Reverse Supply Chain in the Sustainability of the End-of-Life of Aircraft Cabin Seating Material

MOT2910: Master Thesis Project

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AIRBUS

Reverse Supply Chain in the Sustainability of the End-of-Life of Aircraft Cabin Seating Material

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Summary

The global focus on sustainability, aimed at achieving zero emissions by 2050, is pressuring industries like aerospace to reduce their environmental impact through initiatives such as ICAO's CORSIA. This effort extends to non-operational aspects like resource consumption and waste management, as millions of aircraft seats, replaced every 5 to 7 years, contribute significantly to waste. Although some sustainable practices exist, about 47% of cabin products are still unrecycled, where seats contribute 25% of them, underscoring the need for enhanced circular practices and the integration of Close-Loop Supply Chains in the aerospace sector. While studies on reverse supply chains in aerospace have been conducted, there is a lack of research on integrating Close-Loop Supply Chains to improve circularity and enable better recycling of cabin seats

This report, titled "Reverse Supply Chain in the Sustainability of the End-of-Life of Aircraft Cabin Seating Material," delves into the end-of-life (EOL) management of aircraft cabin seating materials within the aerospace industry, emphasizing sustainability amid increasing environmental concerns. The research aims to understand how implementing a close-loop supply chain (CLSC) can enhance sustainability in the EOL of cabin seating materials. This study is driven by the aerospace industry's need to address the environmental impact of retired aircraft, especially given the rising number of aircraft reaching the end of their operational life. It also aims to develop strategies for improving resource management and achieving economic benefits through sustainable practices.

Objective

Sustainability, driven by the goal of zero emissions by 2050, is a pressing global focus, especially impacting industries like aerospace which must reduce their environmental footprint through initiatives like ICAO's CORSIA. This challenge includes addressing resource consumption and waste from non-operational factors, such as the frequent replacement of aircraft seats, which significantly contribute to waste. Therefore, the primary objective of this thesis is:

To understand the potential impact of close-loop supply chain on the End-of-Life management of aircraft cabin seating materials.

This research is vital as the aerospace industry faces increasing pressure to adopt sustainable practices. Approximately 47% of cabin products remain unrecycled, where 25% comes from the cabin seats, highlighting the need for optimized circular practices. By investigating the potential of close-loop supply chains, this study aims to provide insights that could lead to more sustainable EOL management, reducing waste and improving resource efficiency in the industry.

To provide better investigation in achieving the objective, the main research question is

"How can a Close-Loop Reverse Supply Chain be effectively implemented in the EOL management of aircraft cabin seating materials?"

The sub-research question to support the main research question is presented as follows:

Sub-Research Question 1 – "Which components of aircraft cabin seating materials pose the greatest challenges to recycling from economic and environmental perspectives?"

Sub-Research Question 2 – "What kind of end-of-life management practices would be relevant?"

Sub-Research Question 3 – "What are the challenges, perspectives, and potential solutions identified by stakeholders involved in the end-of-life management of aircraft cabin seating materials?"

Methodology

A qualitative research approach has been used for this study, consisting of a literature study and case study with Airbus as the case holder has been taken to gather insights from stakeholders as well as to evaluate findings from the literature study. Semi-structured interviews with relevant stakeholders in the supply chain of an aircraft cabin seat are conducted to gather insights for the case study. Both approaches are adjusted into three phases to achieve the research objective: Preliminary Study; Aircraft Cabin Seating Decomposition and Supply Chain Dynamics; and Case Study: EOL Management of aircraft cabin seating material. The first phase focuses on understanding current EOL management practices in the aerospace industry and examining the materials and components of aircraft seats by reviewing relevant literature from academic and industrial sources such as grey literature. Meanwhile, the second phase involves the decomposition of seat components and supply chain analysis to identify the stakeholders in the current aircraft seating supply chain, assess its challenges, and explore opportunities for improvement. Additional literatures along with identified literatures from the first phase will be utilized to analyze and design the supply chain flow. This phase also examines how integrating Close-Loop Supply Chains (CLSC) can enhance the circularity and recycling of cabin seats. Finally, the third phase involves a case study to evaluate and validate the findings and gather insights from interviewees, aiding in the analysis and formulation of recommendations at the end of the report.

Outline

The report begins with an introduction to the significance of sustainability in the aerospace industry, particularly highlighting the anticipated rise in aircraft retirements. This sets the stage for the research by outlining the environmental challenges associated with aircraft EOL management. The preliminary study follows, offering a comprehensive literature review to identify components of aircraft cabin seating materials challenging to recycle and relevant EOL management practices. This chapter establishes the theoretical framework and identifies research gaps, laying the groundwork for the subsequent case study.

The aircraft seating decomposition and supply chain dynamics chapter analyzes the current and proposed supply chain flows for aircraft cabin seating, focusing on material recyclability and the challenges in implementing CLSC. It identifies key stakeholders, their roles, and the economic and regulatory barriers to sustainable EOL practices. The case study chapter involves interviews with industry experts to evaluate and validate the findings from the preliminary study and aircraft seat decomposition with supply chain analysis and design. It provides real-world insights into stakeholder perspectives, challenges, and potential solutions for sustainable EOL management.

The discussion chapter synthesizes the findings from the preliminary study, aircraft seating decomposition with supply chain dynamics, and case study. It compares theoretical models with practical insights, evaluates the consistency between literature and real-world experiences, and discusses the implications for sustainable EOL management. The final chapter presents the overall conclusions, recommendations for implementing CLSC in EOL management, and reflections on the research process. It highlights the need for economic incentives, improved material separation processes, and supportive regulations to promote sustainability.

Outcomes

The research reveals several critical insights. First, while recycling and reusing aircraft seat materials is technically possible, economic feasibility remains a significant barrier due to the high costs associated with material separation and recycling. Second, aircraft dismantlers and airlines play pivotal roles in EOL decision-making. Airlines often opt for landfill disposal due to cost considerations, complicating the adoption of sustainable practices. Third, establishing a direct communication line between material recyclers and seating manufacturers and implementing a material passport system can enhance recycling and reuse practices. These approaches focus on sharing detailed material properties and supporting informed EOL decisions. Finally, supportive regulations and economic incentives are crucial to overcome the barriers to sustainable EOL management.

Recommendations

To effectively implement a closed-loop supply chain (CLSC) for aircraft cabin seating materials, policymakers are encouraged to create regulations that direct retired seats to dismantlers rather than landfills, ensuring a sufficient volume of materials for recycling. Financial incentives, such as subsidies and tax breaks, can further support the economic viability of sustainable EOL practices.

Standardizing materials and promoting modular design can simplify the recycling process, while investments in advanced recycling and separation technologies can improve efficiency, particularly for non-metallic materials. Collaboration between seating manufacturers, OEMs, and airliners is essential to support these initiatives.

Stakeholder engagement is also critical, with aircraft OEMs leading efforts to foster cooperation among industry players. Academics can contribute by developing training programs and raising public awareness of sustainable EOL practices. Additionally, integrating robust information systems and material passports can facilitate better data sharing, guiding informed decisions for sustainable EOL management in the aerospace industry.

In conclusion, the report highlights the importance of integrating economic, regulatory, and technological strategies to promote sustainability in the EOL management of aircraft cabin seating materials. By addressing economic barriers and enhancing stakeholder collaboration through CLSC approaches, the aerospace industry can achieve significant environmental and economic benefits.

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1. Introduction

This chapter starts by setting the stage with the background and context of the issue that this study aims to tackle. In addition to laying out the study's backdrop, it will cover key concepts, provide an overview of the aircraft seating supply chain, and discuss current circular practices in the aerospace industry. Everything discussed in this section will be pivotal for addressing the problem at hand. Following this, the knowledge gap will be outlined. Finally, the chapter will present the thesis objective and the overall outline.

1.1. Background and Context

Sustainability has become an important topic recently, especially with the ambitions of several countries to reach zero emission (Gerasimova & Mitchell, 2021) which requires cooperation with industries to achieve the target. The ambition to reach net zero emissions by 2050 resulted in increased demand for sustainable practices, impacting every major industry around the world, including the aerospace industry (Gerasimova & Mitchell, 2021; Brinkle, 2023). The pressure to address the environmental impact in the aerospace industry has intensified over the years, especially with the release of the ICAO's CORSIA in 2021 which concerns carbon reduction scheme for international aviation (Aerospace Technology Institute, 2022) where airlines are mandated to buy carbon credits to offset the environmental impact of international flights. While environmental concerns are mostly concentrated around the operational side, such as fuel consumption of aircraft, non-operational aspects such as resource consumption and waste generation should also be considered (Aerospace Technology Institute, 2022).

Around 6,000 aircraft are currently parked at aircraft cemeteries worldwide, with several thousand permanently parked in the USA since the 1950s (Scheelhaase et al., 2022). Between 1980 and 2017, approximately 18,000 aircraft were retired globally, with projections indicating that over 20,000 commercial aircraft will be retired in the next two decades (Elsayed et al., 2019). Although the average retirement age for commercial aircraft is 25 years, passenger seats are typically replaced every 5 to 7 years, potentially leading to three replacements per aircraft lifetime (International Air Transport Association, 2019). This indicates that around 10.8 million seats have already been retired, with an additional 12 million expected in the next 20 years. With the increase of expected aircraft retirement numbers within the next 20 to 30 years, the End-of-Life (EOL) of aircraft production becomes significantly important requiring more environmentally and economically efficient ways of managing this phase (Scheelhaase et al., 2022).

Cabin weight plays a critical role in influencing environmental impact, where the scale of resource consumption and waste issues associated with the production and disposal of cabin products is influenced by their weight and frequency of replacement (Aerospace Technology Institute, 2022). Around 10% of total aircraft empty weight is contributed by cabin weight itself, with roughly 4,000 kg of weight out of 40,023 kg of total aircraft cabin weight in an Airbus A320 (Aerospace Technology Institute, 2022; Obert, 2009). Meanwhile, cabin seating constitutes roughly 41% of total cabin weight, contributing significantly to total resource consumption and waste generation in the cabin itself (Aerospace Technology Institute, 2022). The significant impact on environmental impact has triggered the cabin supply chain to engage in sustainable practices in both its operation and products (Aerospace Technology Institute, 2022).

In order to provide a better understanding regarding this topic, three important aspects will be presented in this section: namely the key concepts, aircraft cabin seating supply chain flow, and the current practices. These important aspects will be presented in this section to provide context to this topic. There are several key concepts that correlate with the topic, such as Circular Economy, Product End-of-Life, and Reverse Supply

Chain. Meanwhile general flow in the aircraft seating supply chain, and the current practices in aircraft cabin seating end-of-life management, will present the reality perspective in this topic.

1.1.1. Key Concepts

Circular Economy

As a widely recognized model and consumption, Circular Economy (CE) enables reductions in the usage of material through repeated material application where its effectiveness lies in the re-use, refurbishment, and recycling of products and components (Aerospace Technology Institute, 2022). Circular Economy (CE) could be defined as a system that prevents waste by continuously reusing materials, regenerating nature, and decoupling economic growth from finite resource consumption to address global challenges like climate change and pollution (Ellen Macarthur Foundation, n.d.). It is a concept that was first initiated in the 1970s, and stems from the idea of reducing input consumption for industrial production (Stahel, 2016). It consists of the following principles: value enhancement, versatile product development, systematic solid waste return, and adoption of a systemic approach to supply chain management (Arruda et al., 2021). Despite its idealistic principles, this concept still entails environmental externalities as it consistently arises due to the consequence of transactions between various entities (Genovese et al., 2017). According to the recycling approach guidelines, a more effective strategy involves first considering solutions with the lowest impact, such as refusing or reusing products (Intergovernmental Panel on Climate Change, 2014; OECD, 2019). Subsequently, if more efficient solutions are unfeasible or inappropriate, one can gradually move toward higher impact options (Aerospace Technology Institute, 2022).

Product End-of-Life

A product End-of-Life (EOL) begins when customers dispose of the product (Ciceri et al., 2010). There are various end routes of EOL, such as product reuse (Huisman, 2003), remanufacturing (Butzer et al., 2016), recycling, and disposal (European Environmental Agency, 2009). While the quantity of End-of-Life (EOL) aircraft is considerably smaller in comparison to electronics or vehicles, it has an economic attractiveness due to high-quality materials and valuable sub-assemblies which is crucial for generating value for all stakeholders (Mascle, 2018; Keivanpour et al., 2013). Additionally, the number of retired aircraft is expected to increase over the years (Scheelhaase et al., 2022), creating significance in terms of challenges and opportunities in managing the EOL of aircraft, especially in cabin materials.

Reverse Supply Chain

As an implementation of Circular Economy values in the supply chain context, the Reverse Supply Chain emerges as an approach that is associated with product design, operations, and end-of-life management; with the objective of optimizing value creation throughout the entire lifecycle (French & LaForge, 2005; Genovese et al., 2017). One of the categories of this supply chain is the Close-Loop Supply Chain (CLSC), which revolves around the practice of retrieving products from customers and returning them to the original manufacturer. This allows for the recovery of added value by reusing either the entire product or a portion of it (French & LaForge, 2005).

1.1.2. General Flow of Aircraft Cabin Seating Supply Chain

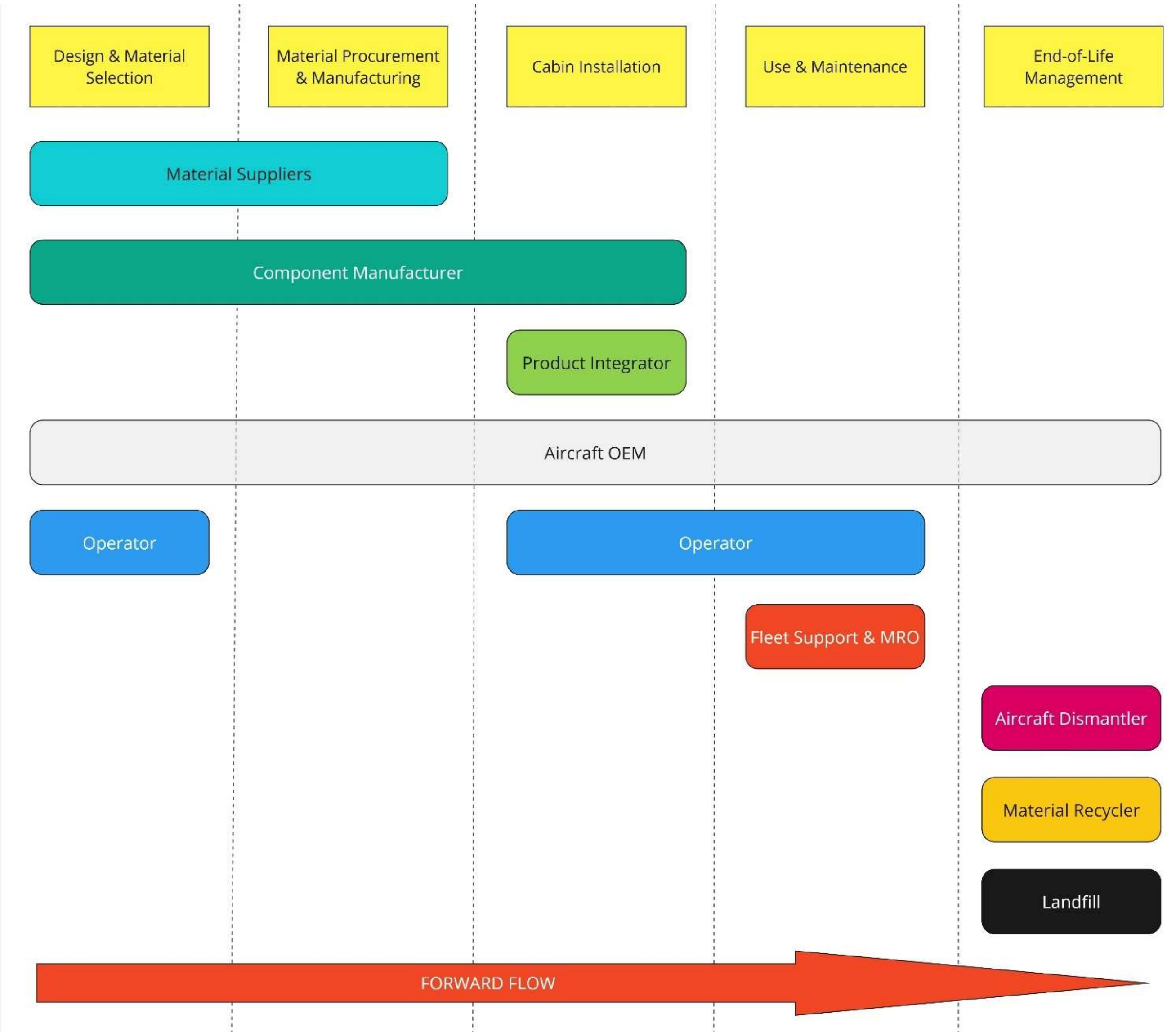

Figure 1. Supply Chain Flow of Aircraft Cabin Seating Industry

Figure 1 provides an illustration about the supply chain flow of aircraft cabin industry. Using reference from Aerospace Technology Institute (2022), the stakeholders are aligned according to their involvement in the supply chain processes which ranges from design & material selection to end-of-life management. It is divided into several phases:

Design and Material Selection

In this stage, the design of the cabin components is decided alongside materials chosen for production. Material suppliers, component manufacturers, and operators are involved in this supply chain stage. The operator will provide specific criteria for the seat design which concerns comfort and weight. The seating manufacturer will then cooperate with the material supplier in finding suitable material in accordance with the customer's demand i.e. operator. Seating manufacturers are an example of the company involved given that such companies do both designing and manufacturing the seats. Meanwhile, Aircraft OEM's involvement in this phase concerns the technical criteria that the manufacturers and suppliers need to fulfill in order to match the aircraft's requirement.

Material Procurement & Manufacturing

The chosen materials in this stage are procured and the components are manufactured. In this stage, component manufacturers will cooperate with the material suppliers in procuring the materials needed as well as manufacturing the components for the aircraft cabin seating before handing over the finished aircraft seating to the product integrator for final installation into the aircraft interior. Aircraft OEM's role in this phase is similar to the design and material selection, ensuring that their products meet the standard of the aircraft OEM.

Cabin Installation

This stage is executed by product integrators, with the process being overseen by Aircraft OEMs. Close coordination with component manufacturers is required in undertaking this process. Once this process is done, it could then be handed over to Aircraft OEMs for further inspection before handing the aircraft over to the operators i.e. airlines. In some cases, seating manufacturers are also involved in integrating the product into the aircraft.

Use and Maintenance

After receiving the unit from the Aircraft OEMs, operators such as airliners will be in charge of the regular use and maintenance of the cabin components. Fleet Support and Maintenance, Repair and Overhaul (MRO) organizations are also involved in this process ensuring the seats are well-maintained and meet operational standards.

End-of-Life Management

Once the cabin components reach the end of their life cycle, the dismantler and recycler will be involved in handling the components. The aircraft dismantler will be in charge of disintegrating components of cabin seating, and sorting materials that could be reused, recycled, or disposed of. Meanwhile, recyclers will be in charge of recycling seating components that could be recycled. Lastly, materials that cannot be recycled will be disposed of in landfills.

Each stakeholder is color-coded in the supply chain flow. The purpose behind it is to display a representation of each role and its involvement in the supply chain flow. One important note is that there is a difference in color transparency in the Aircraft OEM, indicating their indirect involvement in the supply chain flow of the aircraft cabin industry. The reason behind it is that product integrators as well as component manufacturers are directly in charge of this position while Aircraft OEM provides supervising role, ensuring that the quality is according to their standard.

1.1.3. Current Practices

FlyZero (Aerospace Technology Institute, 2022) has developed a model of Circular Economy in regard to cabin sector, which has evolved through literature reviews and interviews with experts. The model outlines the scope of cabin circularity alongside its problem and opportunities for further improvement. The model is displayed in Figure 2 below.

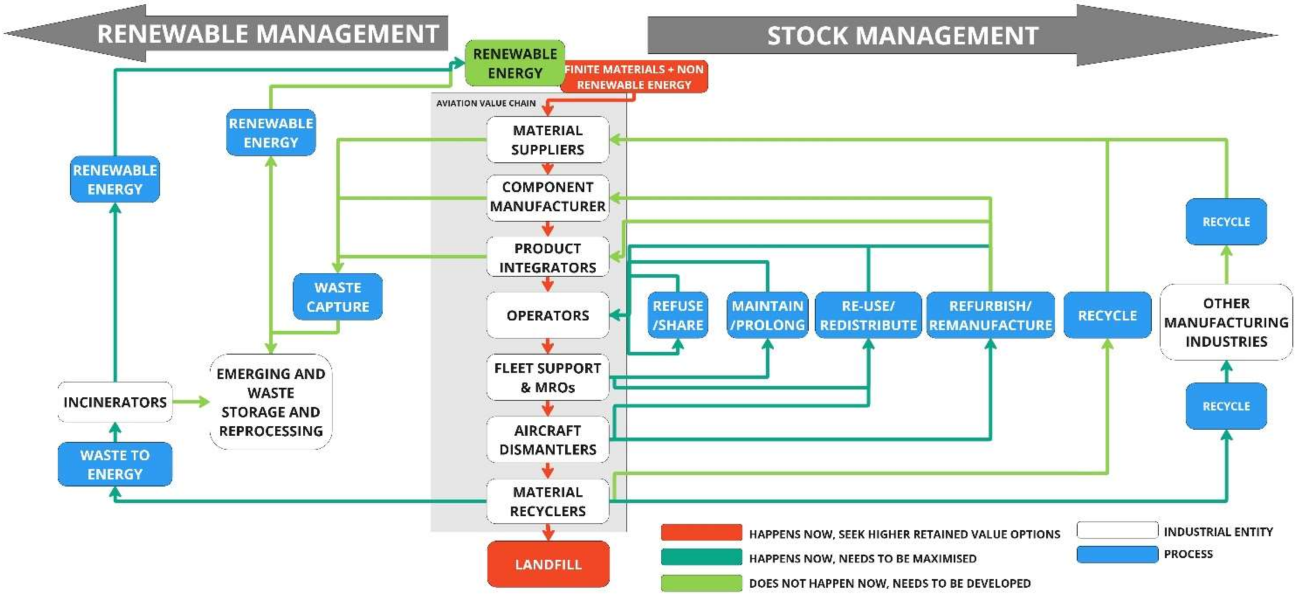

Figure 2. Circular Economy Model (Aerospace Technology Institute, 2022)

Based on the above figure, it is shown that there are circular practices already established in some sectors. However, some opportunities for development remain open (Aerospace Technology Institute, 2022), both on already established practices as well as sectors that have yet to establish circular practices. Based on the Figure 2 above designed by FlyZero (Aerospace Technology Institute, 2022), it is shown that cabin products are repaired, enhanced, and frequently resold or recycled.

In spite of the effort to establish circular practices in the aerospace industry, it is known that certification becomes a major factor discouraging the use of recycled products in the aerospace industry due to the high-quality expectation (Aerospace Technology Institute, 2022). One reason is due to recycled products lose their added value given the purity of the recovered material, causing closed-loop recycling to oftentimes impossible (Hashemi et al., 2013). Given the situation, both certification authorities and airlines have therefore deemed recycled materials to be unfit in-flight or critical in terms of crashworthiness (Aerospace Technology Institute, 2022) resulting in the restriction of manufacturing cabins using such materials.

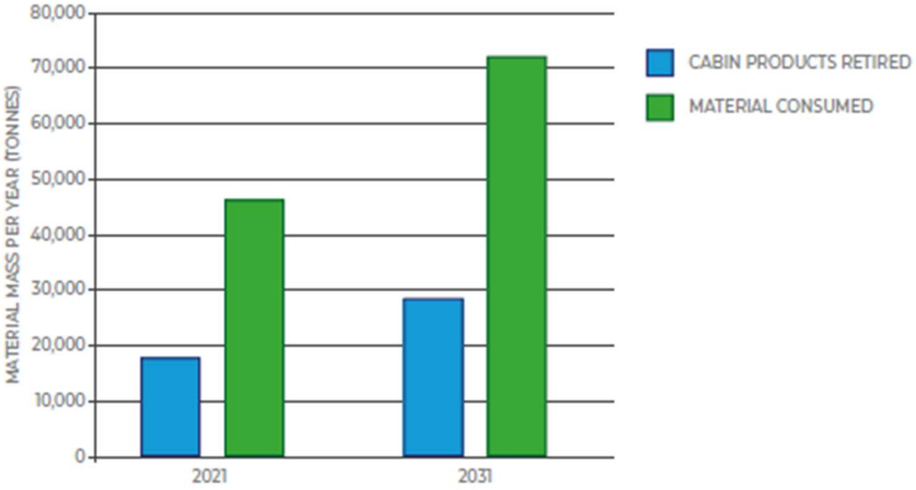

Figure 3. Cabin Material Use Forecast (2021-2031) (Aerospace Technology Institute, 2022)

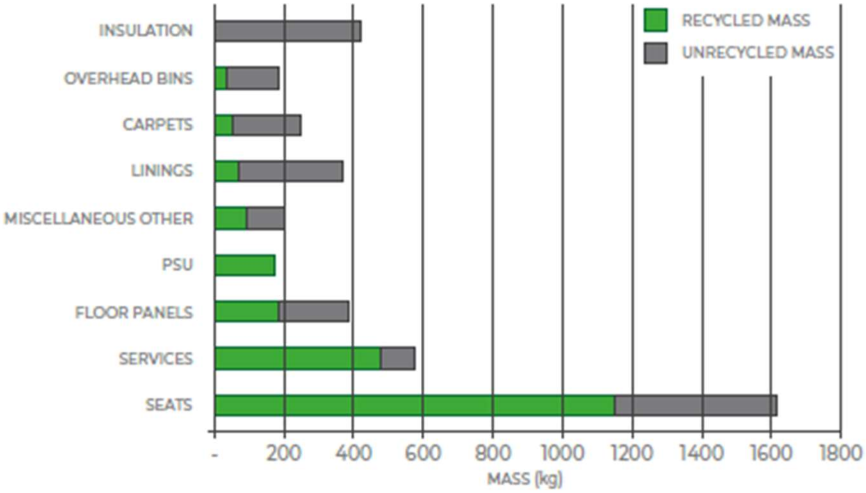

Figure 4. Recycled vs Unrecycled Mass (Aerospace Technology Institute, 2022)

Despite the frequent circular activity conducted, there is significant potential to optimize these practices as well as minimize the necessity for manufacturing replacements (Aerospace Technology Institute, 2022). In addition to the framework that is already developed, the percentage of total cabin products that are not recycled remained significant, estimated at around 47% of total cabin products. Figure 3 shows that OEMs contribute to thousands of tons of manufacturing waste annually which aren't returned to the production process, while Figure 4 shows the proportion of recycled and unrecycled mass in the cabin (Aerospace Technology Institute, 2022). From the figure above, it is shown that seats play a critical role in both total mass and the unrecycled mass in the cabin. This creates a valuable opportunity, as waste can potentially be repurposed as raw material for cabins or other sectors (Aerospace Technology Institute, 2022). The circumstances given above have driven interest in discovering on how a Close-Loop Supply Chain (CLSC) could be implemented effectively in the EOL management of aircraft cabin seating materials.

