost-effectiveness, and repair frequency, the decision tree helps KLM identify parts that are both technically and economically feasible for recycling. Its simple design and clear language make it a practical tool for use across Engineering & Maintenance (E&M) departments, facilitating knowledge sharing and collaboration.

A detailed assessment identified several cabin interior parts with strong recycling potential, particularly parts with high usage rates and significant cost implications. While data availability posed challenges, four plastic components of economy seats—armrests, backrests, armrest fronts, and insert literature pockets—were identified as promising candidates. Together, these parts account for a high amount in estimated annual purchasing costs, highlighting the financial impact of recycling initiatives. Despite limitations in data consolidation, the analysis underscores the broader cost-saving potential across the fleet.

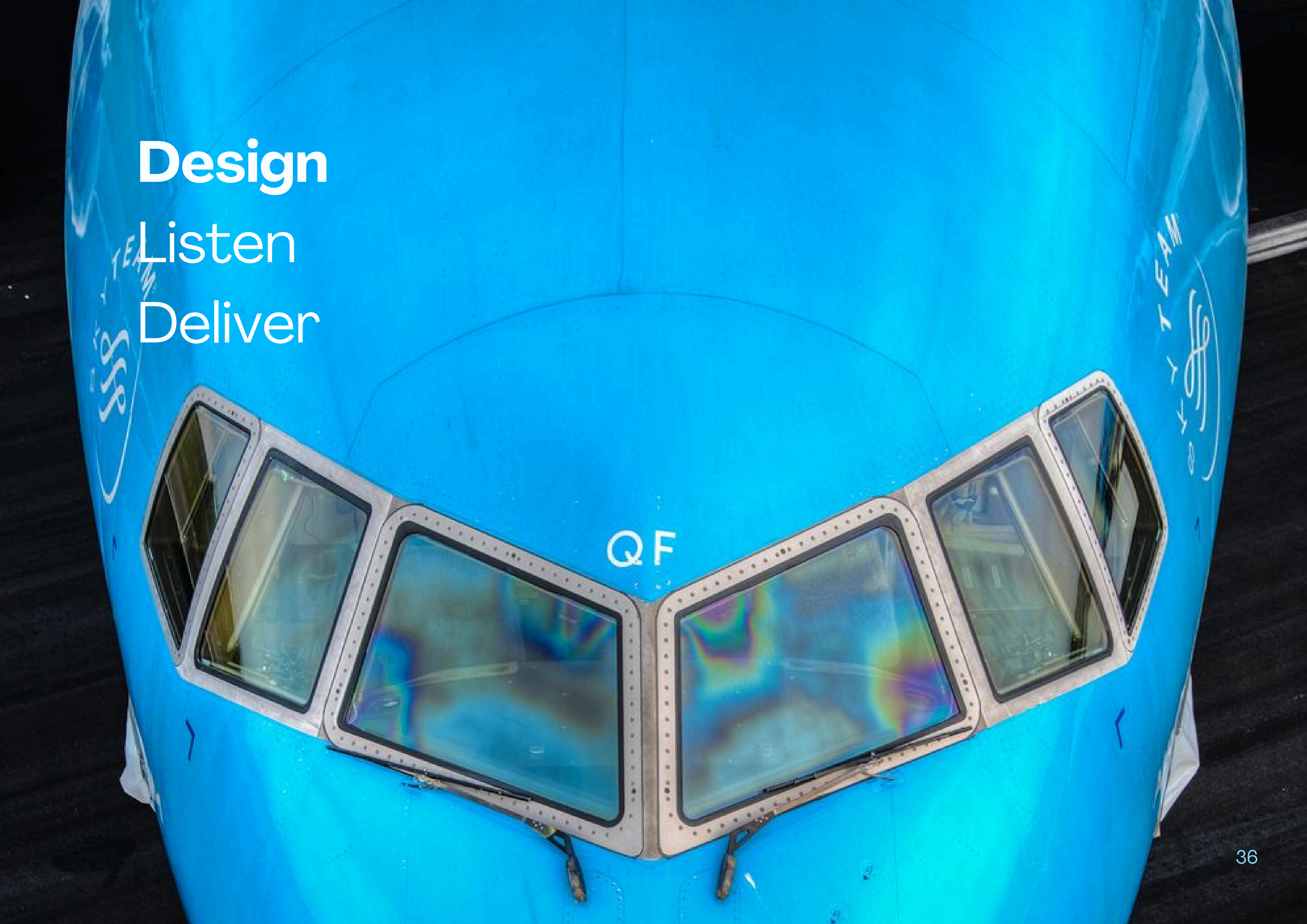
The strategic roadmap provides a structured, phased approach for KLM to implement a circular cabin model. By starting with the current status of cabin part disposal and progressing through exploratory pilots, proof-of-concept validation, and eventual integration into a closed-loop system, the roadmap outlines clear steps for achieving sustainable cabin practices. It emphasizes partnerships with Original Equipment Manufacturers (OEMs) and other stakeholders, positioning KLM as a leader in driving change across the supply chain. This approach advances sustainability goals, fosters interdepartmental knowledge sharing, and lays the groundwork for long-term innovation and collaboration in circular aviation.

A pilot study on backrests successfully demonstrated the feasibility of recycling backrests while maintaining fire resistance certifications, including flammability, toxicity, heat release, and smoke release. This marks a significant achievement, as fire resistance certification is the most critical safety requirement in the aviation industry. While the recycled polycarbonate material meets these fire safety standards and shows potential for use in non-critical applications, further testing is needed for critical or structural components, including assessments of mechanical performance, environmental and ageing effects, and chemical resistance, as required by FAA, EASA, and OEM standards. The pilot also proposed a circular supply chain workflow, involving cleaning and separating materials through a social workplace, followed by processing and reformation into recycled backrests. These findings suggest the technical viability of closed-loop recycling and highlight the potential for cost-efficient implementation.

However, challenges remain, particularly in addressing embedded mounting and repair materials of parts, which affect recyclability, and advocating for changes in OEM requirements to permit the use of 100% recycled materials. Currently, only 25% recycled polycarbonate is allowed in Airbus aircraft, highlighting the regulatory barriers that must be overcome to fully realize circular practices. Addressing these barriers is essential to scaling the process. Nonetheless, the pilot provides a strong foundation for achieving a circular cabin model, demonstrating that recycled materials can be recycled into material that is certified on fire resistance and has the possibility to be made into parts, paving the way for future industry advancements.

The insights from this chapter form the basis for the design brief in the next chapter, which translates these findings into an actionable playbook for implementing circularity within KLM E&M's MRO operations.

Design
Listen
Deliver



6
The Playbook

6.1 Design Brief

Design a **playbook** to guide the KLM E&M department in integrating the **closed-loop recycling of cabin interior parts** into their operations, enabling them to transition towards a **circular cabin model.**

Playbook:
A living document, acting as a guiding framework, in which, the way of working, the current work, opportunities and the future vision are explained.

Closed-loop recycling of cabin interior parts:
The process involves recycling materials from aircraft cabin interiors, such as seat backrests, and reprocessing them into new backrests. This can be repeated multiple times without compromising the material's quality.

Circular cabin model:
A model where the material flow for aircraft cabins forms a closed loop, ensuring components are recycled, reused, or refurbished at the end of their lifecycle to minimize waste and resource dependency.

6.2 Introduction

This chapter outlines the design and structure of the playbook, emphasizing its role in effectively communicating the objectives of the Circular Cabin project and motivating actionable change within KLM. Additionally, it examines the implementation process and highlights how the playbook contributes to fostering a culture of circularity within the organization.

6.3 Design of the Playbook

The concept for the playbook originated during an early meeting with Ton Dortmans, Vice President of KLM E&M, where the project was first introduced. In this discussion, he referenced a playbook used by the Airframe department, emphasizing its effectiveness as a structured guiding document within E&M operations. Recognizing this as a preferred and practical approach, it presented an opportunity to gain support for the project in subsequent phases.

This led to the creation of the following design brief:
Design a playbook to guide the KLM E&M department in integrating the closed-loop recycling of cabin interior parts into their operations, enabling them to transition towards a circular cabin model.

The playbook's design integrates the findings from the subquestions and insights from the literature review, ensuring it reflects both theoretical knowledge and practical applications.

<u>Step 1: Introduction</u>
The first chapter of the playbook serves as the entry point for the reader, offering an introduction to the Circular Cabin project. It provides essential background information about the Tech Hub and illustrates how the project aligns with strategic goals. Additionally, this chapter explains the circular cabin model as a foundational framework of the project.

<u>Step 2 Project Vision</u>
Once the context has been established, the playbook moves on to present the strategic roadmap of the Circular Cabin project. This chapter clearly communicates the project's long-term vision, outlining its objectives and the broader horizons it aims to achieve. It helps the reader understand the ultimate goals of the initiative and how the project is positioned within the larger context of sustainable innovation.

<u>Step 3: Way of Working</u>
With the project context and vision in place, the playbook transitions to explaining the practical aspects of the project. This chapter introduces the "Way of Working," detailing the key ways of working employed throughout the project. A key tool discussed here is the decision tree, which helps guide the evaluation of the recycling potential of various cabin interior parts, ensuring that decisions align with the project's sustainability goals.