1.2. Problem Statement

Based on the findings on previous sections, there are significant environmental and logistical challenges present in managing end-of-life or aircraft cabin seating in the aerospace industry. With the increasing demand on sustainable practices especially in the aerospace industry, it is necessary to understand how close-loop supply chain can increase the circularity of these material's end-of-life and enable better recycling. In spite of its potential benefits, studies regarding the impacts of integrating such a system in existing supply chain dynamics and sustainability outcomes are still lacking. It is also important to point out that 47% of cabin products are still unrecycled, where 25% of them are contributed by aircraft seats, highlighting the need for enhanced circular practices as well as the importance of integrating CLSC in the aerospace sector. While studies on reverse supply chains in aerospace have been conducted (Mascle, 2018; Hashemi et al., 2013), there is a lack of research on integrating Close-Loop Supply Chains to improve circularity and enable better recycling of cabin seats. Therefore, this research aims to understand the potential impact of close-loop supply chain on the end-of-life management of aircraft cabin seating materials. Components challenging to recycle, relevant management practices, stakeholder involvement, and the potential transformation in the supply chain system will be explored in order to achieve enhanced sustainability outcomes.

1.3. Knowledge Gap

Several articles have been identified in relation to studies relevant in regard to close-loop reverse supply chain in the EOL management of aircraft. It is discovered that several papers have discussed the relevant EOL practices for aircraft, such as recycling, remanufacturing, direct reuse, and refurbishing (Aydinliyim et al., 2023; Hashemi et al., 2013; Liu & Papier, 2022; Zhao et al., 2020). Some articles published about breakthrough materials that can accommodate circularity, as published by Bachmann et al. (2021), Dias et al. (2022), and Kim et al. (2020). Another publication by Yakovlieva et al. (2021) mentions the importance of recycling associations and initiatives like AFRA and PAMELA in establishing industry standards for implementing recycling programs Despite the literature identified, it does not have a specific focus in regards to the interior of an aircraft, especially aircraft seats, which opens up the opportunity to conduct further research.

Studies regarding reverse supply chain analysis in product end-of-life in the aerospace industry is already conducted, which is done by (Mascle, 2018). However, it is limited to only the business context of the aerospace industry. Meanwhile, a study regarding the end-of-life of aircraft cabin seating material in the context of a reverse supply chain has not been conducted yet. While several articles already discussed breakthrough materials in accommodating circularity (Bachmann et al., 2021; Dias et al., 2022; Kim et al., 2020), it does not delve deeper into the components of an aircraft seat. Moreover, given that studies regarding the EOL of aircraft are relatively new (Keivanpour et al., 2015), there are not many literatures that cover such topic, leaving gaps for further studies, especially in the context of aircraft cabin seating. Lastly, the topic regarding circularity for aircraft interiors, especially seating, is still lacking, which opens up opportunities to research this topic further.

1.4. Thesis Project Objective and Research Questions

The primary objective of this thesis is to understand the potential impact of implementing a Close-Loop Supply Chain (CLSC) on the End-of-Life (EOL) management of aircraft cabin seating materials. This exploration seeks to uncover how CLSC can enhance sustainability and efficiency in the aerospace industry's approach to managing these specific materials at the end of their life cycle.

To guide this investigation, the following main research question has been formulated:

"How can a Close-Loop Reverse Supply Chain be effectively implemented in the EOL management of aircraft cabin seating materials?"

To provide a comprehensive answer to this main research question, the research will delve into several sub-research questions to help address the main research question. Three sub-research questions have been identified, each necessitating various methods for a comprehensive analysis. The sub-research questions and the corresponding methods required to answer them are detailed below.

Sub-Research Question 1

"Which components of aircraft cabin seating materials pose the greatest challenges to recycling from economic and environmental perspectives?"

This question aims to identify the specific parts of cabin seating that are most problematic in terms of recycling, considering both economically and environmentally.

Sub-Research Question 2

“What kind of end-of-life management practices would be relevant?”

This question’s focus will be on exploring various EOL management practices that could be applied to accommodate Close-Loop Supply Chain in aircraft cabin seating materials, evaluating their relevance.

Sub-Research Question 3

“What are the challenges, perspectives, and potential solutions identified by stakeholders involved in the end-of-life management of aircraft cabin seating materials?”

The sub-research question identified above concerns the EOL management of aircraft cabin seating materials from the challenges and perspectives gathered by stakeholders involved as well as potential solutions they propose to make EOL management of aircraft cabin seating more sustainable

1.5. Thesis Outline

A thesis outline will be presented below, showcasing the steps needed to answer the objective of the research. This thesis is structured to comprehensively address the end-of-life (EOL) management of aircraft cabin seating materials. The research is divided into several chapters, each building upon the previous to create a holistic understanding of the subject matter.

Chapter 1: Introduction

The introduction sets the stage for the research by discussing the importance of sustainability in the aerospace industry and the environmental challenges posed by the increasing number of aircraft reaching the end of their operational life. This chapter provides the background and context, introduces key concepts such as Circular Economy, Product End-of-Life, and Reverse Supply Chain, and outlines the supply chain flow in the aircraft cabin seating industry. It also presents the current practices in EOL management, the problem statement, research objectives, and the main and sub-research questions guiding the study. The chapter concludes with an overview of the thesis structure and the significance of the study.

Chapter 2: Methodology

The methodology chapter outlines the research approach and methods used to address the research questions. It begins with scoping the research to define its focus and then details the data collection and analysis methods. This includes preliminary studies, aircraft seat decomposition with supply chain analysis and design, and case studies involving interviews with industry experts. The methodology is designed to systematically gather and analyze data to answer the main and sub-research questions. This chapter also discusses the framework used for the thesis, including the phases of data collection and analysis, and the types of data sources utilized, such as industrial reports, academic journals, and expert interviews.

Chapter 3: Preliminary Study

This chapter provides a comprehensive literature review to establish the theoretical framework for the research. It identifies key themes such as Circular Economy in the aerospace industry, Reverse Supply Chain, Product End-of-Life, and the Circularity of Cabin Materials. The review discusses the principles of Circular Economy, the challenges in implementing circular practices, and the importance of considering EOL processes early in the design phase. This chapter also identifies gaps in the existing literature, which justify the need for further research on CLSC in the context of aircraft cabin seating materials.

Chapter 4: Aircraft Seating Decomposition and Supply Chain Dynamics

This chapter decomposes the components of aircraft cabin seating to understand the materials used and their recyclability. It presents the current supply chain flow, identifies the stakeholders involved, and discusses the economic and regulatory challenges in implementing CLSC. This chapter evaluates the current supply chain, proposes new supply chain flows, and provides recommendations for overcoming the identified challenges. The analysis is aimed at understanding the roles and responsibilities of each stakeholder in promoting sustainable EOL management practices.

Chapter 5: Case Study: EOL Management of Aircraft Cabin Seating Material

The case study chapter involves conducting interviews with industry experts to validate the findings from the literature review and supply chain analysis. This chapter gathers real-world insights from stakeholders involved in the end-to-end flow of the aircraft cabin seating supply chain. It discusses the challenges faced by stakeholders, their perspectives on EOL management, and their ideas for making the EOL phase more sustainable. The case study provides practical insights that complement the theoretical findings and supports the development of actionable recommendations.

Chapter 6: Discussion

This chapter synthesizes the findings from the preliminary study, aircraft seating decomposition with supply chain analysis, and case study. It compares theoretical models with practical insights, evaluates the consistency between literature and real-world experiences, and discusses the implications for sustainable EOL management. The chapter identifies key points from all methods, highlights similarities and differences, and draws conclusions based on the comparative analysis. This synthesis is crucial for understanding how CLSC can be effectively implemented in the aerospace industry.

Chapter 7: Conclusion, Recommendations, and Reflections

The final chapter presents the overall conclusions of the research, summarizing the critical insights gained from the study. It provides recommendations for implementing CLSC in EOL management, emphasizing the need for economic incentives, improved material separation processes, and supportive regulations. The chapter also reflects on the research process, discussing the limitations and suggesting areas for future research. It underscores the importance of integrating economic, regulatory, and technological strategies to promote sustainability in the EOL management of aircraft cabin seating materials.

2. Thesis Methodology

In this section, an approach to conducting the research of this thesis proposal will be outlined. This section begins with approaches used in conducting the research. The next section outlines what scope the research will focus on. Following the presentation of the thesis scope, data criteria will be outlined to improve sampling methods and ensure effective data collection for the research. Then, an outline on how the thesis project will be carried on will be presented through the thesis project framework. Additionally, an approach to collecting the data will be further elaborated. The process of analyzing data will also be presented in this chapter. Finally, the outcome of this thesis project will be elaborated.

2.1. Research Approach

This research employs a qualitative research method to explore the End-of-Life (EOL) management of aircraft cabin seating materials. The approach is divided into two key components: a literature study and a case study.

The literature study aims to understand the potential impact of a Closed-Loop Supply Chain (CLSC) on the EOL management of aircraft cabin seating materials. Through an extensive review of existing literature, this study will build a theoretical foundation, identify key components and materials used in aircraft seating, and analyze current supply chain processes. Additionally, it will propose future models for supply chain flow to enhance the sustainability and recyclability of these materials. The insights gained from the literature will provide a comprehensive background, guiding the development of more efficient EOL practices.

The case study focuses on Airbus as the case holder, specifically addressing the EOL management of aircraft cabin materials, with an emphasis on seating. Semi-structured interviews will be used in conducting the case study, gathering insights and perspectives from experts involved in the aircraft seat supply chain. Originating from the Leiden Delft Erasmus Centre for Sustainability (LDE Cfs) Circulaerospace thesis lab, the case study highlights the low recyclability of cabin products, which often end up in landfills due to the lack of EOL considerations in their design. By examining the specific challenges and opportunities associated with improving the recyclability of aircraft seating, the case study aims to propose practical solutions and strategies for the aerospace industry. This component of the research will provide in-depth, context-specific insights, ultimately aiming to reduce landfill waste and promote sustainable practices within the aerospace industry.

2.2. Thesis Scope

This thesis aims to explore the possibility on how Close-Loop Supply Chain (CLSC) can be effectively implemented for the End-of-Life (EOL) management of aircraft cabin seating material. The motivation for this research stems from the increasing challenges faced by the aviation industry in managing the life cycle of its assets, particularly in terms of sustainability and resource efficiency.

To provide a comprehensive understanding of the research focus, this section outlines the scope of the thesis. The scope will delineate the specific areas that will be examined and those that will be excluded.

This thesis scope includes:

- Focus on CLSC Impact on EOL of Aircraft Cabin Material: This thesis will concentrate on understanding how the Close-Loop Supply Chain (CLSC) affects the end-of-life (EOL) management of aircraft cabin materials.
- Assessment of Current EOL Management Practices: An in-depth analysis of the existing methodologies and practices employed in the aviation industry for managing the end-of-life phase of aircraft cabin materials.

- Accommodating CLSC into Aircraft Seat Supply Chain: The study will explore how to integrate CLSC into the supply chain of aircraft seats, identifying necessary changes and adaptations to accommodate this model.
- Supply Chain Analysis: The research will present both the current supply chain flow and the proposed CLSC flow, emphasizing the challenges in EOL management.

This thesis scope excludes:

- Economic Analysis: The thesis will not conduct any further analysis regarding economic factors, such as cost-benefit analysis, etc.
- Environmental Impact Assessment: There will be no assessment of the environmental impact related to the supply chain or the CLSC, such as Life Cycle Analysis, etc.
- Detailed Material Recyclability Study: The study will provide only a general view of the recyclability of materials, without delving into detailed studies of material properties and recyclability specifics.

2.3. Data Criteria

This section is intended to improve sampling methods and ensure effective data collection for the research. The data sample is limited based on criteria such as region, part of aircraft, and industries involved.

Region of samples: In terms of region, the data collected will be within Europe and the United Kingdom. The reason behind this is due to the connection between companies in Europe and the UK in the aircraft manufacturing ecosystem historically and commercially. Therefore, companies located within the region will be the sample for collecting data.

Parts of aircraft seats: Meanwhile, aircraft passenger seats, specifically economy class seats, will be the only focus of this research in terms of aircraft parts. The reason behind the choice of economy class is due to the largest volume and share contributed in overall aircraft seats worldwide.

Type of aircraft: The type of aircraft that will be used for this research is all types of commercial planes. The reason behind this is due to the larger potential scale for implementation of close-loop supply chain in the aircraft seating end-of-life management. Moreover, having all types of commercial planes as the scope will help provide a generalization of the research outcome.

Range of industries involved: The aircraft Original Equipment Manufacturer (OEM), airliner, aircraft dismantler, seating manufacturer, and R&D institution will be the focus for data collection.

Material Focus: The type of material studied will be focused on the existing materials used in aircraft passenger seats, analyzing their general recyclability and the challenges behind it. The reason to focus on existing material is due to lesser issues on both regulation and certification. Additionally, this decision aims to streamline the implementation of CLSC practices within the industry, recognizing the importance of feasibility and adherence to existing standards while striving for a more sustainable and economically viable End-of-Life management of aircraft cabin materials. Meanwhile, new materials will be discussed in the background study to provide a better context regarding current efforts in sustainable EOL for aircraft seating.

Circularity Process: Another focus on this thesis project is regarding the process associated with the Circular Economy. It is known that there are many approaches in implementing the circularity of a business process. Using Figure 2 as a reference, reuse, refurbish/manufacture, and recycle would be the focus of this thesis research. The reason behind this selection is due to the relevance of the choice of using existing material in this thesis project. Given that the chance of having recycled cabin material to be reintroduced in the aircraft sector is relatively difficult due to certification and quality issues (Hashemi et al., 2013; Aerospace Technology Institute, 2022), the flow of the Close-Loop Supply Chain would not be a complete close-loop as materials that are recycled or remanufactured/refurbished would be reintroduced into another industry instead.

2.4. Thesis Project Framework

This section presents the framework applied in this research, providing a comprehensive overview of the research process and the analytical steps undertaken. The framework is structured into four distinct phases, each of which will be elaborated upon in subsequent subsections. Subsection 2.4.1 discussed the preliminary study as the first phase, providing theoretical background for this research. Meanwhile, subsection 2.4.2. discussed the decomposition of aircraft components as well as the analysis and design of supply chain flow. Subsection 2.4.3 discussed the use of the case study as an additional source of information, providing support and evaluation of findings from previous methods. Finally, subsection 2.4.4. consolidates the findings from all methods, highlighting key results and synthesizing them to formulate conclusions and recommendations. The first three phases are designated to partially answer several sub-research questions. For more details, Figure 5 provides an overall representation of the framework.

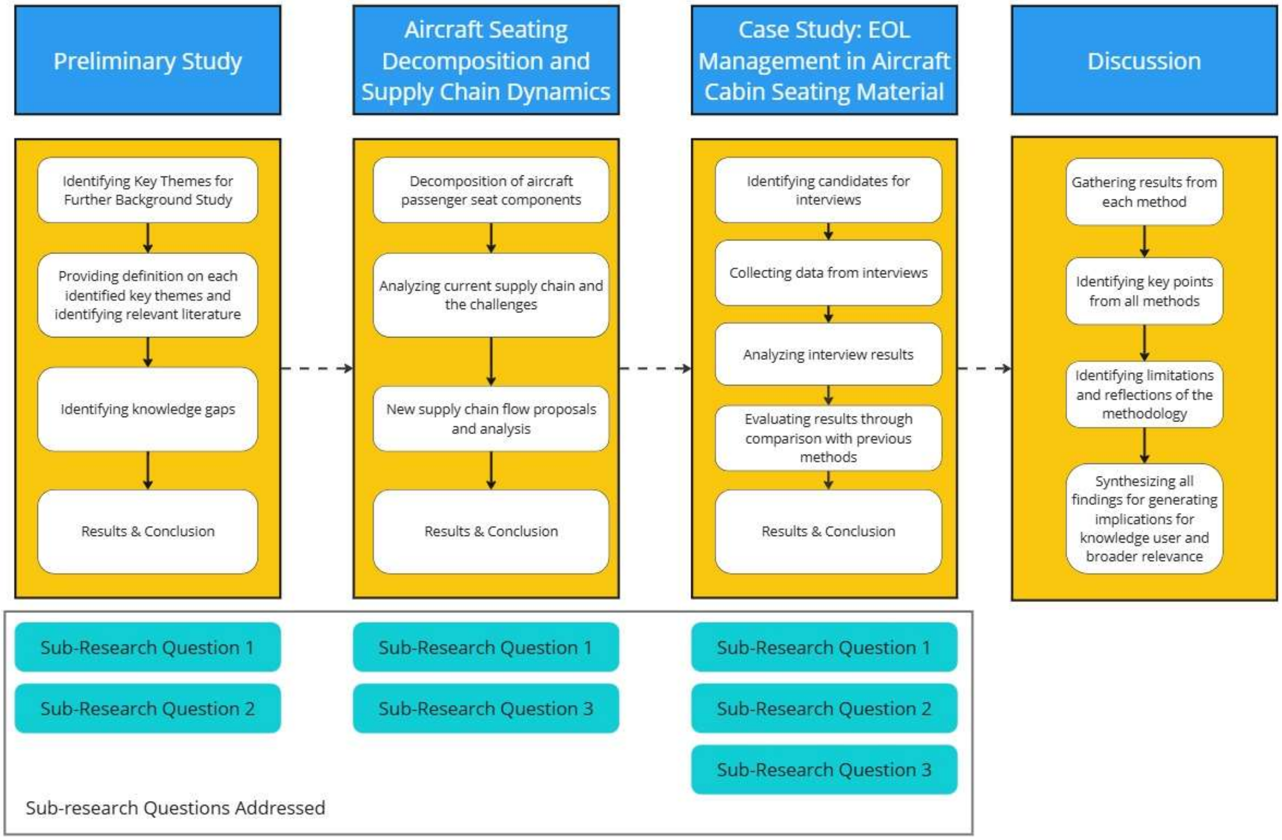

Figure 5. Thesis Project Framework

2.4.1. Preliminary Study

The Preliminary Study's purpose is to provide a theoretical background for conducting the research by identifying relevant literature. This phase is intended to partially answer sub-research questions 1 and 2. The identification of relevant literary sources regarding components and materials that are challenging to treat during EOL will serve as a purpose in answering the sub-research question 1. Also, opportunities for alternative sustainable material will be identified, which will aid in accommodating the use of the Close-Loop Supply Chain for aircraft cabin seating material in the future, giving additional insights in answering the sub-research question 1. Meanwhile, relevant EOL practices in the aerospace industry and other industries will be identified through this preliminary study, which will help in answering the sub-research question 2.

This phase begins with identifying key themes for further relevant literature identification. Following this, each identified key theme will be presented starting from the definition of each key theme and identifying relevant literature associated with each key theme. Furthermore, identified knowledge gaps in the existing literature will be presented afterward, which serves to highlight unaddressed areas or questions. Lastly, this phase will be concluded by generating an overall conclusion from all the findings discovered during the preliminary study where some of the findings will be used to set the stage for further supply chain analysis, which will be presented in the following phase. The answers to the sub-research questions will not be shown in this chapter but rather gathered with other methods' answers in the conclusion chapter.

2.4.2. Aircraft Seating Decomposition and Supply Chain Dynamics

In this phase, a decomposition of aircraft passenger seat components will be first presented. It is intended to provide a deeper understanding of what the components are in an aircraft seat alongside the materials contained. This is further used to identify the recyclability of material, which will be useful in analyzing the current supply chain flow. Furthermore, the approach is intended to partially answer sub-research questions 1 and 3. The decomposition of aircraft seat components and material will serve as a purpose in answering the sub-research question 1, addressing the challenges in recycling the components. Meanwhile, the supply chain analysis and design will be used to design the current supply chain flow, address current conditions, and propose new flows that can accommodate close-loop supply chain and reduce waste. The results from the supply chain analysis and design will be utilized to answer sub-research question 3, as it addresses the challenges of stakeholders concerning EOL management of aircraft seating.

This phase will provide supporting background for the preliminary study in creating a foundation for case study, setting a role in mediating between conceptual models and real-world applications. The current supply chain flow will be presented alongside the challenges. To mitigate the challenges, a new supply chain flow will be presented alongside the justification for implementing the proposed flow. Finally, all the findings gathered from the analysis, both current and proposed flow, will be used for the subsequent case study, intended to provide an evaluation on the proposed flows. The answers to the sub-research questions will not be shown in this chapter but rather gathered with other methods' answers in the conclusion chapter.

2.4.3. Case Study: EOL Management in Aircraft Cabin Seating Material

The Case Study Phase is intended to gather insights through interviews with stakeholders involved in the aircraft cabin seating supply chain. This method is intended to partially answer sub-research questions 1, 2, and 3; obtaining new perspectives and insights from interviewees and adding more answers that the previous methods may not provide. Moreover, this method also serves as an evaluation of the findings from the preliminary study and the proposed supply chain flow design. Therefore, this phase will provide both key findings generated through interviews as well as an evaluation of previous methods. All of them will be presented in Chapter 5.

The data collection is carried out through interviews, which likely involve engaging with experts or stakeholders involved in the end-to-end flow of an aircraft seat. A range of experts will be interviewed, ranging from industrial to academic, to provide diverse perspectives with generalizability from the academic's perspective. The data gathered from these interactions are then carefully analyzed to generate valuable insights. Identifying perspectives from interviewees is a pivotal step, as it contributes a qualitative depth to the research, providing real-world viewpoints on the issue. This phase is rounded off with an overall conclusion, which the result will later be used in building a discussion in the later phase. The answers to the sub-research questions will not be shown in this chapter but rather gathered with other methods' answers in the conclusion chapter.

2.4.4. Discussion

Lastly, in the Discussion Phase, a comparative analysis between the approaches used in the preliminary study, aircraft seat decomposition and supply chain dynamics, and case study is conducted. It begins with collecting all findings generated in each method, followed by identifying key points from all methods. This comparative analysis is crucial for contrasting the theoretical background with practical insights, evaluating the consistency between literature and real-world experiences, and examining how they inform each other. The result of comparison between results will then be followed by identifying limitations in this study alongside reflection. The outcome of this comparison leads to the generation of implications between knowledge users alongside broader relevance, which will subsequently be used in creating recommendations in the last chapter. Lastly, all the results from the discussion will be used to synthesize the conclusion in answering the main research question. These conclusions synthesize the findings from all of the approaches, ultimately contributing to the field of study by providing evidence-based recommendations or identifying room for future research.

2.5. Data Collection

As noted in the section 2.1, a qualitative approach will be used for this thesis through literature study and case study. Regarding data collection, two approaches will be presented, namely literature study and semi-structured interview.

2.5.1. Literature Study

A literature study will be used for the preliminary study chapter, and the chapter of aircraft seating decomposition and supply chain dynamics. In the context of the preliminary study, this approach is used to provide a theoretical background in conducting the thesis project, with the outcome being both research gap alongside key findings for the upcoming case study. In conducting the preliminary study, an integration of a narrative review with a scoping review element is used. A narrative review will be used as a baseline in conducting the literature study, to identify a few studies that describe a problem of interest (Nundy et al., 2022). Moreover, narrative reviews offer flexibility and depth, allowing researchers to explore specific studies in detail and to provide a descriptive synthesis of findings (Nundy et al., 2022). It will start by identifying the key themes to support the preliminary study. Each key concept will be first presented with a concept definition, followed by identifying relevant works of literature using a scoping approach, and finally identifying limitations and research gaps presented by overall relevant literature.

To help identify relevant literature, some elements of the scoping approach will be used. Scoping reviews are designed to map the key concepts, types of evidence, and gaps in research within a broad topic area (Turner, 2023). One of the key elements in the scoping approach is to use a systematic strategy in identifying relevant literature. For starters, relevant keywords and phrases are needed to assist in selecting relevant literature. Web of Science and Scopus will be used as the main literature database for identifying relevant literature on each key theme. Meanwhile, grey literature, such as websites, articles, industry reports, and policy documents will be used to help define the concept of each key theme alongside supporting gap identification by literature. Additionally, the type of relevant literature ranges from articles, papers, proceedings, and reviews. The language of relevant literature must be in English, relevant literature that is not in English will not be included.