Step 4: Pilot
Finally, the playbook concludes with an emphasis on the pilot phase, which acts as an inspiration and springboard for future research and development. This section discusses the practical steps that were taken and lessons learned from the pilot. It positions the pilot as a crucial step in translating the vision into tangible outcomes, paving the way for continued exploration and innovation.

<u>Step 5: Focus Areas</u>
Having established the project's working framework, the playbook shifts focus to identifying the key areas for future research. This chapter outlines the critical focus points that will drive the next phases of the project, highlighting areas where further exploration and potential collaborations are needed. It encourages readers to consider the possibilities for growth and innovation within the project.

Through this structured approach, the playbook effectively guides the reader through the key aspects of the Circular Cabin project, offering a clear and cohesive understanding of its purpose, progress, and potential.

<u>Step 7: Validation session</u>
To iterate the design and content of the playbook the playbook was shared with my team, the Tech Hub, at KLM E&M. The playbook was printed and hung on a board in the office where people could comment and discuss with me directly. These findings were implemented in the playbook.

After other iterations, the final version of the playbook was shared with experts (Repair Lab, Engineering & Hangar) in the internal ecosystem to validate if the playbook was understood correctly by different kinds of people. From this validation round, feedback was gained on clarification of the content and this was then implemented. Resulting in the final version of the playbook.

6.4 Implementation

This playbook is intended to serve as a guiding document, complementing the project report, and will be distributed throughout KLM to help raise awareness about circularity in the company's operations. It aims to highlight the Circular Cabin project and further guide the project. Beyond providing detailed insights into the project, the playbook is designed to inspire colleagues to integrate circularity principles into their everyday work.

The playbook will be printed, also in Dutch, and placed in strategic locations across key departments where it can have the greatest impact. These include the Tech Hub, the Sustainability Office at the head office, Scrap Plaza, Salvation and Warranty teams, and the office of Ton Dortmans (VP). This distribution will ensure the right teams have easy access to the material and can reflect on how they can contribute to circularity in their work.

Additionally, a poster will be created to give insights into the project and further promote the playbook and its message. Which will be hung throughout E&M. The poster will feature QR codes that link to the playbook PDF on SharePoint, allowing employees to quickly access the document digitally. This dual approach—using both printed materials and digital links—will maximize the reach of the playbook, encouraging engagement with the project and motivating staff to take action toward implementing circularity at KLM.

6.5 The Playbook

The playbook and supporting poster were handed in additionally from the report to the project supervisors.

6.6 Conclusion

The playbook directly addresses the main question—How can the circular cabin model be successfully integrated into Maintenance, Repair, and Overhaul (MRO) operations?—by fulfilling the design brief to provide KLM E&M with a playbook for incorporating closed-loop recycling practices. It offers a structured approach to transitioning toward a circular cabin model. Through its design, the playbook translates the project's strategic goals into clear, actionable steps, serving as a practical tool to bridge the gap between vision and operational implementation.

Built on insights from the subquestions, literature review, and pilot results, the playbook provides a comprehensive overview of the Circular Cabin project, its goals, and the methodologies required for success. Each section is crafted to guide KLM E&M employees in understanding the project's context, long-term vision, and practical workflows, such as using the decision tree to evaluate recycling potential. Additionally, it highlights focus areas for further research and collaboration, ensuring that the roadmap remains adaptive and forward-looking.

The iterative validation process, involving feedback from cross-departmental teams and internal experts, ensures the playbook is accessible, relevant, and applicable across various roles within KLM. By addressing challenges and outlining concrete steps for implementation, the playbook empowers employees to actively contribute to embedding circularity into their daily operations.

Through its thoughtful distribution strategy—combining printed copies, posters, and digital access—it maximizes its reach and impact within KLM. Beyond being a guiding document, the playbook fosters a cultural shift, inspiring employees to integrate sustainability into their work. Ultimately, the playbook serves as a blueprint for turning the vision of a circular cabin model into a practical reality.

7 Conclusion & Discussion

7.1 Introduction

This chapter presents the conclusion and discussion of the project, synthesizing the key findings and reflecting on their broader implications. By addressing the main research question—How can the circular cabin model be successfully integrated into Maintenance, Repair, and Overhaul (MRO) operations?—this research provides actionable insights into the adoption of circularity within KLM E&M. The findings offer practical solutions to current challenges while outlining opportunities for sustainable innovation that extend beyond KLM to the broader aviation ecosystem.

7.2 Conclusion

This project answers the main question through a structured exploration of key subquestions. By addressing the regulatory, economic, and operational challenges of recycling cabin interior parts and identifying parts with strong recycling potential the study provides a foundation for embedding circularity into KLM's MRO processes.

The outcome of the pilot study represents a major step forward in the journey toward circular cabin parts. It demonstrated that recycled polycarbonate materials can meet fire resistance certifications, including flammability, toxicity, heat release, and smoke release. As fire safety compliance is the most critical requirement for aviation materials, this finding underscores the technical feasibility of recycling cabin components. Moreover, this result opens the path toward the development of fully circular cabin parts and further testing to ensure their suitability for critical or structural applications. Future assessments of mechanical performance, environmental durability, and chemical resistance will be essential in advancing this development.

Building on these findings, the playbook provides KLM E&M with a clear and actionable framework for implementing circularity. It offers a structured approach to transitioning toward a circular cabin model. Through its design, the playbook translates the project's strategic goals into clear, actionable steps, serving as a practical tool to bridge the gap between strategic vision and operational implementation. By incorporating tools, accumulated by the subquestions, like the decision tree, a strategic roadmap, and focus areas for further research, the playbook equips KLM employees with guidance to adopt circular practices within their operations.

Together, the pilot and the playbook act as a blueprint for KLM to implement the circular cabin model into their operations. They provide not only the technical and strategic foundation but also the practical steps needed to embed circularity into MRO processes. These outcomes demonstrate a clear pathway for KLM to operationalize circularity, setting a strong precedent for its integration across the aviation industry and paving the way for a more sustainable future.

7.3 Broader value and implications

The outcomes of this project extend beyond offering a path forward for implementing circular practices at KLM, offering significant value to the aviation industry and academic research. By demonstrating the feasibility of circular practices in a highly regulated context, this project highlights the potential for sustainability-driven innovation to address financial, operational, and environmental challenges.

Value for KLM

For KLM, adopting circular practices could provide a comprehensive solution to critical financial and operational challenges. By enabling the recycling and reuse of high-value cabin parts, circularity could reduce material costs while simultaneously streamlining supply chain processes. The pilot study demonstrated that recycled polycarbonate materials can meet stringent fire safety certifications, paving the way for scalable cost-saving measures and the reintegration of recycled materials into cabin parts.

This shift enhances KLM's control over its supply chain, reducing dependency on OEMs and creating a more level playing field. KLM could mitigate part shortages and operational delays that often result from inefficiencies in traditional supply chains. Strengthening supply chain resilience through circularity directly supports KLM's financial goals and operational efficiency.

Moreover, circularity offers KLM the opportunity to align sustainability with its brand identity. Visible recycled cabin parts, such as seats, allow KLM to showcase its commitment to circularity directly to passengers, enhancing customer perception and reinforcing its reputation as a frontrunner in sustainable innovation. This dual benefit of operational efficiency and brand value highlights the transformative potential of circularity for KLM.

Value for the Industry
This project emphasizes the importance of collaboration across the aviation industry to overcome barriers to circularity. Partnerships with OEMs, suppliers, and social enterprises are critical for addressing challenges such as regulatory constraints and technical limitations in recycling. By demonstrating that high-quality materials can be recycled and reintegrated into cabin parts while adhering to aviation standards, the project provides a scalable framework for other airlines to adopt similar practices.

The integration of circularity across the industry has the potential to create new markets, reduce resource dependency, ease global supply chain pressures, and enhance sustainability efforts sector-wide. KLM's efforts can serve as a blueprint for collaboration and innovation, showcasing how airlines can drive sector-wide adoption of circular practices.

Value for Academia
From an academic perspective, this research contributes to the understanding of circularity in highly regulated industries like aviation. It bridges the gap between theoretical frameworks and practical applications, demonstrating how design and sustainability principles can be used to address complex operational and regulatory challenges. The pilot study and playbook provide a real-world case study, illustrating how circular economy principles can be effectively implemented.

By aligning sustainability with operational efficiency, this research advances academic discourse on sustainable innovation and provides a valuable reference for future studies. It highlights the potential for integrating circularity into industries where compliance with strict regulations is essential, contributing to the broader goal of advancing sustainable practices in challenging contexts.

7.4 Discussion & Limitations

This project has demonstrated the feasibility of integrating circularity into KLM's MRO operations, but significant challenges remain, highlighting the boundaries of this research and areas for further exploration. These challenges underscore the complexity of implementing circular practices within a highly regulated and financially constrained industry, requiring both internal organizational change and external advocacy.

One key limitation is KLM's siloed structure, which hinders the cross-departmental collaboration necessary to embed circularity into daily operations. While the playbook provides a framework for implementation, its success depends on fostering stronger communication and coordination across teams. Breaking down silos will require strategic efforts to align priorities, facilitate knowledge sharing, and establish shared ownership of sustainability initiatives.