Meanwhile, in the aircraft seating decomposition and supply chain dynamics, the literature study will be used to identify components and materials in the aircraft seat as well as references for designing current and future supply chain flow. In this analysis, a breakdown of an aircraft cabin seat will be presented to provide an understanding about the components and the materials contained. Then, the recyclability of materials associated with the component will be presented to understand the challenges from the material viewpoint. Current supply chain flow alongside current conditions in the supply chain will be presented and used as a foundation for the proposed supply chain flow design. Both academic and grey literature will be used in the aircraft seat decomposition and supply chain analysis. Some of the identified literature from the preliminary study will also be used in the supply chain analysis.

2.5.2. Semi-Structured Interview

A case study approach, where semi-structured interviews with experts, will be used as the second method in constructing this study. The semi-structured interview offers flexibility, enabling researchers to prepare a set of questions while also allowing them to follow new leads during the conversation (Bryman A. , 2016). Moreover, respondents can express their views and experiences in their own words, which leads to a more comprehensive understanding of the phenomena being studied (Yin, 2018). Despite the advantages of flexibility and comprehensive understanding, conducting semi-structured interviews is time-intensive, from preparing and conducting the interviews to transcribing and analyzing the data (Yin, 2018).

The case for this thesis is based on Airbus' case concerning EOL management of Aircraft Cabin Material, which is brought as a topic by the LDE Centre for Sustainability Circulaerospace Thesis Lab. Several experts from various backgrounds, ranging from Head of Cabin Products in the Aircraft OEM to a researcher in an R&D Institution, will be interviewed. Research conducted by (Aerospace Technology Institute, 2022) will be used as a reference in determining the list of interviewees by focusing on the organization type. Moreover, the list of candidates was collected through connections from the LDE's Centre for Sustainability Circulaerospace Thesis Lab as well as visiting relevant organizations at the Aircraft Interior Expo 2024 in Hamburg as recommended by LDE and Airbus. The experts that will be interviewed are anonymized and outlined in **Table 1**.

Table 1. List of Experts Interviewed

No	Organization Type	Interviewee Job Function
1	Aircraft OEM A	Head of Cabin Products
2	Seating Manufacturer A	Innovation Manager
3	Seating Manufacturer A	Sustainability Manager
4	Seating Manufacturer B	Project Manager
5	Airline A	Project Engineer
6	R&D Institution A	Researcher
7	R&D Institution B	Researcher
8	Aircraft Dismantler A	Managing Director

The table showcases a diverse range of interview subjects from various organizations and job functions, providing multiple perspectives on the aircraft cabin business ecosystem. This diversity reveals industry interdependencies and interactions, addresses stakeholder needs, and enhances problem-solving effectiveness with alternative solutions. Additionally, interviewing individuals from different industries offers unique insights and best practice sharing, enriching knowledge and potentially leading to innovative solutions.

Two scenarios will be presented as a prerequisite before conducting the interview, providing further assistance in defining the outcome of all the interviews combined. The scenarios are defined as follows: *First*, a recommendation to accommodate close-loop supply chain will be presented if both recycling and remanufacturing are possible for existing aircraft cabin seating material. *Second*, suggestions on new designs for aircraft cabin seating based on the insight gathered by the interviewees will be recommended if both recycling and remanufacturing are impossible for existing aircraft cabin seating material.

The two scenarios mentioned above will be used as a foundation in composing interview questions for all the subjects involved, which will categorized into general and specific question based on the role of each subject.

2.6. HREC Approval

This methodology will involve human beings as subjects for data collection, which needs to follow HREC guidelines and be approved by TU Delft's HREC. To comply with the regulations, all the required documents were submitted on the 20th of May 2024 and were successfully approved by the Human Research Ethics Committees (HREC) on the 7th of July 2024. The type of data collected are interview recordings and transcripts, and the interviewees alongside their associated organizations will be anonymized. The collected data will be stored in the TU Delft database for up to 2 years and will be deleted afterward.

2.7. Data Analysis

The result of the interview will be further analyzed by coding several keywords. The type of coding that will be conducted is open coding, which will be done inductively which helps in building explanations. Open coding, according to (Bryman A. , 2012) is analyzing, dissecting, conceptualizing, and categorizing data to generate concepts. This approach will help establish a linkage of evidence, thus connecting data to the conclusion. A three-stage coding will be used as proposed by (Pratt et al., 2006). The three stages consist of first order, second order, and aggregate. First-order coding focuses on identifying and labeling concepts directly from the data, using the participants' own words and meanings. In the second-order coding stage, these initial concepts are refined into broader themes by grouping similar first-order codes and interpreting the underlying patterns. Finally, the aggregate dimensions are developed by abstracting and integrating the second-order themes into overarching categories that encapsulate the core findings of the study.

Another analysis is done in the preliminary study, where key theories that are outlined according to the research questions provided are used to find a research/knowledge gap. A gap analysis will be used in analyzing the literature found, addressing areas lacking in existing research through the identification (Swales, 1990). Moreover, a preliminary study is also used to provide supporting evidence for a practical problem which underlines the significance (Ridley, 2008). Lastly, it will also be used to provide historical context and how the current research could fill the gap (Ridley, 2008).

2.8. Relevance to MOT Master Program

This thesis is relevant to the Management of Technology (MOT) program as it addresses the critical challenges in managing end-of-life aircraft cabin materials in the aerospace industry. The research highlights how firms can leverage technology to enhance their resource management and adopt sustainable practices amid environmental and logistical pressures. It integrates background studies, aircraft seating decomposition with supply chain analysis, and case studies to explore the components of aircraft cabin seating materials, relevant end-of-life management practices, and the challenges and solutions identified by stakeholders. The methodology involves analyzing data from industrial reports, academic journals, web articles, and interviews, providing a comprehensive understanding of the current state and future opportunities in managing end-of-life aircraft cabin materials.

Furthermore, the thesis emphasizes the strategic use of technology to improve the end-of-life management of aircraft cabin seating materials, proposing structured strategies for technological innovation that support circular economy practices crucial for sustainability. By identifying the components of aircraft cabin materials and relevant management practices, the research aims to provide firms with the tools to enhance their sustainability efforts and resource efficiency. This study offers actionable insights and strategic recommendations for industry implementation, aligning with the MOT program's objectives and contributing to the broader field of technology management and sustainable practices in the aerospace industry.

2.9. Thesis Outcome

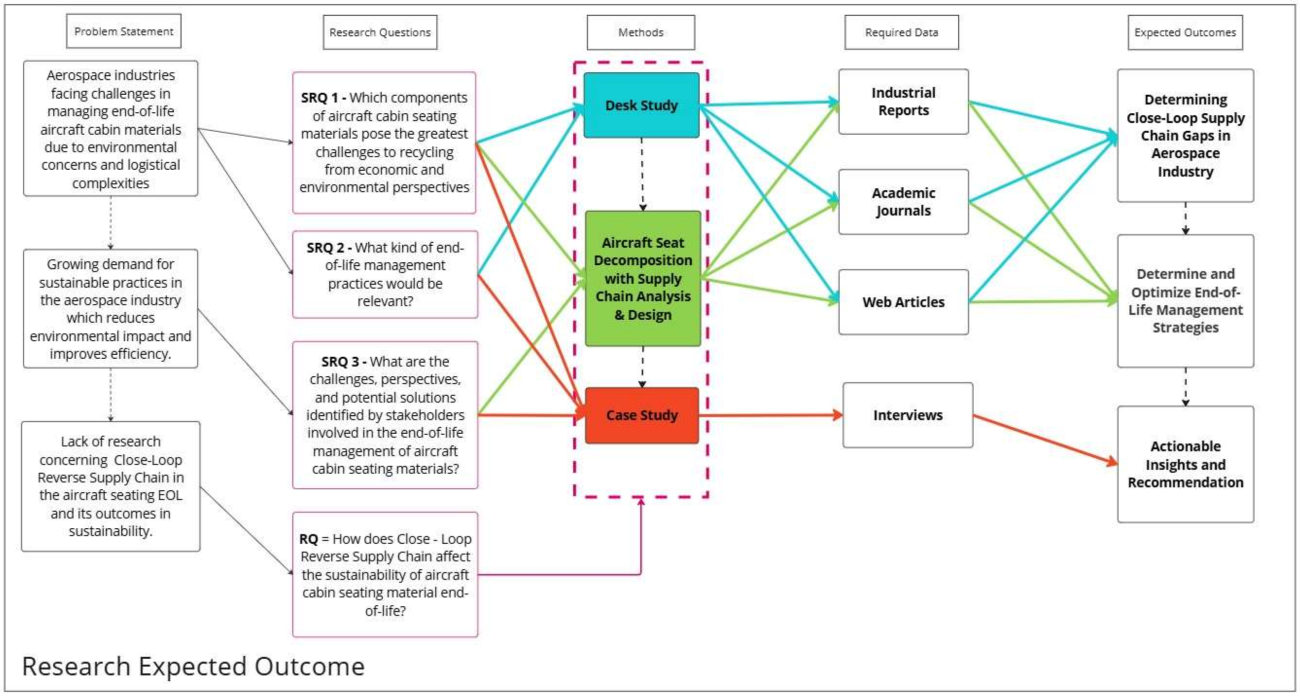

Figure 6. Research Expected Outcome

Figure 6 shows how the flow of the research provides the expected outcome this thesis aims to provide. For starters, the aerospace industry faces challenges in managing the end-of-life (EOL) of cabin materials due to environmental concerns, a demand for sustainable practices, and a lack of research on closed-loop supply chains (CLSC) in aircraft seating sustainability. These factors are addressed by a main research question, on how to effectively implement CLSC in aircraft cabin seating EOL management, followed by 3 sub-research questions to provide a comprehensive answer to the main research question. To answer these, the study employs three methods: a preliminary study, seat decomposition with supply chain analysis and design, and a case study. Each method is symbolized by a colored line and uses specific data sources—two methods rely on industrial reports, academic journals, and web articles, while one uses interviews. The findings from these methods lead to three expected outcomes.

The first expected outcome involves determining gaps in the close-loop supply chain within the aerospace industry. This part of the research aims to identify the challenges in the current recycling and reuse practices of aircraft cabin seating materials by reviewing relevant literature. It also seeks to highlight gaps for further research related to closed-loop supply chains in aircraft seating. By pinpointing these gaps, the study aims to suggest areas where improvements can be made to enhance sustainability within the industry.

The second expected outcome is centered on determining and optimizing end-of-life management strategies for aircraft seating materials. This involves assessing current practices and developing strategies to improve the end-of-life process for aircraft seats. This includes decomposing the seats, analyzing the supply chain, and proposing designs to enhance the efficiency of the EOL process. The goal is to minimize the environmental impact associated with the disposal and recycling of these materials.

The third outcome aims to provide actionable insights and recommendations based on the comprehensive analysis and data gathered through the study. These insights are intended to inform and guide stakeholders within the aerospace industry on best practices and strategic decisions to improve the sustainability of managing aircraft seating materials at their end-of-life. These recommendations could influence policy changes, improve operational efficiencies, and foster a greater focus on sustainability across the industry. A more detailed flow of this outcome is presented in Figure 6 and Appendix A – Research Outcomes.

3. Preliminary Study

A comprehensive study regarding the topic will be presented in this chapter, where a narrative review will be used with some elements of a scoping review to provide a clear objective and develop a rigorous method (Nundy et al., 2022; Turner, 2023). This section's purpose is to provide a theoretical background for conducting the research by identifying relevant literature. As noted from 2.4.1, this chapter is intended to partially answer the following sub-research questions:

- *Sub-research Question 1 – "Which components of aircraft cabin seating materials pose the greatest challenges to recycling from economic and environmental perspectives?"*
- *Sub-research Question 2 – "What kind of end-of-life management practices would be relevant?"*

In this chapter, a further definition of each concept alongside identifying relevant studies of each key concept will be presented. Furthermore, challenges presented by identified relevant studies will be elaborated further which also help identify gaps in the overall key concepts. Lastly, findings on relevant studies will also be outlined, providing a foundation for generating a conclusion, which will later be presented in the later section.

3.1. Key Concepts and Relevant Studies Identification

The key themes were identified by exploring the topic regarding the circularity of aircraft cabin products published by Aerospace Technology Institute, (2022). The topic initially discusses the challenges in implementing circular practices for cabin products during the EOL stage, where seats are one of the elements. The paper later discussed Circular Economy (CE) as a solution for managing cabin products EOL. Implementation of CE could be done by considering the supply chain aspect of a cabin product, especially in seating. There are two supply chain approaches in implementing CE, one is through the forward supply chain and the other through the reverse supply chain, which emerged as an implementation of CE in the supply chain context as well as becoming the identified key theme for this background study. Implementing both forward and reverse supply chains influences product end-of-life (EOL), where products were initially produced linearly, are now more accommodated to circular practices. Therefore, Product EOL becomes a subsequent key theme that will be discussed further. Once Product EOL is further discussed, the circularity of aircraft cabin seating material becomes the last key theme identified. These key themes identified are correlated to each other, where their connections are displayed through a conceptual diagram in Figure 7 below.

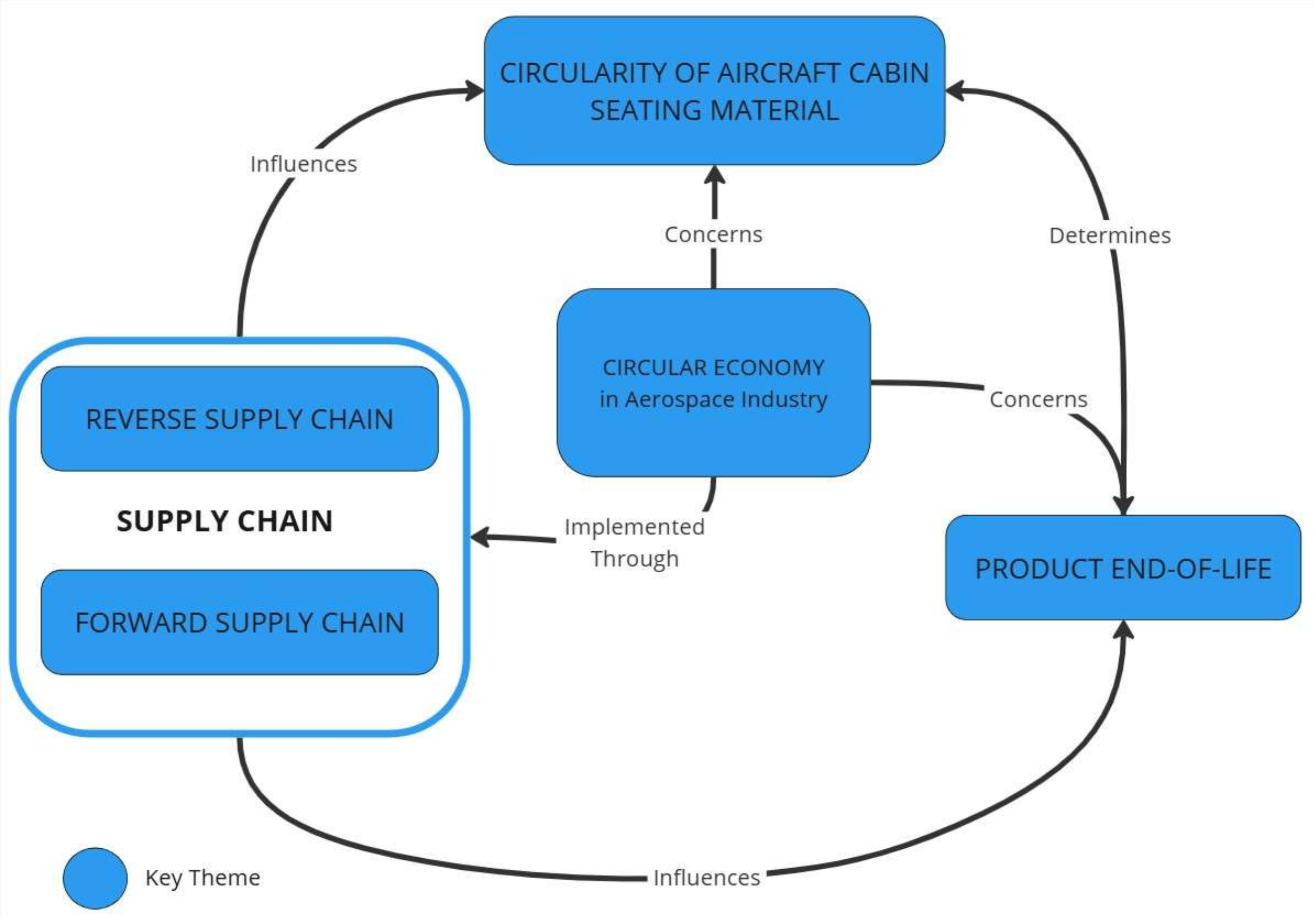

Figure 7. Conceptual Diagram of Identified Key Themes

The diagram illustrates the central theme of the circular economy in the aerospace industry, with a particular focus on the circularity of aircraft cabin seating materials. This concept addresses two main concerns: the product end-of-life and the circularity of aircraft cabin seating material. Implementing the circular economy can be achieved through the supply chain, which consists of both forward and reverse supply chain processes.

The forward and reverse supply chains are essential in influencing the product end-of-life and the circularity of aircraft cabin seating materials. The forward supply chain involves the production and distribution of new products, while the reverse supply chain handles the return, recycling, and disposal of used products. These processes significantly impact how materials and products are managed at the end of their life cycle.

In the end, the product end-of-life determines the circularity of aircraft cabin seating materials. The methods used to handle products at the end of their life cycle, including recycling, reusing, and disposing of materials, directly affect how effectively these materials can be reintegrated into the supply chain. This relationship highlights the critical role of a well-coordinated supply chain in achieving the objectives of a circular economy within the aerospace industry.

Subsequently, all the identified key themes will be further elaborated starting from 3.2 to 3.5. In total, around 24 papers are discovered as relevant literature for all key themes, which could be discovered in more detail through Appendix B – Preliminary Study: Relevant Literature Identification.

3.2. Circular Economy in the Aerospace Industry

Circular Economy, which was first initiated in 1970s, is a concept that stems from the idea of input consumption reduction for industrial production (Stahel, 2016). Additionally, Circular Economy could also be defined as a system that prevents waste by continuously reusing materials, regenerating nature, and decoupling economic growth from finite resource consumption to address global challenges like climate change and pollution (Ellen Macarthur Foundation, n.d.). It is largely based on the following principles: value enhancement through designing manufactured products and maximization of utility throughout extended life cycles; development of versatile products with various applications over different periods, ensuring the reuse of single item; systematically returning solid waste to the industrial sector in an organized manner, where the cost of recycled secondary raw materials is competitive in the market; and adopting a systemic approach to supply chain management, assessing the interconnectedness between energy production, material extraction, and the natural environment (Arruda et al., 2021). In spite of its idealistic principles, the concept of a circular economy still entails environmental externalities. This is due to the fact that external effects consistently arise as a consequence of transactions between various entities (Genovese et al., 2017).

One of the challenges in implementing Circular Economy (CE) in the aerospace industry is to ensure coordination, control, and transparency among stakeholders (Santana & Ribeiro, 2022). With the shift towards a more circular approach, it's essential to address traceability in order to identify the history of products, parts, and materials, maximizing their utility and minimizing waste. (Santana & Ribeiro, 2022). In the aerospace sector, traceability is essential for ensuring product quality, safety, and compliance with standards (Zubiate-Perez & Ordonez-Parada, 2020). By implementing traceability systems, aerospace companies can effectively track the origin and history of components to ensure they meet stringent requirements and regulations (Tekin, 2014), while also aiding in identifying design-related issues if a product underperforms, thereby enhancing its processes and products (Souali et al., 2017).

Many approaches are identified to facilitate traceability in other industries, such as the use of RFID systems, barcodes, IoT design models, product-embedded information device (PEID) for product information tracking and feedback (Santana & Ribeiro, 2022). Another approach to facilitating traceability is the use of a material passport (digital product passport), which plays a key role in decision-making for material recovery, recycling, reuse, and lifecycle information management, promoting optimal use and smart practices (Trubina, 2024; Heinrich & Lang, 2019). It is a comprehensive dataset, containing valuable information such as material properties and potentials for reuse and disassembly (Honic et al., 2024), serving as a guiding source for analysis of the circularity of products (Trubina, 2024).

Further studies in identifying relevant literature found that there are in total 6 relevant papers related to this key theme. Using Web of Science as a database, the keywords used in identifying these relevant papers are {“circular economy”, “aerospace”} and {“Circular Economy”, “Aerospace”, “Aircraft”}. There are in total 70 papers discovered using the keyword {“Circular Economy”, “Aerospace”} and 5 in {“Circular Economy”, “Aerospace”, “Aircraft”}. Out of 5 relevant papers, 4 of them are found in both keywords, leaving 1 paper relevant in the first search strategy.

Based on the findings of each paper, it is found that the research conducted by Dias et al. (2022) mentions the reuse and recycling of materials in aerospace and other industrial sectors relevant in implementing a Circular Economy in the aerospace industry. Another relevant literature concerning Circular Economy mentions 3 assessments of circular economy, such as: LCA, or Life Cycle Analysis; MFA, or Material Flow Analysis; and IO, or Input-Output Analysis (Vogiantzi & Tserpes, 2023). A publication by Ashraf et al. (2023) discussed the preventive maintenance techniques to revitalize metallic materials and extend their lifespan, where they also mentioned other approaches in extending materials' lifespan such as reuse, refurbishment, and recycling. Another study published by (Sabaghi et al., 2016) discussed the end-of-life disassembly efficiency of aircraft by developing a disassembly scoring model, utilizing a hybrid approach combining Design of Experiments (DOE) and the TOPSIS method. It is found that disassembly plays a crucial role in improving the value-added of the products that does not limit to EOL but also during the life-time and maintenance (Sabaghi et al., 2016). Lastly, research conducted by Krauklis et al. (2021) highlighted the importance of selecting optimal recycling methods based on composite type to ensure economic and environmental sustainability through identifying socio-technical drivers for composite recycling technology development, such as landfill bans and increased decommissioning of wind turbines and aircraft.

Despite many researches in Circular Economy (CE) done in the context of aerospace industry, they are not without limitations. First, Dias et al. (2022) mentioned that there are lack of incentives and regulatory support from agencies to implement Circular Economy in the aerospace industry. Moreover, some breakthrough materials studied in accommodating Circular Economy are still in an early phase (Dias et al., 2022), which means that they are not applicable in the current state. Additionally, the challenge in traceability lies in the information gap between stakeholders due to unwillingness to share information as well as the fragmentation of the supply chains (Santana & Ribeiro, 2022). Despite its relevance in assessing circularity, Life Cycle Assessment (LCA) does not necessarily provide circularity assessment. Moreover, due to the amount of work required in conducting LCA, it could be used for further studies.

3.3. Forward and Reverse Supply Chain in the Context of Aerospace Industry

To understand the differences between forward and reverse, it is necessary to understand the definition of supply chain first. According to Chopra & Meindl (2007), Supply Chain could be defined as a collection of entities (manufacturers, suppliers, transporters, warehouses, retailers, and customers), where all the functions involved within each organization in fulfilling a customer request, directly or indirectly. Furthermore, a Supply Chain can be described as a network of parties directly engaged in the distribution of goods, services, finances, and information from the origin to the end customer (Mentzer et al., 2001). With the focus from source to destination, the supply chain could initially be referred as a linear flow of materials and products and, therefore also categorized as forward supply chain.

Meanwhile, Reverse Supply Chain emerged as an incorporation of circular economy values into Supply Chain Management (SCM) (French & LaForge, 2005). It is related to product design, operations, and end-of-life management with the objective to optimize value creation throughout the entire lifecycle (Genovese et al., 2017). The objective is achieved through recovering value from post-use products, either through the original product manufacturer or a third party (Genovese et al., 2017).

According to (French & LaForge, 2005), Reverse supply chains can be categorized as either open-loop or closed-loop. In essence, open-loop supply chains involve materials recovered by parties other than the original producers, capable of reusing these materials or products. Conversely, close-loop supply chains revolve around the practice of retrieving products from customers and returning them to the original manufacturer. This allows for the recovery of added value by reusing either the entire product or a portion of it (French & LaForge, 2005).

As a branch of Reverse Supply Chain, Close-Loop Supply Chain (CLSC) Management originated due to marketing implication of reprocessed products where some researchers incorporating "forward" section of

Reverse Supply Chain, which is re-selling and distributing the recycled product (French & LaForge, 2005). Incorporating forward supply chain elements could be done through evaluating product during the design phase, which in turn could be used to accommodate end-of-life phase during product development, as shown by Sabaghi et al. (2016). Therefore, this concept exists as a reference to this complete loop of supply chain process; which begins from the customer, then moves to the plant which is further undergoing a re-processing operation, and eventually back to the customer (Guide & Van Wassenhove, 2009).

Generally, products or materials that are returned and require decisions about reusing come from either internal or external sources. Past research has predominantly concentrated on external returns within specific industries (Minner, 2001). There are five classifications of reverse flows, encompassing external returns as end-of-use returns, commercial returns, and warranty returns, while internal returns comprise production scrap and by-products (Fleischmann et al., 2000).

A more comprehensive study in identifying relevant literature with this key theme is conducted via Scopus and Web of Science as the database for the literature. There are 3 relevant papers identified through Scopus using keywords “supply chain” and “aerospace” and another 2 relevant papers identified using keywords “supply chain”, “aerospace”, “interior”. Meanwhile, through Web of Science, using combined keywords such as “reverse supply chain” and “aerospace”, 7 papers were discovered where we identified 2 papers that are relevant to the key theme. Meanwhile, 5 papers are discovered with 4 of them being relevant in the context of Close-Loop Supply Chain (CLSC) with keywords “close-loop supply chain” and “aerospace”.

In regards to the forward supply chain, the focus on the relevant literature identified ranges on the performance improvement (Manville et al., 2021), supply chain relationship with suppliers (Schmelzle & Mukandwal, 2020; Cunha et al., 2023), coordination between aerospace industries (Voordijk & Meijboom, 2005) and supplier selection (Roehrich et al., 2017). An article published by Manville et al. (2021) discussed the development of Lean Supply Chain Management for aerospace industries in the UK to assist in standardizing approaches and tools for continuous improvement. The study discovered that collaboration between supply chain partners is necessary for efficient and effective SCM alongside the importance of performance measurements systems (PMS). Meanwhile, a study conducted by Schmelzle & Mukandwal (2020) discovered that suppliers with fewer shared connections to their buyers' competitors demonstrate better inventory efficiency and asset turnover. Additionally, more exclusive, trust-based relations improve operational efficiency. The study by Voordijk & Meijboom (2005) found that the dominant supply chain coordination strategies in the Dutch aerospace industry prioritize enhancing information-processing capacity through investments in lateral relationships and information systems. These strategies are favored over traditional methods such as buffer stocks or self-contained tasks, underscoring the importance of effective information management and collaboration among supply chain partners (Voordijk & Meijboom, 2005).

In the context of the reverse supply chain, it is discovered that there are unique challenges in EOL aircraft recovery identified in the aerospace industry that cannot be addressed by solutions from other industrial sectors (Keivanpour et al., 2015). An article published by Liu & Papier (2022) indicates that remanufacturing reduces the negative environmental effects of manufacturing through materials waste e.g. steel or chemical as well as decreasing consumption of energy and water. In relation to the context of the aerospace industry, Liu & Papier (2022) also mentioned that Rolls-Royce claimed to have their remanufactured product ‘safe for use’ as new component. Meanwhile, in the CLSC context, several findings were discovered regarding waste reduction. One example is to use input material reduction incentives via contracting (Aydinliyim et al., 2023), recycling (Aydinliyim et al., 2023; Hashemi et al., 2013), direct reuse, cannibalization, remanufacturing (Liu & Papier, 2022; Hashemi et al., 2013) and refurbishing (Hashemi et al., 2013). A paper published by Desai et al. (2019) emphasized the importance of integrating different Supply Chain Management (SCM) methods, which includes CLSC, to address unique challenges in the aerospace industry, especially in regards to long lifecycle products. Lastly, in relation to SCM, environmental thinking is suggested to be incorporated due to its importance in the EOL (Keivanpour et al., 2015).

Limitation-wise, it is found that studies regarding End-of-Life (EOL) of aircraft are relatively new (Keivanpour et al., 2015), which leads to missing literature in some aspects due to being incomplete. Moreover, the lack of regulations regarding EOL treatment has made this aspect rather overlooked by the aerospace industry (Keivanpour et al., 2015). An article published by Liu & Papier (2022) also mentioned that their model assumed that all components in return are re-manufacturable while, to some extent, they may not. Moreover, weaknesses in remanufacturing lie in the customers' perception regarding the quality of remanufactured products being lower than new products (Liu & Papier, 2022).

3.4. Product End-of-Life (EOL)

The End-of-Life (EOL) phase initiates when a customer (consumer or business) disposes of the product. This phase encompasses various end routes, including product reuse without structural changes (i.e., lifetime extension) (Huisman, 2003), remanufacturing, which restores discarded, non-functional, or traded-in products to a like-new condition (Butzer et al., 2016), recycling involving the collection and treatment of waste products for use as raw materials, incineration where combustible wastes are burned and transformed into gases (with or without energy recovery), and disposal methods such as underground dumping or landfill (European Environmental Agency, 2009). Alternatively, the product may end up emitting or leaking into the environment (Ciceri et al., 2010)

The quantity of end-of-life (EOL) aircraft is considerably smaller in comparison to electronics or vehicles (Mascle, 2018). Furthermore, the residual value of components and materials within aircraft can be substantial, dependent on the technology employed for dismantling and disassembly (Mascle, 2018). Aircraft often comprise high-quality alloys and valuable sub-assemblies, such as engines and landing gear, contributing to their market value (Keivanpour et al., 2013). The economic attractiveness of treating these aircraft is crucial for generating value for all stakeholders, requiring the use of advanced methods and processes (Mascle, 2018).

Using Web of Science as a database for further literature review, a total of 11 papers are discovered using keywords such as “product end-of-life”, “aerospace”, and “aircraft”. Out of 11 papers, 5 papers are found to be relevant in regard to the key theme. The relevant papers discuss various topics regarding product end-of-life in the aviation industry such as disassembly evaluation of aircraft; economic indicators to evaluate aircraft end-of-life strategies; integration of conceptual design and EOL stages in product lifecycle management; various composites recycling methods; and analysis of existing policies, methods and technologies for handling decommissioned aviation transport means.

To evaluate the product EOL of an aircraft, a focus on evaluating the design phase is considered which emphasizes the importance of considering EOL processes early in the design phase (Sabaghi et al., 2016). This is achieved by incorporating modular design principles, enabling the creation of modules that combine the most suitable components based on their intended end-of-life destination (Sabaghi et al., 2016). Another approach in evaluating product EOL is through designing economic indicators to evaluate aircraft EOL focusing on disposal and recycling (D&R) scenarios (Zhao et al., 2020), where the study highlighted the significant impact of salvage value and D&R cost on the economic efficiency of D&R processes. A study by Thimm et al.

(2007) discusses the integration of conceptual design and EOL stages in Product Lifecycle Management (PLM) through examining influences of EOL on product costs and identified links between conceptual design and EOL stages. It is found that there is little attention in considering EOL process in PLM during the conceptual design stage as well as lack of support for the concerns of integration of the numerous EOL stakeholders, business process etc. (Thimm et al., 2007). Another study emphasized the ecological and economic benefits of introducing recycling programs in the aviation industry by highlighting the crucial role of recycling associations such as AFRA (Aircraft Fleet Recycling Association) and recycling initiatives such as PAMELA, or Process for Advanced Management of End-of-Life Aircraft, in setting the industry standards (Yakovlieva et al., 2021). Moreover, the study published by Yakovlieva et al. (2021) also mentioned that the lack of documentation of retired aircraft on the edges of the airfield can pose potential contamination in the surrounding environment, highlighting the need for identification. In terms of the unrecyclable mass of an aircraft, it is discovered that cabin interior components such as seat cushions are identified as unrecyclable due to containing embedded flame retardants (Yakovlieva et al., 2021).

However, one of the limitations of this study lies in the hypothetical scenarios and selected case studies, which may not cover all possible D&R options (Zhao et al., 2020). Empirical validation is limited by the proposed methodology by (Sabaghi et al., 2016) for other products and industries. Moreover, lack of comprehensive economic analysis regarding EOL due to heavier focus on the technological aspect of recycling is another limitation regarding the study for this key theme (Yakovlieva et al., 2021).

3.5. Circularity of Aircraft Cabin Seating Material

In implementing Circular Economy in the aerospace industry, specifically in the aircraft cabin seating, it is necessary to understand the circularity of the material attached to it. Materials that construct the component of the cabin seating should be able to reduce environmental impact as well as reduce resource consumption (Bachmann et al., 2021). The efforts come in many ways; one could go through bio-based material (Bachmann et al., 2021; Kim et al., 2020) or through emphasis on sustainable practices such as recycling and remanufacturing (Dias et al., 2022).

3 relevant papers were discovered in Web of Science using following keywords “circular”, “aircraft”, “interior”. Both Bachmann et al. (2021) & Kim et al. (2020) discuss the use of new, sustainable material in implementing circularity of aircraft interiors. Article published by Bachmann et al. (2021) discussed the opportunity of bio-based and ‘eco-composites’ as substitutes for conventional composites, which were deemed not environmentally friendly and sustainable.

Despite the opportunities through discovery and development of new material as well as emphasis on sustainable practices, there are limitations and challenges in executing these opportunities. In regards to ‘eco-composites’, the challenges lie in the fulfillment of fire regulations on interior structures given that improvement is needed in terms of heat release without sacrificing smoke density and toxicity (Bachmann et al., 2021). Another challenge in the new materials lies in the applicability in the large scale due to being novel and yet to be mass-produced (Kim et al., 2020). The environmentally friendly material being associated with high cost both in the development and use become an additional challenge in implementing new materials (Dias et al., 2022). Lastly, the lack of incentives alongside the complexity and long lifecycle of aerospace products becomes a challenge in recycling and remanufacturing of aircraft materials (Dias et al., 2022).

3.6. Identified Gaps

Several articles have been identified concerning studies relevant to the closed-loop reverse supply chain in the end-of-life (EOL) management of aircraft. It is discovered that multiple papers discuss EOL practices for aircraft, such as recycling, remanufacturing, direct reuse, and refurbishment (Aydinliyim et al., 2023; Hashemi et al., 2013; Liu & Papier, 2022; Zhao et al., 2020). Some articles highlight breakthrough materials that can facilitate circularity (Bachmann et al., 2021; Dias et al., 2022; Kim et al., 2020). Additionally, Yakovlieva et al. (2021) emphasize the importance of recycling associations such as the Aircraft Fleet Recycling Association (AFRA), and recycling initiatives such as PAMELA, in setting industry standards for recycling programs.

However, despite the identified literature, there is a notable lack of research specifically focused on the interior components of an aircraft, especially aircraft seating. This gap presents an opportunity for further research. While studies on reverse supply chain analysis in product end-of-life in the aerospace industry have been conducted by Mascle (2018), their focus is limited to the business context of the aerospace industry. No studies have delved into the end-of-life of aircraft cabin seating materials within the context of the reverse supply chain.

Although several articles discuss breakthrough materials in accommodating circularity (Bachmann et al., 2021; Dias et al., 2022; Kim et al., 2020), they do not explore the specific components of aircraft seats. Given that studies regarding the EOL of aircraft are relatively new (Keivanpour et al., 2015), there is a scarcity of literature on this topic, leaving significant gaps for further research, particularly in the context of aircraft cabin seating. The lack of research on the recyclability of aircraft interior products, especially seating components, highlights the need for focused studies in this area.

3.7. Conclusion

In this chapter, a comprehensive preliminary study was conducted to the key themes relevant to the circularity of aircraft cabin seating materials and their end-of-life (EOL) management. The study explored critical components of aircraft cabin seating that pose significant challenges during EOL, emphasizing the necessity for effective recycling strategies and sustainable practices.

The review of key concepts and relevant studies highlighted the importance of Circular Economy (CE) in the aerospace industry. The principles of CE, aimed at reducing input consumption and enhancing product utility through extended life cycles, were examined in the context of aircraft cabin seating materials. Despite the promising aspects of CE, challenges such as the lack of regulatory support and early-stage development of breakthrough materials were identified.

The analysis of forward and reverse supply chains provided insights into the integration of circular practices within supply chain management. The importance of close-loop supply chains (CLSC) in recovering value from post-use products was underscored, with a focus on the unique challenges faced by the aerospace industry.

Further, the study delved into the product EOL phase, examining various end routes for disposed products, including reuse, remanufacturing, recycling, and disposal. The economic and environmental benefits of efficient EOL management were highlighted, particularly the potential for significant value recovery from high-quality aircraft components.

Finally, the circularity of aircraft cabin seating materials was assessed, emphasizing the need for sustainable materials and practices. While opportunities for using bio-based and eco-composites were explored, challenges such as regulatory compliance, scalability, and high costs were acknowledged.

Although significant research exists on the end-of-life management of aircraft, including practices like recycling and remanufacturing, there is a notable gap in studies focused on interior components, particularly aircraft seating. This presents a clear opportunity for further research on the recyclability and circularity of aircraft seating materials, which is essential for advancing sustainable practices within the aerospace industry.

The reviewed literature shows that the key themes of circular economy, supply chain (both forward and reverse), product end-of-life (EOL), and circularity of aircraft cabin seating materials are closely related. The circular economy in the aerospace industry focuses on managing the products EOL and ensuring materials used in aircraft cabins can be reused. Achieving this relies on a seamless supply chain, which includes both forward and reverse processes. Forward supply chains handle design, production, and distribution, while reverse supply chains manage the return, recycling, and disposal of used products. These processes directly affect how materials are treated at the end of their lifecycle, promoting their reintegration into the supply chain. This interconnected approach is crucial for improving the circularity of aircraft cabin materials, underscoring the importance of effective supply chain coordination in implementing a circular economy in the aerospace sector.

In summary, this chapter has laid a solid foundation for understanding the complexities and opportunities in implementing CE and CLSC in the aerospace industry. The study identified key challenges and proposed potential solutions, some of which will be further explored in the next chapter, offering deeper analysis and design considerations for the current supply chain. Additionally, these findings will be evaluated through insights from experts in the case study section, providing real-world validation. The outcomes of this method will lay the groundwork for subsequent research phases, which aim to develop practical and strategic approaches for enhancing the end-of-life management of aircraft cabin seating materials.

4. Aircraft Seating Decomposition and Supply Chain Dynamics

In this chapter, an aircraft cabin seating components decomposition is presented at the beginning of this chapter as a prologue for the subsequent analyses. It is intended to provide a deeper understanding of what the components are in an aircraft seat alongside the materials contained. This is further used to identify the recyclability of material, which will be useful in analyzing the current supply chain flow. Recall from 2.4.2, the method presented is intended to partially answer the following sub-research questions:

- *Sub-research Question 1 – "Which components of aircraft cabin seating materials pose the greatest challenges to recycling from economic and environmental perspectives?"*
- *Sub-Research Question 3 – "What are the challenges, perspectives, and potential solutions identified by stakeholders involved in the end-of-life management of aircraft cabin seating materials?"*

In order to provide a firm background in conducting both analyses, a decomposition of seating components alongside their materials will be presented. The decomposition of aircraft cabin seating components is intended to explore the materials used in the seats as well as stakeholders involved in manufacturing an aircraft cabin seat. Moreover, it is also intended to provide an understanding of the recyclability of the materials. Lastly, this decomposition will subsequently help to build up the groundwork for the subsequent supply chain analysis.

In the supply chain analysis, a current supply chain flow of aircraft cabin seating will be presented alongside the analysis of the flow. In this section, an analysis regarding the current condition of the aircraft seating supply chain as well as proposed flows to implement a close-loop supply chain in the aerospace industry will be presented. This chapter is then closed with a conclusion from all the findings gathered in this method.

4.1. Aircraft Cabin Seating Decomposition

Figure 8. Seat Structure and Materials Decomposition

Figure 8 shows a general overview of components and materials in an aircraft seat. An aircraft seat, specifically a passenger seat, consists of key components, namely structural components and non-structural components. The structural component of an aircraft passenger seat consists of seat frame while the non-structural component consists of cushioning, upholstery, plastic moldings and fire blockers. Despite plastic moldings and fire blockers are typically considered as materials, their presence in the non-structural components of aircraft seats becomes a motivation in categorizing them into components to assist in the decomposition of the seat. Therefore, it is crucial to address both materials as a part of the seat decomposition. Both key components comprise different materials. In this section, we will present the materials used in each component and discuss their recyclability. At the end of each section, we will list the companies that supply these materials. Subsequently, the result of the seating decomposition will serve as a foundation in designing supply chain flow alongside its analysis.

Seat Frame

The seat structure covers the lower part of the seats (which provides a support structure between the seats and the fuselage) to the upper part of the seats (provides foundation for cushioning). In terms of material, aluminium frames are used to construct the seat structure due to their lightweight properties (Aglawe & Giri, 2023). Aluminium is known to be a recyclable material, offering high quality able to be used in other industries (Mascle, 2018; Keivanpour et al., 2013). Companies that supply such components are Safran Seats, RECARO Aircraft Seating, Thompson Aerospace, Collins Aerospace, Stelia Aerospace, etc.

Cushioning

Meanwhile, cushioning provide comfort for passengers, situated around the seat cushion, backrest and headrest. The foam in the cushion is formed either cut from existing foam stock and bonded together with adhesives or molded into final shape (Federal Aviation Administration). Polyethylene (PE) foam is used for the cushioning, it has low thermal conductivity and stable property, making it a good thermal insulator (Ter-Zakaryan & Zhukov, 2022). However, it is still required to be equipped with fire-blocking layer to comply with the strict flammability standard imposed by aviation regulatory bodies such as FAA and EASA. Such layer is in a form of fabric, which could either be bonded into a cushion or loosely covered (Aerofoam Industries, n.d.). As polyethylene foam requires additional fire-blocking layer, it requires separation of materials before proceeding into the recycling process. In some cases, fire-blocking layer is loosely covered which could be easily dismantled. If the layer is bonded, it requires separation before proceeding to recycle the foam. Notable companies that supply such materials are Aerofoam Industries, Aircraft Cabin Modification, GmbH; BASF, etc.

Upholstery

Upholstery material choices can vary, depending on the airline’s specifications. Wool, wool/nylon, or leather (both real and synthetic) are examples of upholstery materials, each with its own characteristics (Lyon, 2008). Wool blend with fire blocking treatment is the most common type of upholstery in use due to being one of the most reliable in complying with FAR 25.853(b) and FAR 25.853(c). Moreover, upholstery fabric that contains high percentage of wool fiber are fire resistant as it neither melt, drip or stick to the skin when exposed to flames (International Wool Textile Organization (IWTO), n.d.). Another material used for upholstery is synthetic leather, known for being more durable, lightweight, and ease of maintenance (Spectra Interior Products, 2024). Lower long-term cost of ownership is also an advantage of using this type of leather, which provides economic benefit especially for airliners (Spectra Interior Products, 2024).

Given the unique characteristics of each material, the recyclability potential of each material is also different. On top of that, the fire blocking treatment on each type of material poses a different challenge in recycling it as it requires to separate both materials before proceeding into the recycling process. Wool fiber alone is fire resistant, therefore is not required to be equipped with additional fire blocker, which makes it recyclable (International Wool Textile Organization (IWTO), n.d.). However, wool blend such as wool and nylon requires additional fire-retardant treatment depending on the proportion of the nylon content given that nylon does not have fire retardant properties (Levitex, 2023). The additional fire-retardant (FR) treatment in the fabric requires additional effort in separating the material before proceeding further into recycling.

Companies that supply upholstery are Boxmark, Lantal, Tisca Tiara, Aeristo, etc.

Plastic Moldings and Composites

Plastics and composites play a crucial role in the construction of aircraft seating due to their beneficial properties. Plastic moldings are used throughout the seat for non-structural components such as covers and casing, which characteristics meet strict flammability, smoke, and toxicity standards (Hechtel, 2021). Meanwhile composites can be found in a passenger seatback, providing lighter weight and enables creating design impossible with metallic materials (Richardson, 2019). Composites can be formed through combining thermoplastics with carbon and glass fiber through resin, either thermoset or thermoplastic, forming Carbon Fiber Reinforced Polymer (CFRP) and glass fiber polymer respectively (Bachmann et al., 2021; Franco-Urquiza et al., 2021). Resin plays an important role in binding multiple materials, forming a composite. Most common type of resin used in a composite is thermoset resin such as phenolic resin, known for being fire-resistant making it suitable for aircraft passenger seating components (Bachmann et al., 2021). Wide variety of plastic moldings are used in aircraft seats, such as food trays and arm rests (Lyon, 2008) while composite exist in the sub-frame of the seat structure such as backseat (Richardson, 2019). Examples of plastic molding materials commonly used in aircraft seatings are polycarbonate, acrylonitrile-butadiene-styrene (ABS), and decorative vinyl (Federal Aviation Administration).

Thermoplastics such as polycarbonate, ABS, as well as decorative vinyl are possible to be recycled through mechanical recycling. Mechanical recycling is a process in which a material is shredded and reprocessed into new products (Castrovinci et al., 2008). However, plastics require categorization to identify the type of plastic in the seating in order to prevent cross-contamination during recycling process (Garcia, 2019). Additionally, synthetic polymers, when reaching EOL stage, are often disposed through incineration and landfilling, resulting in air pollution and soil contamination (Kim et al., 2020). On the other hand, composites require separation of material, which is challenging due to the widespread use of thermoset resin in integrating the composites (Bachmann et al., 2021).

Notable companies that supply plastic moldings are Sabic, Ensinger, Universal Plastics. Meanwhile, composites are commonly produced by the seat manufacturer itself, therefore sharing similar companies with seat frame.

Fire Blockers

Lastly, Fire Blockers are important materials that needs to be integrated into the aircraft cabin seating to prevent the rapid spread of fire (Lyon, 2008). Moreover, aircraft seats comprised of wide variety of nonmetallic materials which needs to comply with strict fire safety standards such as: FAR 25.853(b) (for small nonmetallic seat parts); FAR 25.853(a) and (a-1) (for large area components); and FAR 25.853(c). for foam rubber, upholstery fabric and a fire blocker (Lyon, 2008). Heat resistant thermoplastics are commonly used in aircraft seating such as polycarbonate, phenolic, polyvinylchloride/acrylic blends, polybenzimidazole and aramid fiber fire-blocking layer (Lyon, 2008; Fewell et al., 1979).

Various methods of recycling have already been studied by (Castrovinci et al., 2008) in regard to fire retardant materials, showcasing different advantages and drawbacks associated to each process. Based on the findings, it is impossible to determine common routines in recycling available fire retarded plastic materials due to the nature of fire retardant and its chemical interaction with polymer matrix, affecting the recyclability of the material (Castrovinci et al., 2008). Mechanical recycling might be the most economical way of recycling the material, but it also requires setting up complex sorting process due to heterogeneous plastic waste containing unwanted fire retardants (Castrovinci et al., 2008).

Notable companies that supply fire blockers are BASF, LANXESS and Aerofoam.

4.1.1. Recyclability of Materials

Table 2 presents a detailed analysis of various materials used in aircraft seating, focusing on their components, flammability, and recyclability. In the aerospace industry, selecting materials that meet safety standards while also being environmentally sustainable is crucial. This table highlights the balance between these two critical factors by examining the fire resistance and recyclability of commonly used materials in aircraft seating. The materials are categorized by their component use within the aircraft, their flammability properties, and their recyclability, providing insights into the economic and technical feasibility of recycling these materials.

Table 2. Component and Material Flammability and Recyclability

Component	Material Name	Flammability	Recyclability
Seat frame	Aluminium	Fire Resistant	Economically recyclable (Mascle, 2018; Keivanpour et al., 2013)
Cushioning	Polyethylene (PE) Foam	Not Fire Resistant	In pure form, economically recyclable. Economically unrecyclable once infused with FR chemicals. (Bachmann et al., 2021)
Upholstery	Wool	Fire Resistant	Economically recyclable if the material is in a pure form. Require material separation if it is mixed with FR chemicals (International Wool Textile Organization (IWTO), n.d.)
Upholstery	Wool blend (with nylon)	Not Fire Resistant	Required separation of material before recycling due to containing FR chemicals (Levitex, 2023)
Plastic Moldings, Composites, Fire Retardant	Polycarbonate	Fire Resistant	In pure form, economically recyclable. Economically unrecyclable once infused with FR chemicals (Lyon, 2008; Castrovinci et al., 2008; Bachmann et al., 2021)
Plastic Moldings	Acrylic Butadiene-styrene (ABS)	Not Fire Resistant	In pure form, economically recyclable. Economically unrecyclable once infused with FR chemicals (Lyon, 2008; Castrovinci et al., 2008)
Fire Retardant	Aramid fiber	Fire Resistant	In pure form, economically recyclable. Economically unrecyclable once infused into other materials (Lyon, 2008; Castrovinci et al., 2008)

Composites, Fire Retardant	Phenolic Resin	Fire Resistant	Technically difficult to recycle, require high temperatures or strong solvents (chemical recycling) – potentially generates toxic once separated (Bachmann et al., 2021)

The recyclability of the materials is determined by flammability and the purity of the material itself in the component. One important aspect that determines the eligibility of a material is the flammability of the material itself. If a material, in its pure form, does not meet the stringent flammability regulation issued by the FAA (for example FAR 25.853(b), FAR 25.853(a), FAR 25.853 (a-1), and FAR 25.853(c)) then it requires an additional fire retardant (FR) treatment to improve its fire resistance as well as to comply with the aviation safety standards and regulations.

The flammability factor defines the purity of the material, which also poses challenges regarding the recyclability of the material. In a pure state, both metallic and nonmetallic materials are recyclable with the exception of phenolic resin. The challenges lie within the mixture of other materials into nonmetallic materials. Take an example of an ABS, which functions as plastic moldings for armrests and food trays, it does not meet the flammability regulation thus requiring additional FR treatment through an infusion of FR chemicals into the plastic (Lyon, 2008). This requires separation first before recycling.

Despite the large proportion of mass in the total aircraft seats are recyclable as Figure 4 displayed, most of the materials shown in Table 2 indicates that only metallic materials are recyclable. Based on the graph displayed in Figure 4, it can be estimated that around 70% of the total mass is recyclable, which we can assume that the recyclable mass originated from metallic materials, which constitute the entire seat frame. Therefore, the remaining 30% comes from the non-recyclable mass. This indicates that the involvement of FR treatment in material significantly affects the recyclability of material.