Externally, regulatory barriers present significant hurdles. Restrictions, such as the 25% cap on recycled polycarbonate in Airbus aircraft, limit the broader adoption of recycled materials. Advocacy at the industry level is essential to address these constraints, requiring collaboration with regulators, OEMs, and other stakeholders. Further research is also needed to resolve technical challenges, such as the recyclability of embedded mounting and repair materials, which currently limit the full potential of circularity. Additionally, the absence of an NDA (Non-Disclosure Agreement) with Recaro, the OEM for the seat, restricted the ability for direct further collaboration, limiting opportunities to enhance the pilot's outcomes.

The certification processes for recycled materials remain another obstacle. While the pilot study confirmed compliance with fire safety standards, further testing in collaboration with Recaro is essential to meet additional requirements for structural and critical applications. This partnership would enable assessments of mechanical performance, environmental durability, and chemical resistance, unlocking the potential for broader application of recycled materials in aviation.

Finally, KLM's financial constraints add complexity to scaling circular practices. Balancing the need for cost-cutting with investments in sustainable innovation requires careful prioritization and a clear demonstration of long-term cost benefits.

While this project has laid a strong foundation for integrating circularity into KLM's operations, addressing these challenges will require strategic alignment, technical advancements, and strengthened collaboration with industry partners. The following chapter on recommendations outlines practical steps to overcome these challenges and further accelerate the adoption of circularity within E&M. By building on the momentum of this project, KLM can lead the aviation industry in shaping a more sustainable future.

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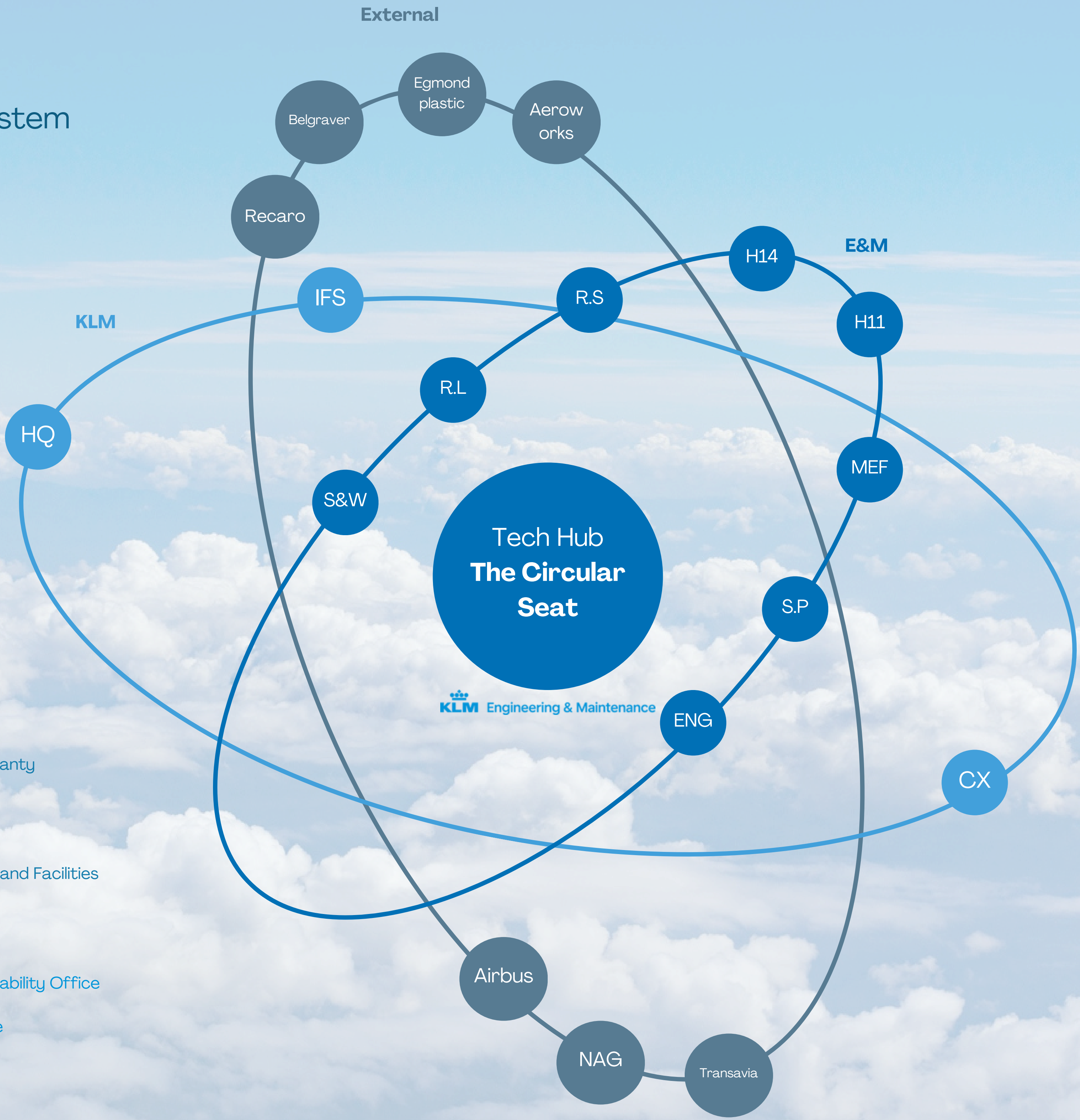
Appendix

Appendix 1 Project ecosystem
Appendix 2 Visit : Egmond Plastic
Appendix 3 Visit : Belgraver
Appendix 4 Visit : Aeroworks
Appendix 5 : Project Brief

Appendix 1
Project ecosystem



Internal:
S&W : Salvation and Warranty
R.L : Repair Lab
R.S : Repair Shop
H14 : Hangar 14
H11 : Hangar 11
MEF : Material Equipment and Facilities
S.P : Scrap Plaza
ENG : Engineering

KLM:
HQ : Head Quatre Sustainability Office
IFS : In Flight Services
CX : Customer Experience

Appendix 2 Visit : Egmond plastic

Location

Egmond Plastic is a specialized company focused on processing and recycling plastic materials for the aviation industry. Their expertise lies in converting plastic into high-quality granulate and molded products through advanced techniques such as shredding, injection molding, and material testing.

Purpose of Visit

The visit aimed to shred the collected backrest material and injection mold it into test plates to evaluate the feasibility of recycling the polycarbonate for future applications.

Main Insights

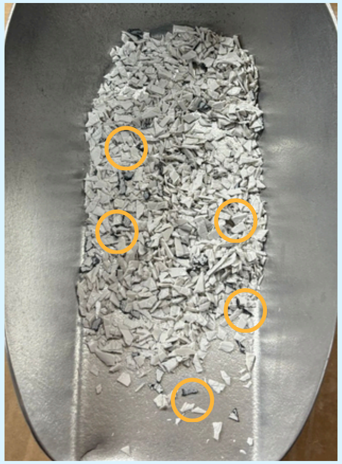
The cleaning and disassembly of the backrests proved to be a time-consuming process due to the additional materials embedded in the parts. These non-polycarbonate materials, such as adhesives and reinforcements, required manual separation to ensure the granulate's purity.

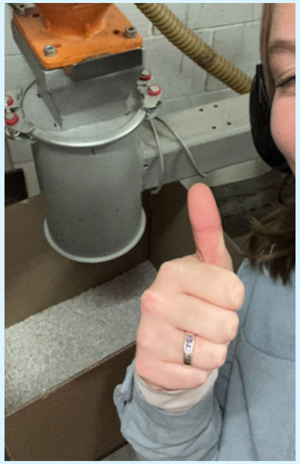
During processing, the granulate was found to contain black material, which was later identified as an embedded repair material occasionally used in the backrest. This material had to be manually separated, resulting in approximately 10 kilograms of "clean" polycarbonate granulate suitable for recycling.

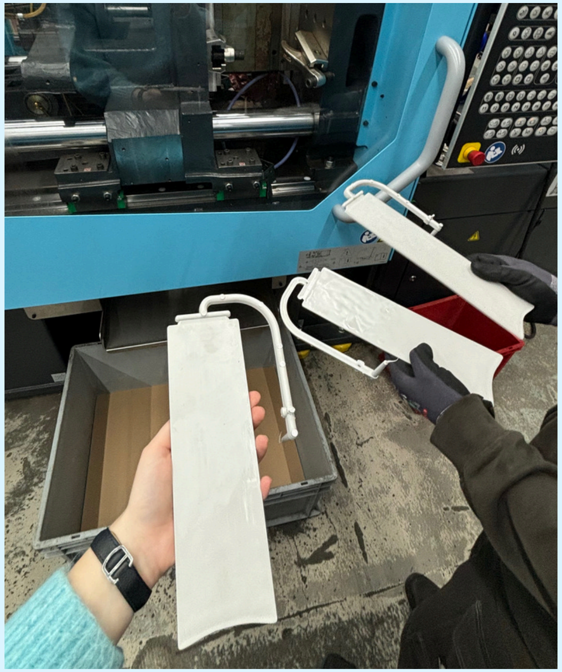
Additionally, the armrests could not be processed as they were discovered to be made from PVC, a material that is challenging to recycle. This highlighted the importance of material selection during the design phase to improve recyclability and reduce waste.