On top of that, different materials are used in an aircraft seat, which also depends on the customer's demand and seat manufacturer, posing challenges in sorting due to the variety of materials and processes used in an aircraft seat. Apart from customer demand, it is also important to address that different seating manufacturer companies have different product portfolios (Aviation Business News, 2024), offering different kinds of materials and designs for the customers to choose from, adding complexity in the aircraft seating. Subsequently, these factors become a challenge for material dismantler to sort the components for further recycling process. Therefore, data transparency of material properties and its process will help material dismantler in assessing the material for further recycling process, thereby reducing waste generation.

4.2. Supply Chain Analysis

In this section, a supply chain flow of an aircraft passenger seating will be presented, starting from raw material sourcing to the end-of-life stage. To provide a general understanding regarding the end-to-end supply chain flow of an aircraft cabin seating, there are two important stages presented, namely: Design, Manufacture, and Operation Stage; and End-of-Life Stage. This supply chain flow presented is relevant for all components of an aircraft passenger seats, starting from the seat frame up to the components that use plastic moldings and composites such as armrests, backseats, and tray tables. Using references from Aerospace Technology Institute (2022), Keivanpour et al. (2013), Zhao et al. (2020), and Hashemi et al. (2013), a supply chain flow is presented below.

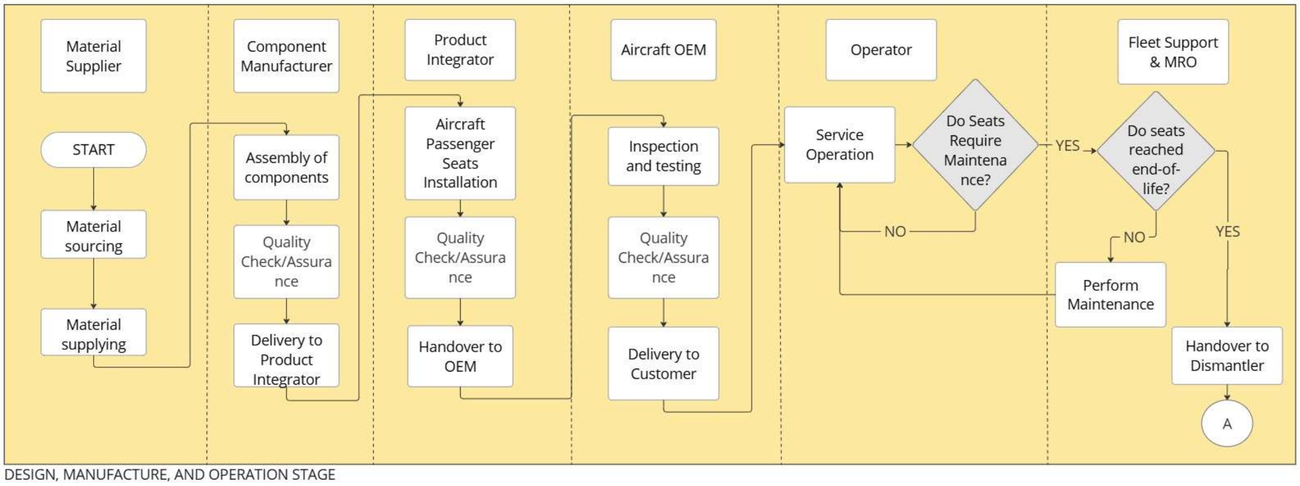

Figure 9. Current Supply Chain Flow of Aircraft Cabin Seating (Design, Manufacture, and Operation Stage)

The journey of an aircraft cabin seat begins during the Design, Manufacture, and Operation stage. Based on the figure above, the aircraft passenger seat begins with the sourcing of raw materials, where the material supplier is in charge of this process. The material supplier will source the material and subsequently supply the material to the component manufacturer. As discussed in 4.1, different companies supply various materials required for aircraft seats. One company provides seat foams, another supplies upholstery, and so on. These materials are then sent to the component manufacturer, which, in this case, is the seat manufacturer. The seating manufacturer produces their seat frame and then assembles all components of the aircraft cabin seating. After all the components are assembled, the manufacturer will then perform a Quality Check and Assurance to ensure that the final product is ready to be delivered to the Product Integrator, who's in charge of installing the aircraft cabin seats into the aircraft. The product integrator will be in charge of installing all the interior components of the aircraft, which also includes the seating itself. After everything is installed, the product integrator will then hand it over to the aircraft OEM for further inspection.

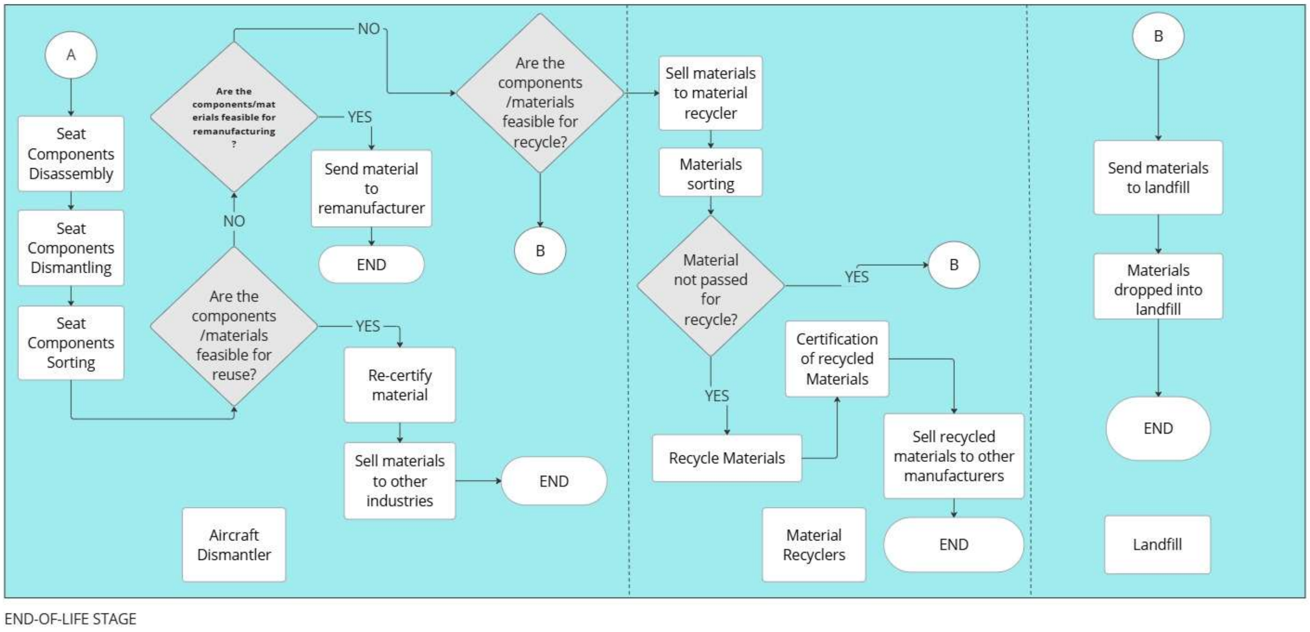

Figure 10. Current Supply Chain Flow of Aircraft Cabin Seat (EOL Stage)

During the EOL stage, the aircraft dismantler will be in charge of disassembling and dismantling the material. During disassembly, the components of aircraft seats will be removed and some of them will be allocated for reuse in other aircraft (Zhao et al., 2020). Meanwhile, dismantling involves material shredding and cutting, which will be used for recycling (Zhao et al., 2020). After disassembly and dismantling are done, the material will then be sorted and treated according to the material condition. If the seat components, such as the leather and the cushioning, can be reused in other industries, then they will be sent to other industries. If the component cannot be reused, then it will be checked whether the component can be remanufactured. The component will be sent to the remanufacturer if it's possible to be remanufactured. Typically, the remanufacturer is often the seat manufacturer itself due to its role in assembling and, to some extent, manufacturing the components. Otherwise, the component will then be checked if it is possible to recycle. If recyclable the component will then be sent for recycling, and the material recycled will be re-certified, and sold to other industries (Zhao et al., 2020). Recall from the previous section concerning the recyclability of material, only metallic materials can be recycled. Therefore, components that contain metallic materials such as seat frames will be sent to a recycler if they cannot be reused and remanufactured. However, the material will be sent to the landfill if it cannot be recycled.

4.2.1. Conditions in Aircraft Seating Supply Chain

According to an environmental report published by the ICAO (Elsayed et al., 2019), there are roughly around 18,000 aircraft retired worldwide from 1980 to 2017 with projections indicating that over 20,000 commercial aircraft will be retired in the next two decades. The average retirement age of a commercial aircraft is 25 years, but passenger seats do not share a similar age. Airplane seats are commonly changed between 5 to 7 years depending on the business needs of an airliner (International Air Transport Association, 2019). This means that an airplane can replace its seats for up to 3 times its lifetime. Assuming that the average number of seats in an airplane is 200 seats, then there are approximately around 10.8 million seats currently retired with an expected 12 million seats retired in the next 20 years. Additionally, if parts of the seats are assumed to be not reused, repurposed, or recycled, there will be roughly 22 million seats in an aircraft graveyard somewhere in the future. It is necessary to take further steps to reduce waste generation considering that most interior products of an aircraft are thrown into the landfill.

Given the amount of effort in identifying each material in the aircraft cabin seats, the cabin seats ended up being thrown out in the landfill. The reason behind this is due to the different materials used in each component of the seat, which requires different treatments to make it recyclable or reusable (Castrovinci et al., 2008). Moreover, the lack of transparency of material properties became an issue in handling the retired seats properly (Garcia, 2019). This resulting in most materials ending up in a landfill, with exceptions from the structural components of seats which are made of aluminium.

4.2.2. Proposed Solutions in the Supply Chain

Despite the challenges in recycling and other circular EOL efforts, there are opportunities to improve them by looking at other industries. In reference to the previous chapter, it is highlighted that lack of regulation becomes a factor that sets back the implementation of CE in the aerospace industry, including Close-Loop Supply Chain itself. Therefore, looking at relevant regulations from other industries could help as a benchmark in improving the circular effort. This will help in justifying the proposed design flow by referring to the relevant regulation.

One example is through looking at the regulation from the EU regarding the circularity of vehicles, where the European Commission is currently proposing regulations that address the entire life cycle of vehicles, starting from design to the end-of-life (European Parliamentary Research Service, 2023). The proposal contains requirements in circularity regarding vehicle design and production such as reusability, recyclability, recoverability, and the use of recycled content (European Parliamentary Research Service, 2023). Moreover, it also defines the requirements concerning labeling and information of parts, components, and materials in vehicles. By looking at other sector's regulations, it is possible to implement similar regulations in aerospace industries, especially regarding aircraft interiors.

Another reference from the previous chapter discussed traceability as an approach to implementing CE. As discussed in the previous chapter, the aerospace industry currently faces the challenge of ensuring transparency, coordination, and control among stakeholders. Implementing traceability can effectively address these issues, such as tracking components' origin and history to comply with stringent requirements and regulations of the aerospace industry.

From the preliminary study, it is discovered that there are many ways to improve traceability such as the use of RFID, IoT, etc. The proposal for two design flows is driven by the current and future conditions of aircraft seat manufacturing. Presently, a communication flow between aircraft dismantlers and seat manufacturers is suggested. For the future state of the aircraft seat supply chain, the use of material passports is proposed to facilitate waste reduction.

The lack of documentation identified in retired aircraft (Yakovlieva et al., 2021), along with the information gaps between stakeholders due to unwillingness or inability to share information (Santana & Ribeiro, 2022) become a motivation in designing a communication flow between aircraft dismantlers and seating manufacturers. Moreover, the different product portfolios the companies offer along with customer preferences pose additional challenges in sorting the seat components and materials also become a motivation in designing this flow, as discussed in the previous sections of this chapter (Aviation Business News, 2024). Meanwhile, the use of a material passport (digital product passport) is driven by the need for a platform that ensures traceability from the product's inception, aiding aircraft dismantlers in making more sustainable decisions. The use of a material passport unlocks the potential for reuse and disassembly by providing valuable information contained in the dataset (Honic et al., 2024).

Using insights from the paragraphs above, two types of approaches are proposed: first utilizing communication between aircraft dismantler and seating manufacturer, and second utilizing material passport to reduce waste.

4.2.2.1. Flow I: Communication Flow between Aircraft Dismantler and Seating Manufacturer

One way to mitigate this issue is through creating a communication flow between aircraft dismantlers and seating manufacturers. The underlying reason for the creation of this flow is due to the lack of identification mark of the current seats both in operation and EOL (Garcia, 2019). Additionally, seat manufacturers have their own design and material choices, and it is deemed proprietary in order to maintain a competitive edge (Aviation Business News, 2024). Moreover, the aircraft supply chain in general, including the aircraft seat itself, is considerably complex due to the involvement of multiple stakeholders, each with their own set of requirements, further complicating the transparency of material properties (Boyer et al., 2015). Having a standardized flow of information between dismantlers and manufacturers can enhance material recovery and recycling as well improving the overall sustainability of the aerospace industry. Given the total number of seats retired for the next 20 years, it opens up an opportunity for sustainable practices in handling the EOL of seats. The proposed flow is shown below.

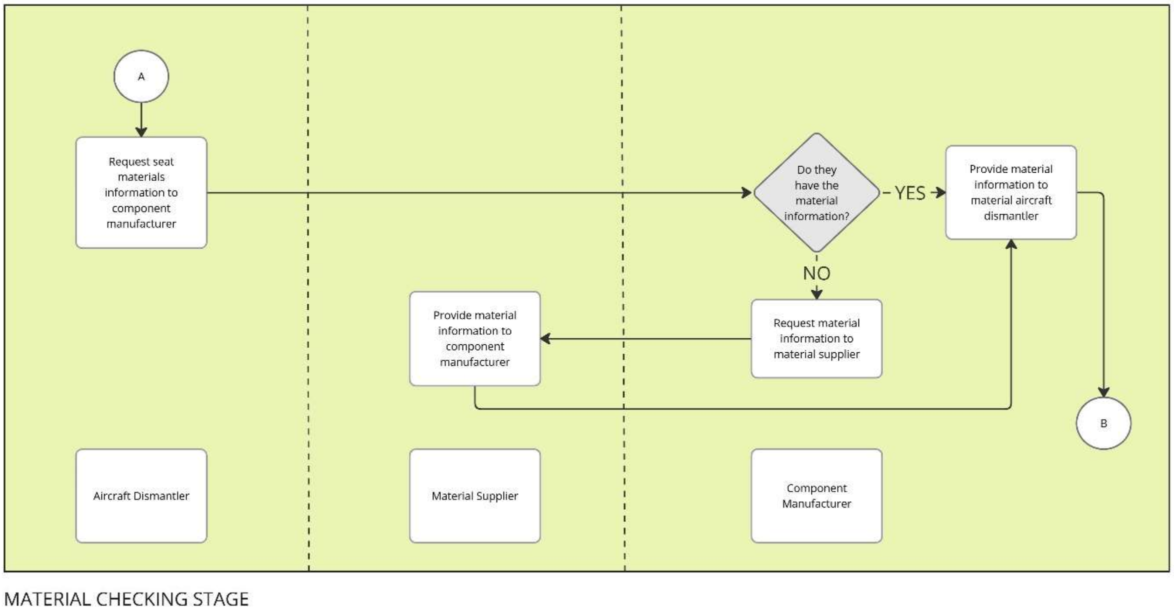

Figure 11. Communication Line between Aircraft Dismantler and Component Manufacturer

In this flow, an additional phase is incorporated, namely the material checking stage. In terms of supply chain flow, it is similar with Figure 9 and Figure 10 but with an additional phase included between the two. Based on the flow displayed above, the aircraft dismantler will proactively communicate with the seating manufacturer to gather information about the material contained in each component before conducting further dismantling. If the component manufacturer is unable to provide information, then they will reach out material supplier to gather material information. Once the component manufacturer gathers the information, they will provide all the information to the aircraft dismantler. Having information regarding materials contained in the aircraft seat could assist aircraft dismantlers in terms of decision-making regarding each component's EOL.

4.2.2.2. Flow II: Use of Material Passport

Another way to mitigate this issue is through the use of material passport to accommodate close-loop supply chain flow as well as reducing material waste. Material passports provide a systematic way to track and manage materials used, which is essential in Circular Economy (CE). As a concept that has been developed since 1982, material passport emerges as a promising tool that collects and manages data essential in Circular Economy (CE) decision making, providing access of a material's lifecycle data which assists stakeholders in making decision (van Capelleveen et al., 2023). Having a unique identity, connected with other identities in a shared repository, the material passport can function as an object for data sharing where stakeholders in the supply chain could utilize their data property to accommodate reverse supply chain (Jensen et al., 2023). Implementation of material passports for aircraft seats facilitates identification of seat composition such as details on the type of materials, components, as well as hazardous substances present (Kedir et al., 2021).

Contribution to CE by material passports can also be done through facilitating the reuse and recycling of materials from retired aircraft seats (Munaro & Tavares, 2021). Moreover, having a detailed record of material used in the seats can assist manufacturers in making informed decisions on how to disassemble and recycle the seats efficiently (Yang et al., 2023), which also contributes to waste reduction in aerospace industry

(Keivanpour et al., 2016). Therefore, having a platform that enables tracking material's properties and conditions could assist stakeholder especially aircraft dismantler in decision making according to CE principles.

Based on the forecast published by Airbus (2023), there are in total 40,850 new passenger aircraft between 2023 and 2042, potentially replacing 75% of current aircraft in-service, where the current number of aircraft operating is around 22,880 aircraft. On average, there will be roughly 2,150 new aircraft produced each year and around 179 new aircraft produced each month. Using the average number of seats per plane, it is estimated that there are approximately 35,800 new seats produced each month (excluding replacement every 7 years per plane). If we include the replacement every 7 years, there will be roughly 3 times replacement with the average age of an aircraft around 25 years. Therefore, around 107,400 seats are roughly produced monthly, and it is expected to reach around 1.3 million seats produced each year. This means that there is another potential of millions of new seats within the next decades which could be better utilized during their EOL stage through implementing material passport from the design and manufacture phase. The proposed flow is presented in Figure 12 below.

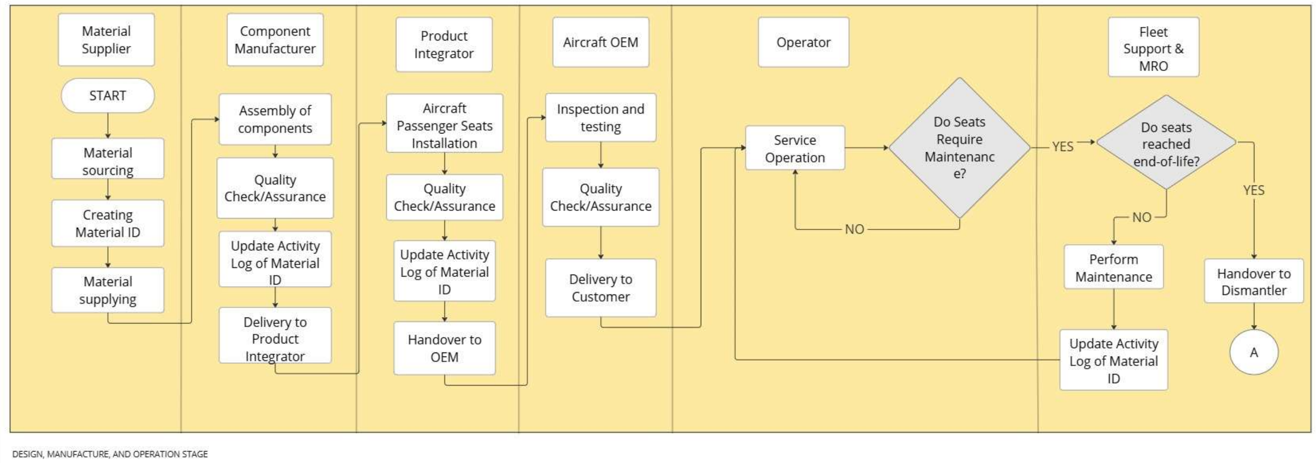

Figure 12. Proposed Supply Chain Flow Using Material Passport (Design, Manufacture, and Operation Stage)

The difference between this proposed flow lies in the incorporation of material passport element, involving many stakeholders in the supply chain flow to provide information of the material. In this case, the material ID will not be embedded in the material but in the component, which could be comprised of several materials. The underlying reason in having a material passport embedded in each component is to assist the material dismantler in disassembling and dismantling the seats once they reach retirement age.

The embedding of the material passport begins during the material supplier's work in sourcing and distributing the material. An identification will be created, which will provide information on the material property. This means that seat foams, upholstery, and plastic moldings will have identification marks before being supplied to the seat manufacturer. Once identification is added, the material supplier will then distribute the material to the component manufacturer, where they will assemble all the components into a seat. The manufacturer will then add an identification number to their seats, which will later be used for the product integrator to update the seat information once the seat is installed. The aircraft OEM will hand over the plane after the quality check and assurance are accomplished. In this stage, the operator will be in charge of operating and managing the aircraft, which also includes the seats installed.

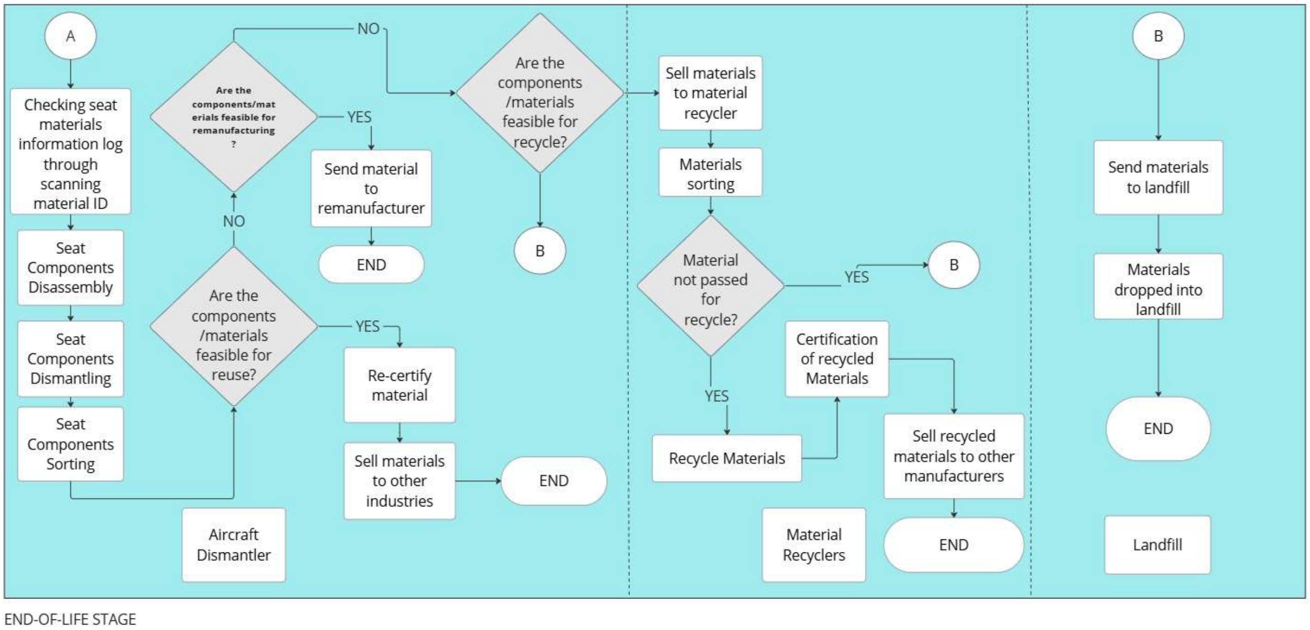

Figure 13. Proposed Supply Chain Flow Using Material Passport (EOL Phase)

Meanwhile, in the EOL stage, the aircraft dismantler only needs to scan the material ID to assist in sorting and decision-making. This will streamline the flow of aircraft passenger seating once retired, ensuring quicker EOL treatment as well as minimizing waste in the future. In comparison to Figure 9, Figure 10, & Figure 11, this proposed flow simplifies the work of aircraft dismantlers. Moreover, there are no differences with the existing supply chain flow except for the additional step of material ID scanning.

Some industries have shown successes in sorting and recycling materials in passenger seating, which will be very useful if both of these proposed flows could be implemented. Components such as plastics, seat cushions, and seat covers were able to be recycled, where their recycled form could be reused in other products (Aircraft Interior Recycling Association, 2020; Garcia, 2019). However, the challenge in recycling the materials lies in the volume of retired seats, where airliners store some of their retired seats as well as send them to landfills, leaving less volume available for recycling (Garcia, 2019). Another effort in recycling is made by Airbus, which opened its first facility that focuses on the entire lifecycle of an aircraft on the 24th of January, 2024, called the Airbus Lifecycle Services Centre (ALSC) (Airbus, 2024). The facility provides a comprehensive range of services, including parking, storage, maintenance, and the dismantling and recycling of various aircraft types, all in one convenient location (Airbus, 2024). As many companies are already showing their efforts in recycling seating components and are successful in doing so, it is possible to have Close-Loop Supply Chain to accommodate their workflow in processing volumes of retired seats and soon-to-be-retired seats.

4.3. Conclusion

In this chapter, we have successfully studied the components and materials that constitute an aircraft cabin seat, which provide a comprehensive decomposition highlighting the complexity and recyclability of each element. Furthermore, this analysis pointed out the significant role of aluminium, polyethylene foam, upholstery, plastic moldings, composites, and fire blockers in the overall structure and functionality of aircraft seats. This chapter complements the findings from the preliminary study by offering a detailed breakdown of the components and materials related to an aircraft passenger seat, as well as their flammability and recyclability. These details are crucial for addressing the challenges of recycling these materials. Additionally, the findings contribute to partially answering the sub-research question, providing further insights that support the conclusions drawn in the previous chapter.