Repair of KLM Repair shop R6

- " VAC FORMER DOUBLERS"
- Thermoplast
- Material is formed using a hair blower
- Used for all plastic parts that are in the plastic repair manual







Appendix 3 Visit : Belgraver

Location

Belgraver is a company specializing in the refurbishment and repair of aircraft interiors, particularly seat covers and other cabin parts. With decades of experience in the aviation industry, Belgraver plays a critical role in maintaining high-quality standards for airline interiors while exploring sustainable practices.

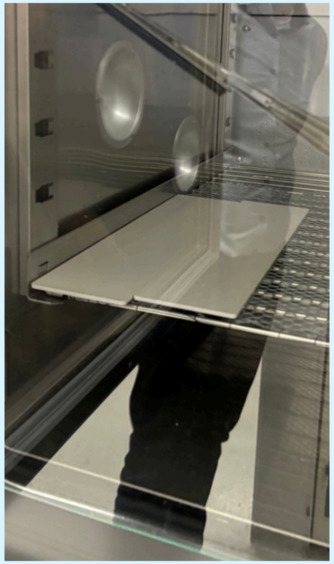
Purpose of Visit

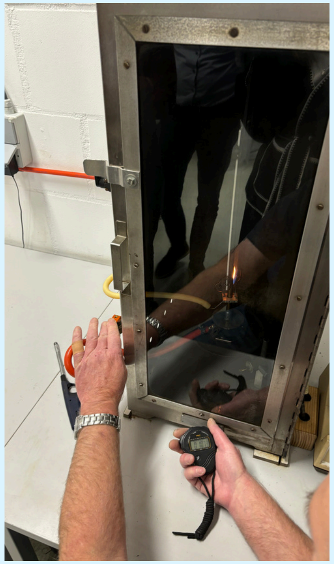
The visit aimed to test the recycled polycarbonate samples for fire resistance and to understand Belgraver's processes. Specifically, the goal was to evaluate how these recycled materials could be integrated into backrest production and to explore the handling and lifecycle of other cabin materials such as seat covers.

Main Insights

The recycled polycarbonate samples successfully passed the fire resistance tests. During testing, the plates were evaluated against three critical criteria: no burning material dripped for five seconds, the burning length did not exceed twenty centimeters, and the flame self-extinguished within fifteen seconds. These results confirm the material's compliance with essential safety standards for aviation use. The certification can be found on the following page.

Additionally, the visit provided insights into Belgraver's operations, particularly the handling of seat covers. Belgraver washes and repairs seat covers in bulk, but these covers are automatically scrapped after ten washing cycles. This raises questions about whether scrapping is always necessary and if alternative uses could be found for these materials. Exploring ways to repurpose or recycle scrapped seat covers could present new opportunities for sustainability within cabin interiors.



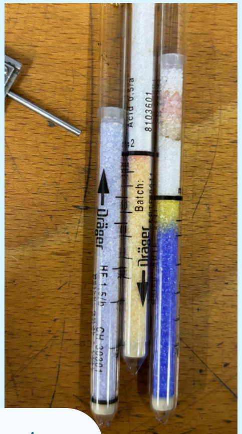


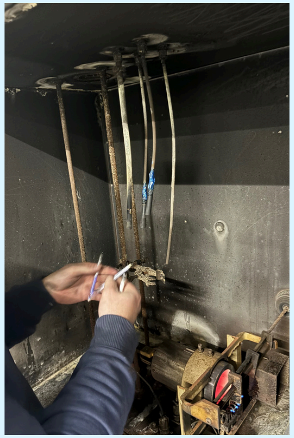
Appendix 4 Visit : Aeroworks

Location
Aeroworks, located in Middenmeer North-Holland, is an international company specializing in lightweight composite and metal components for the aerospace industry. They supply parts like panels and cabin components and operate an advanced testing lab for fire resistance certifications. Aeroworks collaborates with major aerospace clients, like Collins and Safran.

Purpose of Visit
The visit aimed to test the recycled polycarbonate samples for smoke, heatrelease and toxicity and to understand Aeroworks processes.

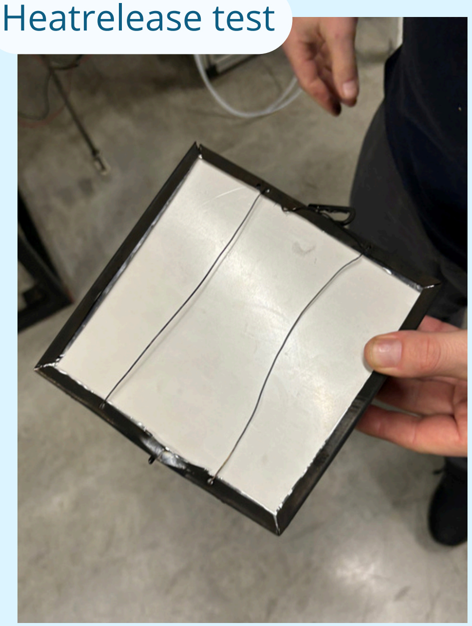
Main Insights
The recycled polycarbonate samples passed all three tests. The heatrelease test was conducted by measuring the energie that was released by the material when put aflame for 5 minutes. The Toxicity and smoke test where conducted by measuring the densitiy of the smoke produced and by measuring several chemical substances released in the air when burned for 4 minutes. The certification in shown on the next page





Smoke & Toxcicity tests

Heatrelease test



Appendix 5 : Project Brief

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

Project title The circular cabin

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)

In our modern world, aviation plays a crucial role in connecting people and driving technological innovation. However, the industry now faces the pressing challenge of integrating sustainable practices to ensure its long-term viability. Sustainability has become a strategic necessity, guiding aviation's future trajectory.

The Intergovernmental Panel on Climate Change (IPCC) highlights that aviation contributes around 2% of global man-made CO2 emissions. With rising concerns over global warming, initiatives to reduce the industry's carbon footprint are crucial. At the 77th IATA Annual General Meeting in 2021, member airlines committed to achieving net-zero carbon emissions by 2050, aligning with the Paris Agreement's goals. This ambitious target requires coordinated efforts across the industry, including airlines, airports, manufacturers, and government support.

A circular economy, where waste is minimized, and resources are kept in circulation through recycling, refurbishing, and reusing, offers a promising path forward. Circular design focuses on creating products that are reusable, repairable, and recyclable, contributing to sustainability. In aviation, integrating circularity into operations is critical for reaching the net-zero goal by 2050.

Airbus and other industry leaders are developing timelines and strategies to address these challenges. KLM has established a Sustainability Trajectory and a detailed roadmap to achieve its short-term and long-term goals. This project aims to support KLM in reaching its 2030 targets and contribute to the broader vision of sustainable aviation, ensuring the industry's future resilience and environmental responsibility.

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

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 Technology Hub is positioned within the Engineering & Maintenance department of KLM. With the purpose of executing KLM's strategic objectives of pioneering sustainable aviation. The Tech hub translates the strategic goals of E&M towards a tactical level and supports operational activities by a standardized methodology. While doing so, they connect and inspire external and internal ecosystems. Next to technological innovation, they also focuses on social innovation.
Due to the extraction and processing of raw materials, Aero purchasing is by far the biggest category in terms of emissions at the E&M department. Repairing a broken part is always more sustainable than discarding it. However, this cannot always be the case due to third-party manufacturers and high R&D costs.If a component gets discarded (correctly) it ends up in on of the waste streams. Residual waste being the largest category.

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:

Design a comprehensive system to optimize the end-of-lifecycle management of cabin parts, enabling the KLM E&M department to transition towards a circular cabin model.

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)

The theme of the project will be the circular cabin. The project will be conducted from an overall life cycle perspective. The whole life cycle of a product will be taken into account. Besides that, converging and diverging design thinking will be utilized.

Data gathering and data analysis methods will be utilized in combination with creative methods to find opportunity spaces.

These opportunity spaces will be explored and ideation will be implemented to find fitting solutions for the opportunities at hand. Overall taking into account the non-linear path of design thinking.

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	6 September 2024
Mid-term evaluation	22 Oct 2024
Green light meeting	19 Dec 2024
Graduation ceremony	31 Jan 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)

Since I was a child I have had the luck to fly across the globe and experience different cultures. I think travelling is one of the most precious parts of life. Cliche, I believe it is the only thing that you can buy that makes you richer. The downside to this treasure is that flying is one of the biggest parts of a human's environmental footprint. As sustainability is one of my other passions in life, my goal is to reduce the impact of flying. To ensure that future generations continue to benefit from aviation as much as I and the current generations have. The easiest solution would be to reduce the amount of flying. I think sustainable innovation is the solution. I believe the aviation industry can move towards Net-Zero and I want to be a part of this evolution.

Besides that, I want to feel confident in social corporate environments, working comfortably with different kinds of people. Last but not least I want to foster future research and innovation in aviation. Paving the way for future innovation and research.