We then explored the current supply chain flow of aircraft cabin seating, detailing the processes from raw material sourcing to the end-of-life stage. This examination revealed the intricate network of stakeholders involved, including material suppliers, component manufacturers, product integrators, and aircraft OEMs, each playing a crucial role in the lifecycle of aircraft seats.

The current state of the supply chain was evaluated, identifying key challenges such as the lack of material transparency and the complexities associated with recycling diverse materials. Furthermore, the varied portfolio of aircraft seat products, including differing designs, material selections, and customer demands, adds to the complexity of managing seats at their end of life (EOL). These issues often result in many components being discarded in landfills, particularly due to the stringent fire safety regulations that require additional treatments, complicating the recycling process.

Examining relevant regulations from other industries that promote product circularity can serve as a reference for identifying opportunities to enhance circularity in aircraft seats. For instance, we found that the automotive industry has regulations that support circularity by setting requirements for vehicle design and production, as well as for labeling and identifying parts. Another opportunity stems from the challenges in ensuring transparency and control in the aerospace industry, which were addressed in the preliminary study. Implementing traceability of components can effectively addressing this issue, through tracking components origins, etc. As noted in the preliminary study, various methods for implementing traceability exist, such as RFID and IoT technologies. However, it is essential to propose solutions that consider both the current and future conditions of aircraft seats. Presently, there is a lack of identification, but in the future, enhanced identification methods can be utilized.

To address these challenges, we proposed enhanced supply chain flows incorporating better communication between aircraft dismantlers and component manufacturers. Introducing a material passport system was suggested as a means to improve data transparency and facilitate more effective recycling and reuse of materials. This system would provide detailed information about each material's properties, aiding stakeholders in making informed decisions regarding the end-of-life management of aircraft cabin seating.

In summary, this chapter has established the foundation for implementing a closed-loop supply chain in aircraft seating, highlighting the need for improved practices and systems to enhance sustainability and circularity in managing aircraft cabin seating materials. Additionally, the findings from the previous chapters contribute to the design and analysis of the supply chain flow, which will be valuable for future implementation and expert evaluation to provide real-world validation, a topic that will be explored in the next chapter.

5. Case Study: EOL Management of Aircraft Cabin Seating Material

In this section, a case study will be presented, which is based on the LDE CfS Circulaerospace thesis lab topic concerning the EOL management of aircraft cabin material, with Airbus as the case holder. The purpose of this case study is to gather insights and evaluate findings from the previous methods through interviews with stakeholders involved in the aircraft cabin seating supply chain. In reference to 2.4.3, this method is intended to partially answer the following sub-research questions.

- *Sub-research Question 1 – "Which components of aircraft cabin seating materials pose the greatest challenges to recycling from economic and environmental perspectives?"*
- *Sub-research Question 2 – "What kind of end-of-life management practices would be relevant?"*
- *Sub-Research Question 3 – "What are the challenges, perspectives, and potential solutions identified by stakeholders involved in the end-of-life management of aircraft cabin seating materials?"*

To answer the sub-research questions above, an interview with experts from various fields will be conducted, exposing diverse insights and perspectives which in turn could help in answering the sub-research questions above. This chapter begins with an explanation of the interview flow, which provides a better understanding of how the case study will be conducted. After presenting the flow, the next section will discuss about the data analysis from the interview results. In this section, several key aspects are discovered through three-stage coding, where each section will elaborate on each key aspect identified. Evaluation of the interview results through comparison of results from preliminary study alongside the evaluation of supply chain flow will be presented after data analysis, where several key points gathered from interviewees will be used to improvise the proposed flow presented. Finally, the conclusion from this chapter will be presented.

5.1. Interview Flow

The case study will be in the form of a semi-structured interview, where its purpose is to gather deeper insights from interviewees as well as to evaluate findings from the previous chapters, namely Chapter 3 and Chapter 4. This includes identifying materials in the aircraft cabin seating that are challenging to recycle, relevant practices in the EOL management of aircraft cabin seating material as well as challenges in material recycling and remanufacturing of aircraft cabin seating. The interview consists of 3 sections:

The first section discusses the relevant sustainable practices, possible recycling initiatives, and alternative solutions to accommodate close-loop supply chain in the EOL management of aircraft cabin seating material. This section is intended to provide evaluation and validation of findings from background study and supply chain analysis.

The second section provides specific questions tailored to each stakeholder involved in the aircraft cabin seating supply chain flow. This section is a continuation of the first section with a focus on the perspective of each stakeholder. This is also intended to offer additional insights that might not be covered in the first section, providing evaluation and support from previous findings in the previous chapter.

The third section presents two proposed supply chain flows, which will then be discussed with interviewees to provide an evaluation of the proposed flow. The first one is a proposed supply chain flow that display a communication line between aircraft dismantlers while the second flow incorporates material passport as an instrument to assist waste reduction through traceability of components.

Overall, there are approximately 10 to 12 questions depending on the interviewees' position in the supply chain flow. Further details regarding the question can be seen in Appendix F – Interview Question List.

5.2. Data Analysis

A three-stage coding will be used to analyze the interview results. Starting with marking several words, phrases, or sentences into a code then group several related codes into one subtheme before merging it into another subtheme to become a major theme. The result of this three-stage coding will be further used in evaluating and validating findings from the interview. Recall from the data analysis section of Chapter 2, three-stage open coding will be conducted, which will help in building explanation and providing linkage of evidence to generate conclusion. The stages consist of first order, second order, and aggregate (Pratt et al., 2006). In this section, we will categorize those stages into codes (first order), sub-groups (second order), and groups (aggregate). Only the aggregate groups will be analyzed further in this chapter, as they encompass the broadest themes, allowing for the identification of insights and opinions expressed by the interviewees.

The codes are collected based on the interview transcript of interviewees. Each interview lasted approximately 45 to 60 minutes, covering all three sections outlined in section 5.1. After conducting data analysis on all the collected transcripts, there are around 700 codes generated, categorized into 33 sub-groups and 6 groups. The codes are derived from the interviewees' quotes. These identified codes are then organized into sub-groups based on their similarities. Finally, these sub-groups are consolidated to form larger groups, which are then used for the analysis of the interview results. The six groups concerning environmental consideration, economic factors, regulation, customer influence, EOL management, and support for the proposed flow. Findings on each group will be elaborated further in the subsection below, where it will subsequently provide important insights for the next chapter.

5.2.1. Environmental Consideration

One important category this group outlined is that there is no environmental consideration when designing an aircraft seat, where all of the experts interviewed confirmed on this matter. There are two major reasons underlying this situation: the first reason is that reducing carbon footprint is more important than end-of-life, while the other reason is concerning cost effectiveness – making seats more lightweight saves fuel, thus reducing carbon footprint. One of the stakeholders interviewed claimed that based on their own Life Cycle Analysis, airplane creates more environmental impact during its operation compared to end-of-life, thus resulting in focusing on designing lightweight seats to reduce fuel consumption irrespective of the environmental impact the material may generate when retired. The Innovation Manager from seat manufacturer A said that *"…the decision is we always need lightweight solution, and every solution needs to be on the same weight level, or even better to stay on the CO2 footprint as good as possible. So, this is the main driver for us…"* This is also supported by the sustainable manager from seating manufacturer A claiming that *"…lightweight is the main driver at the moment for our design. So that means environmental impacts at the end of life. I don't think that this is the big topic to decide how we design our products. So, weight is everything at the moment."* Additionally, the claim on the LCA concerning environmental impact was made by the Sustainability Manager from Seating Manufacturer A, saying that *"90% of the carbon emissions are emitted during the flights. So, that means, this is the biggest impact that we want to reduce. So, end of life, it's very, very small impact."* The interviewee from Seating Manufacturer B also added that *"aviation industry is a bit of behind after other industries when it comes to designing for sustainability."* Therefore, she concluded that *"these considerations were not really in place where the seats that are flying today that were designed 15 years ago or 10 years ago, these practices were not in place."*

This situation is also amplified with findings from another category in the same group, concerning the barriers in seat recycling and remanufacturing. In this category, one of the most common keywords found is the use of additives in aircraft seating materials. The use of additives is necessary to comply with flammability regulation, ensuring that material is not easily burnt once exposed to fire. Furthermore, the additives are embedded into the material rather than blanketing it, where the reason behind this approach is due to saving more weight. *"Additives are embedded into foam and this is purely due to the fact that you can make a seat more lightweight, because adding every next layer causes higher weight of the of the product,"* the Project Manager of Seating Manufacturer B added. However, the problem lies in the disintegrating and separating the components for recycling. Moreover, some additives were found to be toxic once dissolved and the different plastic types mixed with the additives creating additional challenge in sorting the material for recycle. As the Project Manager of Seating Manufacturer B added, *"when you try to dissolve the plastic, then the additive can emit some toxics and it's dangerous."* She also further added that thermoset resins are more commonly used instead of thermoplastic resins, and it is *"very resistant to heat changes, you also cannot dissolve it later."* Lastly, the design process of aircraft does not allow for recycling, thus leaving most of the materials end up in a landfill.

In spite of this, there are current effort in designing aircraft seats with environmental consideration in mind through R&D. As the Project Manager from Seating Manufacturer B said *"…we do a lot of R&D on materials that can be recycled in the end of life, for example composites using the biodegradable resins or bio-based resins."* However, she also added *"…but these are still R&D projects."* This indicates that alternative, sustainable materials for aircraft seats are still under development stage, therefore yet to be used in the industry. One of the reasons is that it is a long process to introduce the material into the market, as the Project Manager of Seating Manufacturer B further added that *"…development stage in the aviation industry takes three, to five, to 10 years…It's a long process to actually introduce the product to the market, to certify it and to actually have it in the aircraft."* She also discussed the possibility of designing seat to be more recyclable in EOL, but it turned out to be heavier. *"And if the product is heavier, then you will use way more emissions during the operational stage then you actually save because you can recycle it,"* she further added.

Another effort in environmental consideration is done through other ways outside the design and material use of a seat. One example is to create sustainable metrics to assess suppliers on how sustainable the product they offered, resulting in a more sustainable practice. This insight is gathered from the aircraft OEM and the airliner, where they show similar effort in creating a metrics regarding sustainability. From the perspective of aircraft OEM, the Head of Cabin Product stated that *"We are trying to find a metrics on how to specify to our suppliers and how to create the requirements and metrics for environmental friendliness of product. So that we can assess which supplier offers more environmentally friendly products and which supplier does not."* However, the effort itself is still *"...in progress.",* as the Head of Cabin Product of Aircraft OEM A added, *"But we realize that it is an important aspect and we are working on it how the best way to integrate this into our specification and requirements."* Same case also applied to the airliner, where *"…they are auditing the company based on sustainability,"* as the Project Engineer from Airline A stated. Moreover, the engineer also informed that the airline will rank all the vendors and will work with the vendors that are ranked the highest.

5.2.2. Economic Factors

Economic factor is also another reason that holds back recycling effort as the lack of volume and the amount of effort needed to recycle significantly outweighs the benefit they can generate. In terms of design, it is known previously that lightweight is the main objective in designing an aircraft passenger seat. This is confirmed by interviewees from all seat manufacturers and the aircraft OEM, where they emphasized on being lightweight and easy to manufacture.

In terms of lack of volume, it is discovered that lack of quantities becoming a bottleneck in recycling effort, as other companies that recycle materials would just accept other industries' waste due to larger volume. The Project Manager from Seating Manufacturer B informed that there are attempts to recycle retired seat foams through offering them to mattress companies. However, the project manager added that *"...for the mattress companies, it was way more profitable to go to IKEA and ask them for old mattresses that were either being returned by people or were damaged as they have way bigger quantities than we do have from seats."* This concern is also supported by the Head of Cabin Product of the Aircraft OEM A, where some attempts to use alternative materials were halted due to lack of volume. For example, the company is interested to use a bio-based steel made of specific spider web and requested the startup company to produce the material for the aircraft OEM. However, as the Head of Cabin Product recalled, that the startup company *"…would rather be working with shoe companies, or even auto industry would be a better market, while aircraft industry does not. Because we are not making millions of aircraft there."*

End-of-life treatment wise, recycling is costly from the manufacturer's perspective – aluminium generates profit, but other materials incur costs indicating economic disadvantage. While aluminium is feasible to recycle, other materials are economically unfeasible due to additives that require additional costs for material separation. Moreover, interviewees from the Seating Manufacturer A stated that customer expect to gain money from recycling, while it actually cost money to recycle the seats. Additionally, the researcher from R&D Institution B also stated that *"there's an economy side. Yes, you can separate it, but it's costing too much money."* He also added that the journey an aircraft seat has endured is so long and complex, starting from the seat manufacturer to aircraft manufacturer and airliner, that it lacks a system that could track the journey of the chairs after it got received by the airliner. When maintenance happen, all chairs are removed and *"transported somewhere… there is nobody involved in thinking about taking these chairs apart, because that would mean another supply chain afterwards."*

Additionally, interviewees from Seating Manufacturer A stated that despite they can earn money from the metal parts, "*we are still not able to cover the transportation cost, the disassembly cost and so on. So more or less it is a minus business."* This is also supported by the aircraft dismantler, where they have to consider the extra manpower to separate the material, and the materials separated must generate revenue, otherwise it will cost them money. Lastly, quantity plays an important factor in recycling material, as interviewee from the material dismantler stated *"It needs to be enough to feed somebody who can use a recycle that."*

5.2.3. Regulation

Regarding regulations, there are no specific requirements on what type of material should be used in an aircraft seat. As long as the material fulfills regulatory requirements such as flammability and the ability to withstand up to 16 G, the material can pass and be used to manufacture components for aircraft passenger seats. "*Fire safety, 9 or 16 G testing, those are the regulation that needs to be fulfilled"* the Head of Cabin Product at Aircraft OEM A said. Regulation, alongside lightweight and comfort, becomes a critical aspect in the design and material choice of an aircraft passenger seat. Despite no limitation in material choice, *"it takes testing to get it certified,"* as the researcher from R&D Institution B added. Therefore, regulation requires certification, and it is costly. The cost of certification is considerably high, around € 1 million or $ 1 million. This is confirmed by interviewees from Seating Manufacturer B, Aircraft OEM A and R&D Institution B. Moreover, a change of color requires recertification, therefore resulting in multiple millions of Euros spent in certification itself. The project manager from Seating Manufacturer B also added '*'…when you change the color of anything, for example, you use the red paint instead of blue paint, you need to certify the product from the beginning...*

not only that it takes two years, but it cost around $ 1 million." Therefore, any changes in color requires re-certification, which is a burden in the manufacturer's point of view.

5.2.4. Customer Influence

Customer preferences significantly influence seat designs to be lightweight, flexible, and cost-effective. The reason behind this is that seating color and design represent the corporate identity of the airline. This results in seats being diverse in material, design, and dimension, as different airlines have different designs due to customization. Based on the interview with a researcher at R&D Institution A, she mentioned that *"airliner want things to look good, to be attractive to their passenger, easy to clean & maintain, last reasonably long, and incredibly light."* Another opinion also comes from the researcher at R&D Institution B, where he stated that different airlines have different business model. For example, a flagship carrier has "*a whole different coloring, seating and comfort. And they design their own seats and their own supplier,"* while this is not the case with Low-Cost Carrier as they used standard seats from the aircraft OEM. "*So, the chairs of Ryanair are replaceable with any chair over standard aircraft. On the other hand, the KLM chairs don't fit anywhere because they're different from all other airplanes,"* he also further added. His statement is also confirmed by the interviewee from the Aircraft OEM A, stating that *"we do have standard seats in our catalog, but a lot of the airlines don't choose for it. Only very small airlines do."* She also added that *"bigger airlines like Lufthansa, KLM, and Emirates have their own seats because it's for their own identity and competitive edge."* From the airline's perspective, it is discovered that easier to clean, sturdy, and easy to maintain become their main criteria. Having a strong material in the seat reduces the possibility for the seats to break down frequently, which will affect the airline's operation. *"So, you have a lot of issues than the seat will be broken very quick and then most of the time operations want their aircraft to be flying. When we ask for replacement parts, it takes up to two weeks to have all the parts in place. Otherwise, we need to block the seat because they are broken and we cannot put passengers in it, and that will cost time to repair,"* as the engineer from the Airliner A added.

5.2.5. EOL Management

Another important group identified from this analysis concerns EOL management, where it is discovered that airlines play a critical role as decision-makers for seats EOL. Based on the interview conducted with experts, it is discovered that airlines decide the fate of the seats end-of-life as the seats themselves are owned by the airline. Other stakeholders do not know what will happen when the seat reaches the end-of-life, as the one deciding the fates for the retired seats are the airlines themselves. Despite aircraft dismantlers being in charge of the retired seats, airlines could just decide to dispose of the seats in the landfill if it is more economically viable.

Another important factor regarding EOL is concerning the use of alloys, which are informed by interviewees from R&D Institution B and Aircraft Dismantler A. *"So, the biggest challenge is that aviation uses a lot of special alloys. And therefore, it's not easy to enter global recycling,"* said the interviewee from the Aircraft Dismantler A. Furthermore, a researcher from R&D Institution B also added that the seating contains *"different sets of alloys in one chair."* He also added, *"When you separate the alloy, you should separate the typical alloy before you can reuse it, and that makes it somehow being wasted somewhere in the landfill."*

Remanufacturing parts is not possible at this moment, despite other industries, such as the automotive industry, engaging in this practice. *"I think we are not in this industry where it makes sense to do remanufacturing,"* the sustainable manager from Seating Manufacturer A said. Furthermore, he added that he is aware of the topic, but doubts that such an approach could be used in the aerospace industry. In the context of recycling, it is not possible to be reused in the aerospace industry due to the degrading quality of recycled products. However, recycled materials could be repurposed in other industries, but not in aerospace due to the degrading quality. *"So, you can recycle aluminium and steel. But you cannot reuse it in the aviation industry. You can reuse it in automotive or any other industry,"* the project manager of Seating Manufacturer B confirmed on this matter.

Additional challenge in the EOL management lies in the plastics, as it has additives in it, making it difficult to recycle. This is confirmed by interviewees from seating manufacturers, aircraft OEM, and research institutes. Regarding the challenge in the materials, the project manager of Seating Manufacturer B stated *that "I would say mainly additives and also the products are not being really designed for sustainability."* This is further confirmed by the aircraft OEM, stating that *"the difficulty is really to disintegrate it because if it's only just components, you can take it out. But if it's something that is blended, between plastic and metal for example, and plastic and fabric. Then, you cannot disintegrate it thus becomes difficult to recycle."*

5.2.6. Support for Proposed Solution

Lastly, another important group in the analysis concerns the communication and support needed to implement the proposed solution. Based on the interview conducted, all of the 8 experts interviewed are in support of the use of material passport and building a communication line between the dismantlers and seating manufacturers. All of the experts have the same opinion regarding this matter, highlighting the contribution the proposed approaches in reducing waste and increasing the recyclability of the material. However, there are some important aspects that need to be addressed. Regarding communication lines between stakeholders, experts emphasize the importance of cooperation to accommodate recycling approaches, which could be done through applying NDA between stakeholders. Meanwhile, a safe environment is needed to accommodate material passport, ensuring that information of material is secured while also traceable.

Efforts in traceability has already been done by the airliner, as the interviewee claimed. They are currently studying the use of RFID in an aircraft cabin to check which part of the cabin requires replacement. *"Right now, we are also doing study with live testing where we use RFID. Suppose that we walk through the cabin, the RFID will get all the signal and then we will get instruction on which part we need to replace, or which oxygen bottle do we need to replace"* the project engineer from Airline A confirmed. The interviewee also added that they currently have a built-in RFID tag in their fire extinguisher as an example. "*And I agree with this approach as well"* said the interviewee supporting the use of material passports in the future.

From the perspective of the aircraft dismantler, it is important to address the simplicity of identification marks for components in the aircraft seat. Because in his point of view, the people that are disassembling the components are concerned more in regard to practicality rather than high tech. *"So don't make it too high-tech. you are working with people in a more practical level, and they want to do it quick,"* the interviewee added. Moreover, the interviewee also highlighted the importance of legislation to implement this approach, with the law being applied worldwide. He further added, *"if it's only a law in the Netherlands, people will start moving their planes to another country where they don't have to pay the extra cost."*

5.3. Evaluation of Results

After gathering all the findings discovered during the interview, an evaluation of results will be presented, comparing findings discovered from the preliminary study as well as evaluating supply chain design flow. This section will be divided into two sections, discussing the comparison of results between desk study and case study and evaluating supply chain design flow based on the feedback received during the interview.

5.3.1. Comparison with Preliminary Study

Environmental consideration. Breakthrough materials studied in accommodating CE are still in early phase, as discussed by Dias et al. (2022) from the preliminary study. This is confirmed through the case study based on statements from seating manufacturer B and aircraft OEM. Findings from the case study indicate that most of the new materials are still under the R&D phase, and the duration for the new material to be introduced into the market is considerably long and costly. Support for recycling through the importance of aircraft recycling association as a standard setter is mentioned during the preliminary study (Yakovlieva et al., 2021). There are no explicit statements from the interviewees regarding this matter, but there are some clues that also discuss this. One of them comes from the seating manufacturer where it mentioned cooperation between companies to facilitate the recycling process through having NDA between all parties involved. Another aspect that the interviewee discussed is creating a safe environment for exchanging data to facilitate the recycling process. Despite not being directly related to the preliminary study, the insights gathered from the interviewee could provide an introduction to having an aircraft recycling association in setting standards for recycling through cooperation between stakeholders.

Economic factors. The volume of production is discussed in the preliminary study by (Kim et al., 2020). This is supported by seating manufacturers and the aircraft OEM. One example is that the aircraft OEM has already shown interest in a company producing sustainable material but was unable to secure a deal due to lack of volume. Another case comes from the seating manufacturer offering retired seat foams to a mattress company, showing a similar response. The lack of incentives alongside the complexity of materials is highlighted by Dias et al. (2022). This is supported by the Aircraft Dismantler A, Research Institution B, and Seating Manufacturer A. Both interviewees from Aircraft Dismantler and Research Institution B mention the use of alloys in the aircraft seat, which comprises mixed materials, resulting in the complexity of materials. The high cost of development for environmentally friendly material is also addressed in the preliminary study, where one interviewee supports this claim. Based on the opinion of the project manager of seating manufacturer B, the high cost of development of environmentally friendly materials comes from the cost of certification as well as the duration it takes to introduce the materials to the market. She also added some of the environmental materials do not meet the flammability requirement, thus becoming a reason why such materials are still in development age

Regulation. Fulfillment in fire regulation has been discussed in the preliminary study, as stated by Bachmann et al. (2021). This is supported by all interviewees who discussed the importance of material in fulfilling the flammability requirement. From the perspective of the aircraft OEM, it is one of the regulations that must be fulfilled. Moreover, fulfilling this regulation requires certification, and it is found to be both costly and time-consuming. This is confirmed by the project manager of seating manufacturer B, who added that the cost itself is estimated to be around € 1 million or $ 1 million and two years of certification process. Additionally, the change of colors and other specifications requires recertification of materials, including the flammability requirement.

EOL management. In the preliminary study, it was discovered that metallic materials offer economic attractiveness. However, due to the presence of alloys, it requires special methods and processes to treat them (Mascle, 2018; Keivanpour et al., 2013). Special methods and processes required for alloys are confirmed during the case study by a researcher from Research Institution B where there are different sets of alloys in one chair, requiring identifying typical alloys before reuse, which is challenging and eventually wasted. Another finding from the case study shows that remanufacturing could reduce the negative environmental effects of manufacturing through material waste, with Rolls-Royce being the prime example in the aerospace industry claiming that their remanufactured product is 'safe for use' as new components. However, it is in contrast to what the case study discovered in regards to remanufacturing, as the sustainable manager of Seating Manufacturer A considers remanufacturing to be not suitable for their industry. Although the automotive industry serves as an example of this approach, he believes it would not be effective in the aircraft seat industry. In spite of the contradiction, one of the limitations that the preliminary study identified is that one of the identified works of literature assumed that all components can be remanufactured, which means that the result of the case study reconfirms what the preliminary study identified.

Collaboration between supply chain partners is discussed in the preliminary study. This is supported through a case study with an emphasis on cooperation to accommodate recycling approaches. Similar to the aspect of environmental consideration, having an NDA between parties would be useful in facilitating collaboration as well as creating a safe environment for data sharing.

The findings of this study highlight the importance of collaboration and innovation in the aerospace industry, particularly in advancing sustainable practices. The insights gathered confirm that while new materials and recycling processes are in the early stages of development, their successful implementation depends on overcoming significant economic and regulatory challenges. The study reinforces the need for cooperative efforts among stakeholders, such as aircraft manufacturers, dismantlers, and research institutions, to establish industry-wide standards and processes that facilitate recycling and end-of-life management. By addressing the complexities associated with material certification and regulatory compliance, these collaborative approaches could significantly reduce environmental impact and promote a more sustainable future for the industry.

5.3.2. Supply Chain Design Flow Evaluation

This section presents two supply chain flows, the first one is a proposed supply chain flow which displays a communication line between aircraft dismantlers and seating manufacturers while the second flow incorporates material passport as an instrument to assist waste reduction through traceability of components. Both flows presented are intended for validation and evaluation of the design.

Several important points were identified during this section of the study:

1. Decision-Making by Airlines/Operators:

Airlines/operators are the ones who decide the fate of retired seats, holding significant influence in deciding whether to send retired seats directly to landfills or sell them to dismantlers. Interviews revealed that seats are often replaced without considering sustainability, leading to most seats ending up in landfills. This applies to all seat components, including the aluminum seat frame, which consists of various alloys requiring additional separation, making recycling cost-prohibitive. This key takeaway is crucial for evaluating the current flow of the aircraft seating supply chain.

2. Certification and Clarification in Supply Chain Flow:

It is necessary to include certification for each stakeholder involved in the supply chain, as it is crucial in the manufacture of aircraft passenger seating. Additionally, clarifying the difference between disassembly and dismantling is essential due to the different outcomes they produce.

3. Support for Proposed Supply Chain Flows:

All interviewees supported both proposed supply chain flows:

- The first flow establishes communication between aircraft dismantlers and seat manufacturers.
- The second flow proposes using a material passport to trace aircraft seat components, reduce waste, and assist dismantlers in sorting components efficiently.

These points are important for evaluating and improving the design of the proposed supply chain flows for aircraft seating. Moreover, the inputs and feedback received from the interviewees also help in refining the proposed design flows. Additionally, the input received during the interview also helped refine the current flow of the supply chain.

Based on all the inputs and feedback received during this session. The revised supply chain flows, starting from the current supply chain flow to the proposed supply chain flows will be presented below.

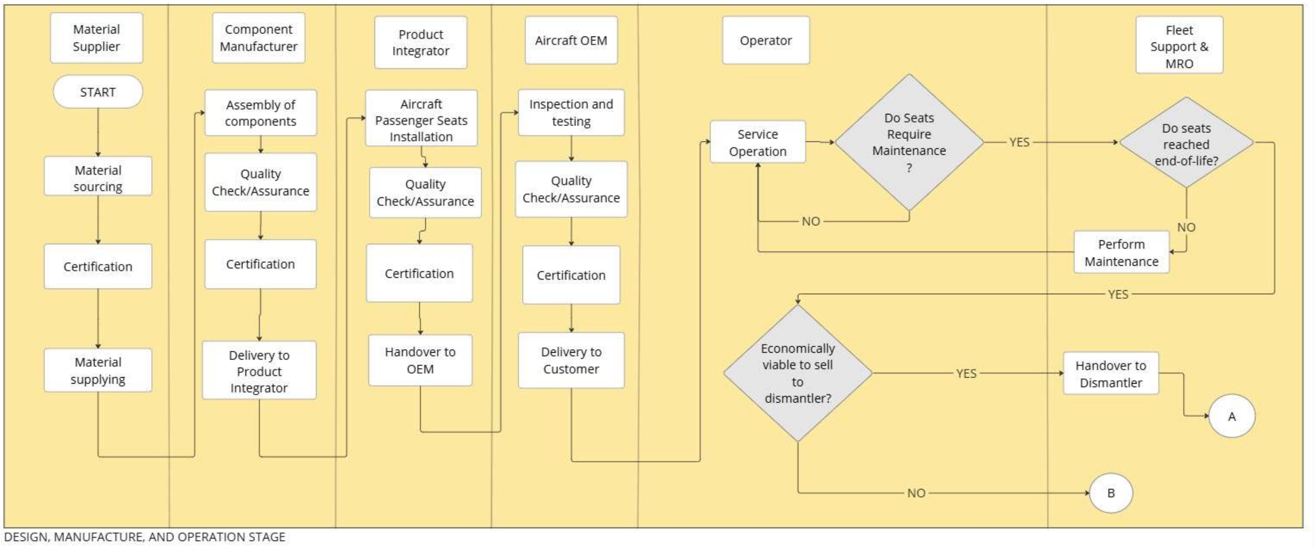

Figure 14. Current Supply Chain Flow After Evaluation (Design, Manufacture, and Operation Stage)

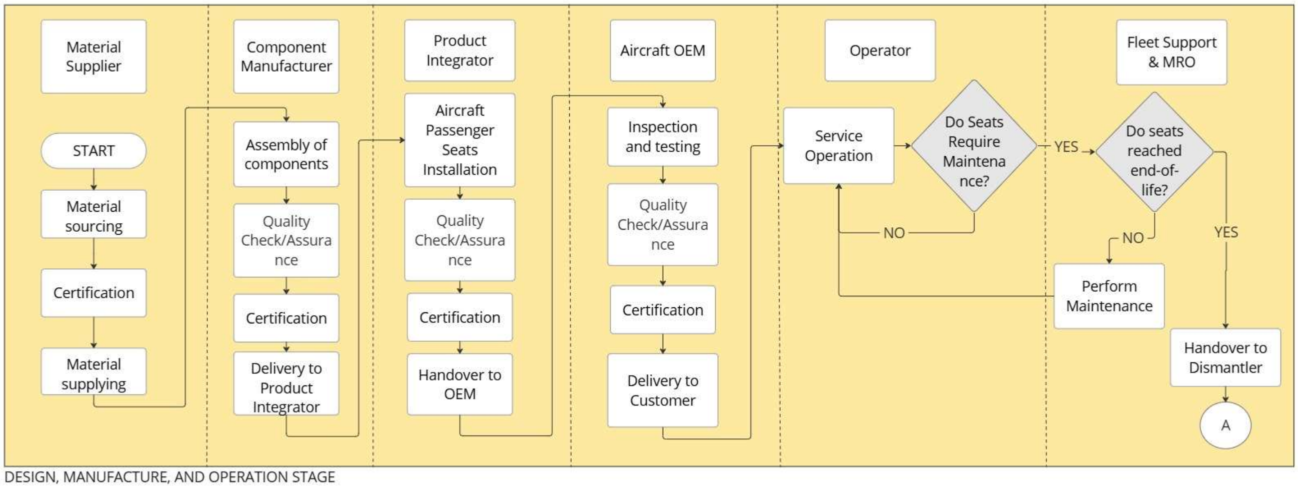

Figure 15. Proposed Supply Chain Flow After Evaluation (Design, Manufacture, and Operation Stage)

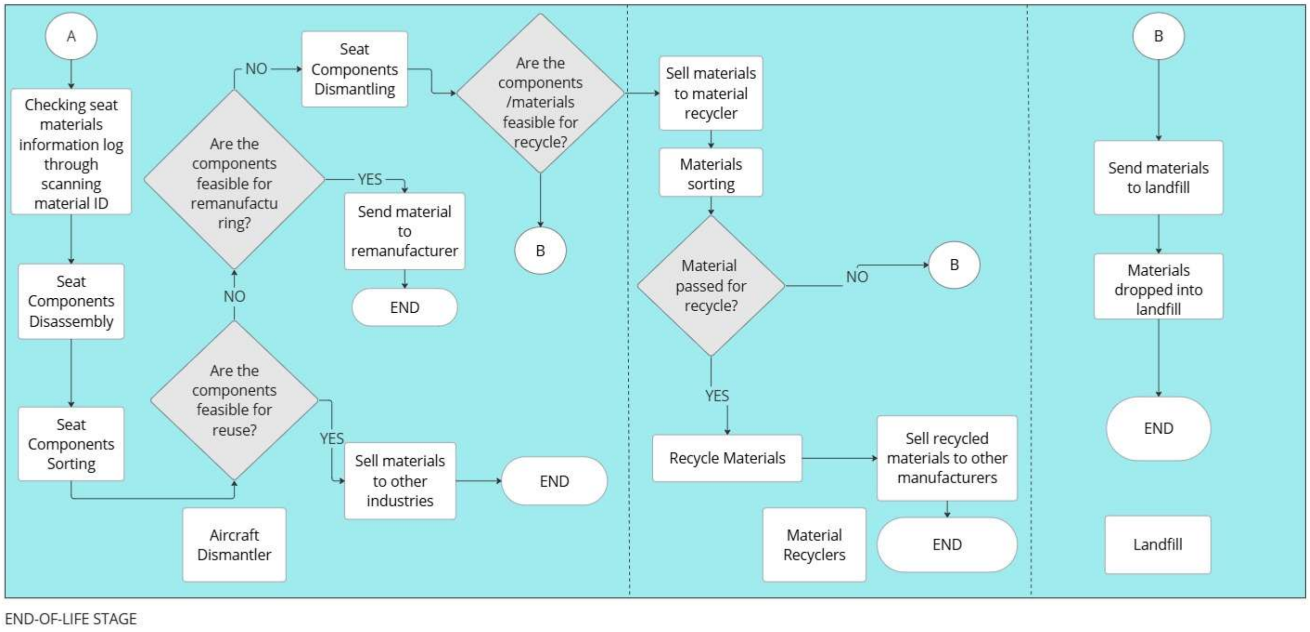

Figure 16. Proposed Supply Chain Flow After Evaluation (EOL Stage) for the use of Material Passport

The current flow in Figure 14 and the proposed flow in Figure 15 showcase differences between the revised flow and the initial flow where it lies in the additional flow for certification on each stakeholder. In the current flow, a decision flow is added in the airliner given that their decisions affect the status of the retired seats whether they are sold to the dismantler or discarded to the landfill depending on the economic viability. The current flow is revised based on the input gathered during the interview despite not being explicitly discussed during the supply chain flow session. Moreover, the change of the flow is applied to all proposed flow and the current flow, to reflect the current condition of how the supply chain model in the aircraft cabin seat works. Meanwhile, Figure 16 showcases the difference between the initial and revised flow based on the position of dismantling, where it occurs once the component cannot be reused or remanufactured. Similar to Figure 15, this change of flow is applied to all proposed flows and the current flow. The change of the flow is intended to provide clarity regarding the process as well as to prevent confusion.

The study provides actionable recommendations that could significantly enhance the sustainability of the aircraft seating supply chain, particularly through the introduction of a material passport for better waste reduction and traceability. It also highlights the importance of collaboration between aircraft dismantlers and seat manufacturers, as well as the critical role of airlines in making informed decisions about retired seats. These improvements have the potential to reduce environmental impact and set new sustainability standards in the aerospace industry. For further details, the evaluated flow can be seen in Appendix C – Existing Supply Chain Flow (After Evaluation), Appendix D – Proposed Supply Chain Flow: Communication Line During EOL Phase (After Evaluation), and Appendix E – Proposed Supply Chain Flow: Material Passport (After Evaluation).

5.4. Conclusion

The case study has managed to gather perspectives from many stakeholders interviewed, which are important in providing key insights in addressing the challenges in regard to EOL management of aircraft cabin seating. The three-stage coding conducted has managed to gather around 700 codes from 8 interviewees, where the codes are then gathered into 33 categories and finally grouped into 6 major groups. The 6 major groups are: environmental consideration, economic factors, regulation, customer influence, EOL management, and support for the proposed solution.

From the environmental consideration aspect, it is discovered that there are no environmental considerations in aircraft cabin seating designs and material selection. The underlying reason is that lightweight became the main priority in designing an aircraft seat, which was found to be more impactful in reducing carbon footprint and fuel consumption. Furthermore, this claim is justified by seating manufacturer A through their own Life Cycle Analysis, where airlines create more impact during the operational stage thus compromising end-of-life. In terms of economic factors, manufacturers focus on designing lightweight seats to reduce fuel consumption, which is found to be cost-effective. It is also discovered that the bottleneck in recycling lies in the lack of volume, which discourages companies from recycling retired seat materials. Another factor lies in the money it generates from recycling retired seat materials. It is found that only aluminium makes money, while others do not, resulting in creating more cost than benefit.

Regulation-wise, it is not specified which materials could be used in an aircraft seat. However, requirements are found to be strict that it must all be fulfilled, such as flammability and 16 G testing. Having to fulfill all the requirements requires certification, and it is costly. Customer preferences influence aircraft seating design and material choices, such as: lightweight, flexible, and cost-effective. In the context of EOL, remanufacturing and recycling in the aerospace industry is not possible due to degrading quality. However, it is possible to have recycled materials to be used in other industries instead. Having additives in aircraft materials poses challenges in recycling as it requires separation, and some additives are also found to be toxic which holds back any recycling effort. Lastly, all interviewees support both proposed solutions while pointing out the importance of cooperation and safe environment for data exchange.

The findings gathered in this chapter were also used to evaluate findings from the preliminary study. The findings from the case study support the preliminary study's discovery of new materials for accommodating the circular economy. The materials examined are still in the early stages, or as the interviewees describe it, the R&D phase, and will therefore require a considerable amount of time before being introduced into the market. The preliminary study highlights the complexity of materials, a point confirmed by the interviewees in this chapter. They noted that the use of mixed materials is common in the aerospace industry, particularly in seatings, which further increases the complexity of materials. The importance of meeting fire regulations was addressed in the preliminary study and further validated during the case study, where interviewees confirmed it as a critical regulation that must be adhered to. Remanufacturing, highlighted in the preliminary study as a potential way to enhance the circularity of components, faces skepticism in the case study findings. Interviewees expressed doubt about its effectiveness, particularly in the context of seating, suggesting that remanufacturing may not be a viable solution.

Regarding the evaluation of the proposed flow, several key aspects needed to be addressed. The first aspect concerns the role of airliners as the decision maker for retired seats, pointing out the importance of their role in EOL management practices, playing a huge role in influencing EOL management efforts. Another aspect that needs to be addressed is regarding certification, as there are no steps of certification in each stakeholder, which needs to be included in each flow. Using all the key aspects above, a new supply chain flow design has successfully been designed to accommodate feedback and evaluation made by interviewees.

All in all, this method has managed to gather insights and perspectives regarding the challenges in EOL management for aircraft seating as well as support for better sustainable practices via the proposed flow presented. Also, the input received from interviewees has assisted in evaluating the design of the flow and improvising it. Finally, this method strengthens and evaluates findings from the previous methods by incorporating insights gathered from the interviewees. These insights will also complement the discoveries from earlier chapters, helping to answer the sub-research questions.

6. Discussion

This chapter discusses the results generated on each methodology and the differences between theoretical and practical perspective in accommodating Close-Loop Supply Chain (CLSC) for aircraft cabin seating EOL management. The first subchapter of this chapter will summarize findings from previous chapters. Meanwhile, the second subchapter will highlight important findings which will be useful in generating conclusions as well as providing recommendations for future works.

6.1 Summaries of Results

Every result generated from all methods will be presented in this section. The purpose of presenting results from every method is to show similarity and differences regarding the findings gathered during data collection. This section begins by showing the results generated from the preliminary study, followed by the result from the aircraft seating decomposition and supply chain dynamics, and finally concluded with the result gathered from the case study.

6.1.1. Preliminary Study

There are several important findings discovered from the preliminary study, which are grouped based on the sub-research questions that this methodology addressed. The sub-research questions that this methodology addressed are sub-research questions 1 and 2, which concern the components of aircraft cabin seating challenging to recycle alongside relevant EOL management practices for the seats.

The structural components of aircraft seats, particularly those made from metallic materials like aluminium, have high economic value, making them attractive for stakeholders. However, the use of these materials requires special processes and advanced methods. Other materials, such as polymers and composites, are critical for creating lightweight and strong aircraft seating but are less frequently discussed in the literature compared to metallic materials. Most publications focus on the main structure of the aircraft rather than the interior, including seating.

Several articles have identified various end-of-life (EOL) practices that support a circular economy, including mechanical and chemical recycling for composites and polymers, as well as remanufacturing, direct reuse, and refurbishing. Furthermore, optimizing EOL is also identified through evaluating products from the design phase to assist in disassembly at end-of-life, which is done through design for modularity. Despite these options, economic feasibility remains a significant challenge, as the costs associated with separating and recycling materials often outweigh the benefits. The lack of regulation further discourages stakeholders from adhering to circular practices in EOL treatment of aircraft seating materials. Both economic considerations and regulatory support are crucial for implementing sustainable EOL management practices and reducing waste.

The sustainable management of aircraft seating materials at their end-of-life faces several challenges, primarily economic and regulatory. While there are technically feasible options for recycling and reusing materials like polymers and composites, the high costs and lack of economic incentives make these practices less viable. Additionally, the absence of stringent regulations further hampers the adoption of circular economy practices. To promote sustainable EOL management and reduce waste, it is essential to address these economic barriers and implement supportive regulations. Encouraging modularity in design and prioritizing materials that facilitate easy recycling and reuse can also contribute to more effective and sustainable EOL practices for aircraft seating materials.

6.1.2. Aircraft Seating Decomposition and Supply Chain Dynamics

During this section, several findings were discovered, which will be grouped based on the sub-research question this methodology intended to answer. The sub-research questions that this methodology aims to address are sub-research questions 1 and 3. The sub-research questions address crucial components of aircraft seating during EOL alongside stakeholders involved in the EOL.

Non-metallic materials in aircraft seat components pose significant challenges during the end-of-life (EOL) phase due to the mixture of materials used in their construction. This complexity leads to most seat components being discarded in landfills, adding to waste generation. In contrast, metallic materials like aluminium can be treated and recycled to reduce waste.

Aircraft dismantlers are the primary stakeholders in managing the EOL of aircraft cabin seating, but their actions depend on the decisions made by airlines, which own the passenger seats. This dependence gives airlines significant power in determining the future of retired seats.

Two approaches are proposed to accommodate a close-loop supply chain (CLSC) for aircraft seats. The first approach establishes a communication line between material recyclers and seating manufacturers, applicable to both retired and active seats. The second approach uses a material passport platform to assist aircraft dismantlers in making informed decisions to support circular practices and reduce waste. Both approaches aim to promote better circular practices, ensuring materials and components have a second life in other sectors. The first approach focuses on data sharing of material properties between dismantlers and manufacturers, while the second approach involves pre-shared material properties information to enable direct EOL treatment decisions by dismantlers.

Managing the end-of-life phase for aircraft seat components, particularly non-metallic ones, is challenging due to the complexity of mixed materials, often leading to landfill disposal and increased waste. Metallic materials like aluminium, however, offer more feasible recycling options. Aircraft dismantlers play a crucial role in EOL management but are heavily influenced by airline decisions.

Some companies are already making recycling efforts for non-metallic materials and the aircraft as a whole. One example is done by the Aircraft Interior Recycling Association, which claimed that they are successful in recycling aircraft seat parts such as plastics, seat cushions, and seat covers. However, the challenges lie in the volume of the material, considering that some of them are stored by the airlines themselves. Another effort is shown by Airbus, who has launched its one-stop facility for its aircraft, which also offers dismantling and recycling services for various aircraft types. Apart from efforts made by companies, regulation in supporting circularity in their product lifecycle has already been proposed in other industries. One example is the regulation made by the European Commission concerning the lifecycle of vehicles, starting from the design to the EOL. Circularity requirement regarding vehicle design and production is addressed in this regulation alongside the identification of material and parts of the vehicle. Therefore, these efforts both in industry and in regulation open up the possibility of implementing Close-Loop Supply Chain in the aircraft passenger seats.

To enhance circular practices and sustainability, two close-loop supply chain approaches are proposed. The first involves creating direct communication between material recyclers and manufacturers, while the second uses a material passport to guide dismantlers in EOL decisions. These approaches aim to facilitate better data sharing and decision-making, ensuring materials can be repurposed in other industries, thereby reducing waste and promoting sustainability. Addressing the economic and regulatory challenges, along with implementing these proposed flows, is essential for effective EOL management of aircraft seating materials.

6.1.3. Case Study: EOL Management in Aircraft Cabin Seating Material

Recall from the previous chapter, this methodology is intended to gather insights from stakeholders involved in the end-to-end process of an aircraft passenger seat. Furthermore, this approach also serves purpose as validating and evaluating findings from previous methodologies, including the proposed flow presented in the supply chain analysis. 3 sub-research questions are addressed in this methodology, concerning components of aircraft seating challenging to recycle during EOL alongside relevant EOL practices and perspectives from stakeholders involved in the aircraft seating supply chain.

All components of an aircraft passenger seat pose challenges during the end-of-life (EOL). While the seat frame, made partially of aluminium, is somewhat recyclable, it contains mixed materials that necessitate additional separation processes. This challenge is similar to that of components containing non-metallic materials, highlighting the need for attention to all seat components.

Opinions on relevant EOL practices vary. Recycling, reuse, and downcycling are theoretically possible for all seat components, but remanufacturing is not feasible due to the aerospace industry's strict material condition criteria and regulations. While technically all materials can be recycled, the high cost of recycling is a significant barrier. Economic factors are crucial in hindering sustainable EOL practices, as the costs often outweigh the benefits. Airlines play a critical role in the decision-making process regarding the EOL of passenger seats, determining whether retired seats are recycled or sent to landfills. Reusing components is also a possibility, but the variety in design and materials, driven by the customized nature of aircraft passenger seats to reflect airline identities, makes it challenging.

The management of aircraft passenger seat components at their end-of-life phase is complex due to the mixture of materials in each component. While recycling is technically possible, the additional separation processes required for mixed materials, particularly non-metallic ones, present significant challenges. Economic factors are a major hindrance to sustainable EOL practices, as recycling and other methods often incur higher costs than the benefits they provide.

Airlines have significant influence over the EOL decisions for passenger seats, determining whether they are recycled or discarded in landfills. The customized nature of aircraft seats, reflecting corporate identities, adds further complexity to the reuse of components. To enhance sustainable EOL management, it is essential to address economic barriers and consider the diverse materials and designs of aircraft seats. Implementing more effective separation processes and encouraging airlines to adopt more sustainable practices could help reduce waste and promote a circular economy in the aerospace industry.

Despite the challenges, there are efforts shown by different stakeholders regarding sustainability. One example is through creating metrics in assessing how sustainable the products that vendors offer, which are done by both airliner and aircraft OEM. This will assist both stakeholders in making more sustainable decision from the beginning of production, which will also help in reducing waste.

6.2 Discussion of Results

Using all the findings generated from all methods, there are several key points on each method that are important to address. In this section, all the key points gathered from all the methods will be first discussed with some limitations and reflections included. Then, scientific contribution will be presented, followed by methodological reflection. Finally, an implication for knowledge user and broader relevance will be displayed, where it will be used as a foundation in creating recommendations in the following chapter.

The first key point that all the methods addressed is concerning recycling challenges in aircraft components. Based on the result from the preliminary study, it is discovered that structural components such as seat frames have high value, particularly those made of aluminium. However, the challenge lies in the presence of mixed materials, which further complicates recycling processes. This is further supported by the findings from the aircraft seating decomposition and supply chain analysis, where the complexity of mixed materials poses challenges in EOL management, resulting in landfill disposal. Results from the case study also add justification regarding the complexity of mixed materials in aircraft seats, where the interviewees mentioned that additional separation is needed to separate the materials. Moreover, the variety in design and materials makes reuse difficult. This factor is first discovered in Chapter 4, identifying the diverse materials, dimensions, and portfolio of seat manufacturers, along with the different requirements of customers, all of which add complexity to the management of end-of-life processes. Results from the case study also confirm this matter, adding that the reason behind the different designs and material choices made by the airliners is due to corporate identity. Additionally, results from the preliminary study also show that modular design could be used to assist in disassembly at end-of-life, facilitating a better EOL process. To address these issues, modular design and prioritizing materials that are easily recyclable and reused can help mitigate these challenges.

The second key point concerns the EOL management practices, where it is found through a preliminary study that there are several identified practices relevant to all materials such as mechanical and chemical recycling, remanufacturing, direct reuse, and refurbishing. However, the overall challenges lie in the economic feasibility being a significant barrier, given that the cost of separating and recycling further discourages sustainable EOL practices. Based on the findings gathered in the case study, interviewees discussed relevant EOL practices where recycling, reuse, and downcycling are possible, but remanufacturing is hindered by strict industry criteria. Economic factors are a significant barrier. In addition to the economic barrier, regulation also becomes an additional barrier to implementing sustainable practices. Results from the preliminary study indicate that lack of regulation in facilitating circular effort discourages companies from conducting sustainable EOL management. Furthermore, strict flammability regulation was identified in all methods. Despite the lack of regulation in the aerospace industry, other industries have shown effort in accommodating circularity through regulation, which was identified during supply chain analysis. Regulation that addresses the entire life cycle of vehicles is currently proposed by the European Commission, where it concerns the requirement for circularity in vehicle design and production as well as labeling and information of components in vehicles. This indicates that such regulation can also be implemented in the context of the aerospace industry, subsequently facilitating circularity in their entire lifecycle. Similar to the first key point, modular design and prioritizing materials that are easily recyclable and reused could mitigate these issues, with an emphasis on creating regulations that can facilitate this approach.

Third, stakeholders such as aircraft dismantlers are primary stakeholders but are influenced by airline decisions regarding the future of retired seats. Two approaches were proposed to mitigate this issue, namely establishing communication between material recyclers and seat manufacturers and utilizing material passports to aid dismantlers in decision-making. Lastly, it is recommended to improve data sharing and decision-making to ensure materials and components can have a second life, addressing economic and regulatory challenges. Regarding case studies, stakeholder influence became another key point identified where airlines play a crucial role in EOL decision-making, determining whether seats are recycled or landfilled. Establishing better communication between material recyclers and seat manufacturers, utilizing material passports, and enhancing data sharing can aid dismantlers in decision-making. Addressing economic barriers and implementing effective separation processes are essential for promoting sustainability and ensuring materials and components can have a second life.

The last key point that is identified concerns the current effort stakeholders are making to accommodate circularity in the aerospace industry. Based on the result from the supply chain analysis section, it is discovered that some recycling companies such as the Aircraft Interior Recycling Association is able to recycle non-metallic materials such as plastics, seat covers, and seat cushions, where the recycled materials could be used in other industries. Airbus has also launched a new facility that supports sustainable EOL management through recycling and dismantling. From the case study, it is discovered that seating manufacturers are currently working on sustainable materials in their aircraft seatings. Meanwhile, both aircraft OEMs and airliners are currently working on creating sustainable metrics, which are useful in assessing vendors that produce sustainable products, facilitating both aircraft OEMs and airlines in creating sustainable products starting from the sourcing process. All these sustainable efforts identified by stakeholders could enable the implementation of a Closed-Loop Supply Chain for aircraft seating within the next 10 years.

Despite all the findings and results gathered, this research is not without its limits. The first important matter that needs to be addressed is the limited number of stakeholders involved in the case study. While the majority elements of stakeholders were successfully interviewed, including seating manufacturers, the aircraft OEM, the airliner, and the material dismantler; gathering insights from the material supplier was not able to be conducted, considering their insights and perspective might provide further support for this thesis project. However, clues on this matter were successfully gathered from the interviewee mentioning the effort of material suppliers in recycling old materials offering the material a second life. This information could be useful for further studies.

Another aspect that needs to be addressed is the potential bias this study might generate due to graphic displays during the interview. The display of graphics during the case study is intended to validate findings, which also influences interview results and provides a lack of interaction during the interview. Interaction with stakeholders from the early stage of design would be more useful in designing the supply chain flow, which could be useful for future studies. While this thesis focuses on economy class seats, it would be better to explore other classes in aircraft seats to explore opportunities regarding this topic. Additionally, the estimated total number of seats currently retired and those potentially retiring in the future (including new seats from new airplanes) may not be entirely accurate. Moreover, the number of recycled mass and unrecycled mass of the aircraft seats may also not be accurate due to estimation and reliance on one source of reference. Therefore, it is possible that the numbers presented could be inaccurate. Another limitation comes from the use of only 2 proposed flows, where there may be more alternative designs that could better accommodate traceability and reduce waste, as indicated in the preliminary study. Exploring other approaches to traceability could be valuable for future research. Lastly, the supply chain analysis is deemed to be too generic, based on the input received during the case study. While it is intended to provide generalizability, it will be better to have a deeper exploration regarding the supply chain for the aircraft cabin seating material. All of the limitations mentioned might be useful for further studies on this topic.

Eventually, this research has profoundly enhanced my understanding of end-of-life (EOL) management for aircraft cabin seating materials, highlighting the complexities of economic viability, material composition, stakeholder influence, and regulatory frameworks. Key insights include the high costs and lack of financial incentives that hinder recycling implementation, addressing the need for cost-effective technologies, and economic incentives. The study revealed the challenges of mixed material recycling, emphasizing material standardization and modular design. Interaction with stakeholders highlighted the significant influence of airlines in EOL decisions, advocating for collaborative close-loop supply chain approaches. Proposed models like data sharing and material passports show promise but face challenges in stakeholder cooperation and regulatory support. Despite limitations such as interview biases and a narrow focus, this research underscores the importance of interdisciplinary approaches to sustainable aviation practices

6.2.1. Scientific Contribution

This research contributes to the development of sustainable end-of-life (EOL) management practices through identifying economic and regulatory barriers to sustainable EOL practices in aircraft seating as well as proposing two close-loop supply chain (CLSC) approaches to improve EOL management. The study emphasizes the importance of high recycling costs and the lack of economic incentives, suggesting that improving these areas can enhance the feasibility of recycling and reuse. Moreover, the proposed models for better communication and data sharing between stakeholders offer practical solutions to these challenges, paving the way for more effective EOL management practices in the aerospace industry.

The study conducted in the preliminary shows a significant gap concerning aircraft interior products, particularly aircraft seats and their EOL considerations. This research highlights the need for further research concerning aircraft interiors, specifically seats. This opens opportunities for further research in more sustainable approaches for aircraft seating through improving its recyclability as well as recycling and other circular approaches to reduce waste generated by the aircraft's retired seats.

Another aspect of contribution is that this research enhances the understanding of material challenges, in particular the material composition of aircraft seating, which is found to be complex due to the presence of mixed materials, thus posing difficulties in their recycling process. Additionally, the research identifies specific challenges posed by non-metallic materials such as the presence of fire retardants in polymers and composites. By highlighting this issue, the study encourages focused research into developing more effective recycling technologies. The concept of a material passport for dismantlers is a novel idea that can be explored further to facilitate better tracking and recycling of materials, contributing to a circular economy.

The study also underscores the critical role of airlines in EOL decision-making, revealing how their influence often determines whether seats are recycled or sent to landfills. This insight can be used to develop strategies that engage airlines more effectively in sustainable practices. The integrative methodology combining the preliminary study, aircraft seating decomposition with supply chain analysis, and case studies provides a comprehensive approach that can be applied to other complex systems. By recommending future research to include other aircraft seat classes and involve material suppliers, the study lays the groundwork for broader implications, promoting sustainable aviation practices and informing policy-makers, industry stakeholders, and researchers about the necessary steps to enhance sustainability in the aerospace industry and beyond.

6.2.2. Methodological Reflection

The integration of these three methods allowed for a comprehensive and multi-faceted understanding of EOL management for aircraft seating. The preliminary studies provided a theoretical framework, the aircraft seat decomposition and supply chain dynamics connected this framework to practical supply chain dynamics, and the case studies offered real-world validation and insights. This triangulated approach ensured that the research addressed both the breadth and depth of the issue, capturing the complexities of material composition, stakeholder influence, and economic viability.

However, some areas could be improved. The findings might be limited by the relatively small number of stakeholders involved in the case studies, especially the absence of input from material suppliers and recyclers. Furthermore, the supply chain analysis was considered too broad, indicating a need for a more detailed exploration of specific supply chain processes. The methods that I have chosen for this study help in providing insights that are necessary to answer the sub-research questions addressed. However, it lacks in providing in-depth insights using the current approach of data collection. A dedicated section to collect data in designing the supply chain flow through interviews with stakeholders could provide better results in the design, which helps in increasing its validity. Despite these limitations, the integrative nature of the methodology greatly enhanced the understanding of sustainable EOL practices and laid a strong foundation for future research and practical applications.

Overall, the methodology's strength lies in its ability to combine diverse methods into a cohesive and comprehensive analysis, addressing theoretical, practical, and stakeholder perspectives. This integrative approach not only enriches the research findings but also provides a robust framework that can be applied to other complex systems in need of sustainable management solutions.

6.2.3. Implications for Knowledge Users and Broader Relevance

The study has significant implications for various knowledge users, especially policymakers, regulators, aircraft manufacturers, and airlines. Policymakers and regulators can leverage the findings to create economic incentives and supportive regulations that make recycling more financially viable and promote circular economy practices. Standardizing material separation and recycling processes is crucial to ensure industry-wide consistency and feasibility. Aircraft manufacturers and airlines are encouraged to design seats with modularity and recyclability in mind, simplifying disassembly and reducing waste. Enhanced collaboration between airlines, manufacturers, and dismantlers, through close-loop supply chain approaches and material passports, can improve data sharing and decision-making, fostering more sustainable EOL practices.

The broader relevance of this study lies in advancing the circular economy and promoting sustainability within the aviation industry. By addressing economic and material challenges in EOL management, the research supports reducing landfill waste and improving recycling, therefore lowering the industry's environmental impact. The introduction of innovative concepts like material passports and close-loop supply chains can be applied to other sectors, contributing to global sustainability efforts. Additionally, the integrative methodology used in the study serves as a model for interdisciplinary research, offering a comprehensive approach that can be applied to other complex systems seeking sustainable solutions and encouraging cross-disciplinary collaboration.

7. Conclusion, Recommendations, and Reflections

In this chapter, the conclusion generated from the previous chapter will be discussed alongside recommendations to accommodate CLSC in the EOL management of aircraft cabin seating. Limitations of this research will also be discussed afterward. Future work will also be addressed in regard to this work, providing opportunities to delve further into the topic of implementing CLSC for aircraft passenger seats, followed by reflection as a personal evaluation of this work.

7.1. Conclusion

This research uncovered several significant findings from the methodology, which are crucial for addressing the research questions. In this section, we will discuss how the findings from the methodology provide answers to these questions. Regarding the sub-research questions, each method applied contributes a partial answer that complements the others when combined within the sub-research question. The conclusion for the main research question, on the other hand, is derived from synthesizing the findings from all methods, as discussed in the previous chapter.

"How can a Close-Loop Reverse Supply Chain be effectively implemented in the EOL management of aircraft cabin seating materials?"

Based on the methods conducted, there are several factors that influence the implementation of Close-Loop Supply Chain in EOL management of aircraft cabin seating materials. Economic factors become the first aspects that needs to be addressed, both on the design of the seats and the EOL treatment of retired seats. Using results from the case study, aircraft seats are designed to be lightweight in order to reduce fuel consumption as well as carbon footprint. This resulting in seat manufacturers only focusing on making the seats lighter by any means necessary, compromising EOL. Moreover, the use of materials in designing the seat pose challenges in recycling the material, where most of them end up in landfill. One factor that influences the choice of material is the stringent regulation in flammability, which resulting in the use of fire retardant in every material that does not pass the flammability in order to comply with the regulation. This factor also adds the complexity of recycling the material as it requires separation, and some of them are found to be toxic as well. Lastly, certification is also another factor that significantly influences the choice of materials in aircraft seating. It is confirmed by many interviewees that any changes in color, or development of new materials require certification, which are found to be costly and time consuming. Many of the new materials developed also were found not production ready due to development stage as well as not passing the flammability regulation.

Despite the challenges addressed, there are opportunities to implement this approach in the EOL management of aircraft cabin seating material. Based on the result from case study, there are efforts already done from several stakeholders to support sustainable practice regarding aircraft cabin seating EOL. Also, the result from supply chain analysis also shows that there are companies that are successful in recycling non-metallic materials of aircraft seats as well as showing effort through establishing facility that support better EOL treatment. This indicates that implementing Close-Loop Supply Chain for the EOL management of aircraft cabin seating material is possible within 10 years, justified by the current effort done by seating manufacturers, aircraft OEM, airliners and aircraft recycler. Regulation to accommodate circularity is therefore necessary to have this approach to be implemented effectively, ensuring that aircraft seats are produced with sustainability in mind from the design stage up to the EOL.

Sub-research Question 1 – "Which components of aircraft cabin seating materials pose the greatest challenges to recycling from economic and environmental perspectives?"

From both economic and environmental perspectives, the components of aircraft cabin seating materials present significant recycling challenges. Based on the result of the preliminary study, structural components made of metallic materials like aluminum hold high economic value and are recyclable. However, the recycling process for aluminum is complicated by the need for special processes and advanced methods. Non-metallic materials, such as polymers and composites, are essential for creating lightweight and strong seats but pose severe challenges during the end-of-life (EOL) phase. In the aircraft seating decomposition chapter shows that these materials often use thermoset resin for fire resistance, making them toxic and difficult to separate, leading to substantial environmental impacts.

During the EOL phase, the complex composition of non-metallic materials in seat components complicates recycling efforts, resulting in many seat components ending up in landfills and increasing waste generation. Even aluminum, despite its recyclability, is often mixed with other materials, necessitating further separation processes. Case studies show that all components of aircraft passenger seats are challenging to manage at EOL. Therefore, attention is needed across all components of an aircraft seat to improve recycling processes and minimize environmental impact.

Sub-research Question 2 – "What kind of end-of-life management practices would be relevant?"

Several articles have identified various End-of-Life (EOL) practices supporting the circular economy, such as mechanical and chemical recycling for composites and polymers, remanufacturing, direct reuse, and refurbishing. However, these methods face significant challenges, primarily economic feasibility. While technically possible, the costs of separating and recycling materials often outweigh the benefits, making many EOL practices economically unviable. Additionally, the lack of regulatory support hinders the adoption of circular practices, especially in the context of aircraft seating materials, where economic considerations and regulatory enforcement are crucial for sustainable EOL management.

The case study results reveal mixed opinions on relevant EOL practices, noting that recycling, reuse, and downcycling are viable for all seat components, but remanufacturing is not feasible due to strict industry criteria and degrading material quality. Interviewees highlight that while technically possible, the high costs of recycling materials pose a significant barrier to sustainable EOL practices. Airline decision-making plays a crucial role in determining the fate of retired passenger seats, with economic factors often leading to landfill disposal rather than recycling. The customized nature of aircraft passenger seats further complicates reuse due to the diverse designs and materials reflecting corporate identities.

Sub-Research Question 3 – "What are the challenges, perspectives, and potential solutions identified by stakeholders involved in the end-of-life management of aircraft cabin seating materials?"

The end-of-life management of aircraft cabin seating materials presents significant challenges, particularly due to the difficulty of recycling various materials treated with fire retardants and the lack of transparency in material information. This lack of data hinders dismantlers' ability to sort and recycle materials effectively, often resulting in many seats being discarded in landfills. The substantial volume of seats retired each year further complicates logistics, emphasizing the need for efficient recycling methods and improved stakeholder communication. The economic complexity, high recycling costs, and use of mixed materials and additives often make landfill disposal the more feasible option for airlines. These concerns and are initially discussed in chapter 4 and are further reinforced by expert opinions gathered during the case study.

Several solutions are proposed to address these issues. Enhancing communication and data sharing through material passports can provide detailed material information, aiding dismantlers in the recycling process. These solutions are first discussed in chapter 4, with experts supporting on the proposed solutions in chapter 5. Implementing advanced recycling technologies and sorting methods can better handle complex material compositions, while promoting sustainable design practices, such as designing for disassembly and prioritizing recyclable materials, which can significantly improve the end-of-life management of aircraft seating. Financial incentives, regulatory support, and improved collaboration among stakeholders are also crucial. These strategies aim to streamline the recycling process, reduce waste, and promote environmental sustainability in the aerospace industry.

7.2. Recommendation

To accommodate the effective implementation of CLSC in the EOL management of aircraft cabin seating material, there are several key aspects defined as recommendations. The key recommendations are outlined below.

Addressing Economic Feasibility

- Policy Makers (Government, Regulatory and Industry Bodies)

To encourage a sufficient volume of materials for recycling, we suggest that policymakers (including government, regulatory, and industry bodies) consider creating regulations that encourage operators to send retired seats to dismantlers rather than disposing of them in landfills. This approach will enable aircraft dismantlers and material recyclers to secure the necessary volume of materials, thereby making the recycling process more economically viable. We suggest that governments and industry bodies worldwide to cooperate in designing such a policy.

Additionally, it is essential to incentivize these practices through various financial mechanisms to promote the economic viability of recycling and reuse. Governments and industry bodies may provide subsidies and grants to reduce the cost burden associated with recycling. Moreover, implementing tax incentives for companies that invest in sustainable EOL practices and recycling technologies can further encourage adoption.

- Seating Manufacturers, Aircraft OEMs, Aircraft Dismantlers and Material Recyclers

Investing in research and development can play a crucial role in creating more cost-effective recycling and separation technologies, particularly for non-metallic materials, which material recyclers might implement. Additionally, exploring sustainable materials can lead to improvements in the separation process once materials are retired, a task that seating manufacturers and aircraft OEMs may consider. Fostering partnerships between industry and academic institutions could also help drive innovation in recycling methods.

Enhancing Material Separation Processes

- Policy Makers (Government, Regulatory and Industry Bodies)

Standardizing materials used in aircraft seating can greatly simplify the recycling process. Utilizing sustainable materials for aircraft seats can also enhance the efficiency of recycling and separation during end-of-life (EOL) stages. Governmental and industry bodies may promote and encourage the adoption of standardized and sustainable materials that are easier to recycle and separate, helping the industry reduce the complexity and cost of EOL processes.

- Seating Manufacturers, OEMs, Airliner, Aircraft Dismantlers, and Material Recyclers

Encouraging modularity in design can greatly facilitate the dismantling and reuse of components, where seating manufacturers, OEMs, and airliners can collaborate on this effort. Standardizing materials can also promote recycling and enhance circularity, which manufacturers may consider adopting. Additionally, developing and deploying advanced separation technologies can improve the efficiency of material separation. Manufacturers might design seats with ease of separation in mind to support recycling efforts once the seats are retired. Exploring chemical separation technologies could also offer effective solutions for handling complex material mixtures.

Strengthening Regulatory Support

- Policy Makers (Government, Regulatory and Industry Bodies)

Governments, along with regulatory and industry bodies, can cooperate in providing strong regulatory support to accommodate the circularity of aircraft seats. A robust regulatory framework is necessary to support sustainable EOL practices. Regulations requiring airlines and manufacturers to follow specific EOL management practices that prioritize recycling and reuse should be implemented. Similar to the first section of this recommendation, having regulation requiring operators to send retired seats to dismantlers rather than to landfills could better support sustainable EOL practices.

Additionally, policymakers might consider prioritizing recycling within regulations to assist aircraft dismantlers and recyclers in efficiently managing materials and ensuring a steady flow of waste for recycling. Developing certification standards for sustainable EOL practices could help promote industry-wide compliance. Furthermore, encouraging the use of material passports, which document the materials used in aircraft seats, could facilitate easier recycling and more informed EOL decision-making.

Given that it has been previously identified that the numerous certifications and associated costs required to promote new materials pose a significant challenge in implementing sustainable materials in aircraft seats, we propose that regulatory bodies consider streamlining these certification processes. By reducing the number of required certifications, particularly in areas such as flammability compliance, it would help lower barriers and encourage the adoption of these sustainable materials, thereby supporting circularity efforts in the industry.

Promoting Stakeholder Engagement

- Aircraft OEM

Collaboration among stakeholders is vital for effective EOL management. Organizing workshops and forums where airlines, manufacturers, dismantlers, and recyclers can share best practices and develop shared solutions can foster cooperation. Aircraft OEMs such as Airbus can play the role as initiator in creating this forum considering their major role as aircraft manufacturers in the aviation industry ecosystem. Forming industry consortia to collectively address EOL challenges can lead to more coordinated and effective approaches.

- Academic

Academics can take the lead in developing training programs to educate stakeholders on the importance of sustainable EOL practices and the latest technologies available. These programs could be coordinated with industries such as aircraft OEMs and seating manufacturers. Additionally, academics might drive public awareness campaigns to highlight the benefits of sustainable EOL practices, helping to build broader industry and public support.

Implementing Close-Loop Supply Chain Approaches

- Policy Makers (Government, Regulatory and Industry Bodies)

Policymakers, such as governments and regulatory bodies, are encouraged to consider proposing regulations to support these initiatives. Enhancing data sharing and transparency is critical for the success of closed-loop supply chain approaches. Developing robust information systems that enable seamless data sharing between material recyclers, manufacturers, and dismantlers can facilitate better recycling and reuse practices. Implementing tracking systems to monitor the end-of-life (EOL) journey of aircraft seats and report on sustainability metrics can provide valuable insights. Additionally, the integration of material passports could be prioritized to offer detailed information on material composition and EOL options, guiding dismantlers in making informed decisions.

- Seating Manufacturers, OEMs, Airliners, Aircraft Dismantlers, and Material Recyclers

From the industries' side, adopting circular economy models that focus on the continuous reuse and recycling of materials can significantly reduce waste and promote sustainability in the aerospace industry. This could be done by creating a material/product passport from the seating manufacturer and subsequently being updated by OEMs and airlines to ensure traceability. Making informed decisions about EOL management is necessary for airliners, favoring recycling and reuse over landfill disposal. In this way, the close-loop supply chain can be implemented as waste can be reduced and material can have a second life in another industry. Having an integrated tracking system between stakeholders is necessary, ensuring traceability and facilitating aircraft dismantlers and material recyclers in making informed decisions on EOL management.

By implementing these recommendations, the aviation industry can overcome the economic, regulatory, and material complexity challenges associated with the end-of-life management of aircraft passenger seats. These actions will contribute to more sustainable practices, reducing waste, and promoting a circular economy in the aerospace sector.

7.3. Limitations

This research has several limitations that need to be acknowledged. Firstly, there is a potential bias introduced by the graphic displays used during interviews. The graphics, intended for validation purposes, may have influenced the responses of the interviewees. The lack of interactive discussion between stakeholders in designing the flow further supports this point. Instead of collaborative design sessions, stakeholders were presented with pre-designed graphics, limiting their ability to contribute actively and provide diverse perspectives on the supply chain flow.

Secondly, the study involved a limited number of stakeholders. While the interviews provided valuable insights, expanding the range of participants in future research could yield a more comprehensive understanding of the challenges and opportunities in end-of-life (EOL) management of aircraft cabin seating. Engaging a broader spectrum of stakeholders, including manufacturers, airlines, dismantlers, and recyclers, would add important insights and enhance the robustness of the findings.

Additionally, this research focused solely on economy class seats. While this focus allowed for a detailed exploration of a specific segment, examining other classes of aircraft seating, such as business and first class, could reveal additional opportunities and challenges in implementing a closed-loop supply chain. The unique materials, design features, and usage patterns of higher-class seats might necessitate different EOL management practices and strategies.

Another limitation is the depth of analysis of the supply chain flow. The research provides a generalizable overview but does not delve deeply into the specifics of the supply chain, making it appear somewhat generic. A more detailed and comprehensive examination of the supply chain could offer greater insights into the nuances and complexities of EOL management for aircraft cabin seating. Additionally, the estimated number of currently retired and future retiring seats, as well as the figures for recycled and unrecycled aircraft seat mass, may not be accurate due to reliance on estimates and a single reference source. Therefore, the presented numbers could be inaccurate. Moreover, the proposed supply chain flow design includes only two flows, but there may be alternative designs that could better accommodate traceability and reduce waste, as indicated in the preliminary study. Therefore, exploring other approaches to traceability could be valuable for future research.

Another limitation arises from the use of the term 'material passport.' In this report, 'material passport' is used to refer to 'digital product passport' or ‘product passport.’ The term 'material passport' is commonly used in the construction industry, whereas 'digital product passport' or ‘product passport’ is the preferred term in other industries.

Addressing these limitations in future studies could enhance the validity and applicability of the findings, contributing to more effective and sustainable EOL management practices in the aerospace industry.

7.4. Future Work

There are several future works identified to enhance and support findings from this research. The possible future works identified are presented in points below.

Product Passport in Aircraft Seating

Further studies regarding the implementation and effectiveness of product passport in aircraft seating products are needed. A product passport could provide detailed information about the materials and components used in the seats, their origin, and EOL options. Research should focus on how such a system can enhance transparency, facilitate better recycling and reuse practices, and support a circular economy. It is important to investigate the technological and logistical challenges of integrating product passports into the existing supply chain and assess the overall impact on sustainability and efficiency. Further research into regulating the use of product passports as a standard for aircraft seating products could help facilitate their implementation, thereby encouraging industries to adopt this system.

Data Sharing in the Supply Chain

Another critical area for further research is regarding data sharing within the aircraft cabin seating supply chain are needed, which includes the willingness to share data. Studies should examine the current barriers to data sharing, including concerns about confidentiality, competitive advantage, and technological limitations. Understanding the willingness of different stakeholders to share data and the conditions under which they would do so is essential. Research should also explore the development of secure and efficient data-sharing platforms that can enhance collaboration and support sustainable EOL management practices.

Regulation to Support Circularity

Another crucial aspect in regards to further studies are concerning regulation in supporting circularity practices to accommodate close-loop supply chain in aircraft cabin seating. Future research should focus on identifying regulatory gaps and proposing new policies that encourage or mandate circular economy practices. This includes investigating how regulations can incentivize recycling, reuse, and remanufacturing, and how they can support the implementation of closed-loop supply chains. Comparative studies of regulatory frameworks in other industries or regions could provide valuable insights and best practices for the aerospace sector.

Stakeholder Engagement

Lastly, more stakeholders interviewed are needed to gain better perspective and add more important insights. Apparently not all stakeholders in the supply chain flow of an aircraft seat are involved during the case study, where the insight from the missing stakeholders could be crucial in providing further recommendations in accommodating this process. Having stakeholders such as material suppliers involved in the case study would assist in enhancing the findings generated resulting in a more comprehensive study regarding this topic.

7.5. Reflections

Undertaking this research has been a profound learning experience, offering valuable insights into the complexities of end-of-life (EOL) management for aircraft cabin seating materials. Throughout the study, I have had the opportunity to explore the intricate interplay between economic viability, material complexity, stakeholder influence, and regulatory frameworks, all of which significantly impact the sustainability of EOL practices in the aviation industry.

One of the most enlightening aspects of this research has been understanding the critical role of economic factors in shaping EOL management decisions. It became clear that while technical solutions for recycling and reusing materials exist, their implementation is often hindered by high costs and lack of financial incentives. This realization underscored the importance of developing cost-effective recycling technologies and providing economic incentives to encourage sustainable practices.

The complexity of material composition in aircraft seats, particularly the challenges posed by mixed materials, was another significant discovery. The need for advanced separation processes highlighted the technical difficulties in achieving effective recycling. This understanding has deepened my appreciation for the importance of material standardization and modular design in facilitating easier and more economical EOL management.

Engaging with various stakeholders during the research provided diverse perspectives and enriched the study. However, it also revealed the significant influence airlines have in the decision-making process for retired seats. This insight emphasized the necessity of involving all relevant stakeholders in designing and implementing closed-loop supply chain approaches to ensure a holistic and collaborative effort toward sustainability.

The proposed closed-loop supply chain models, focusing on data sharing and material passports, emerged as promising solutions to enhance circular practices. Reflecting on these models, I recognize the potential they hold in transforming EOL management by promoting transparency, informed decision-making, and effective material reuse. However, the challenges of implementation, particularly regarding stakeholder willingness to share data and the need for robust regulatory support, remain critical areas for further exploration.

The limitations identified in this study, such as potential biases during interviews, limited stakeholder engagement, and the focus on economy class seats, have highlighted areas for improvement and future research. Expanding the scope to include other classes of seating and a broader range of stakeholders will provide a more comprehensive understanding and drive the development of more effective EOL strategies.

In conclusion, this research journey has been both challenging and rewarding. It has broadened my understanding of the complexities involved in EOL management for aircraft seating and reinforced the importance of interdisciplinary approaches to address sustainability challenges.

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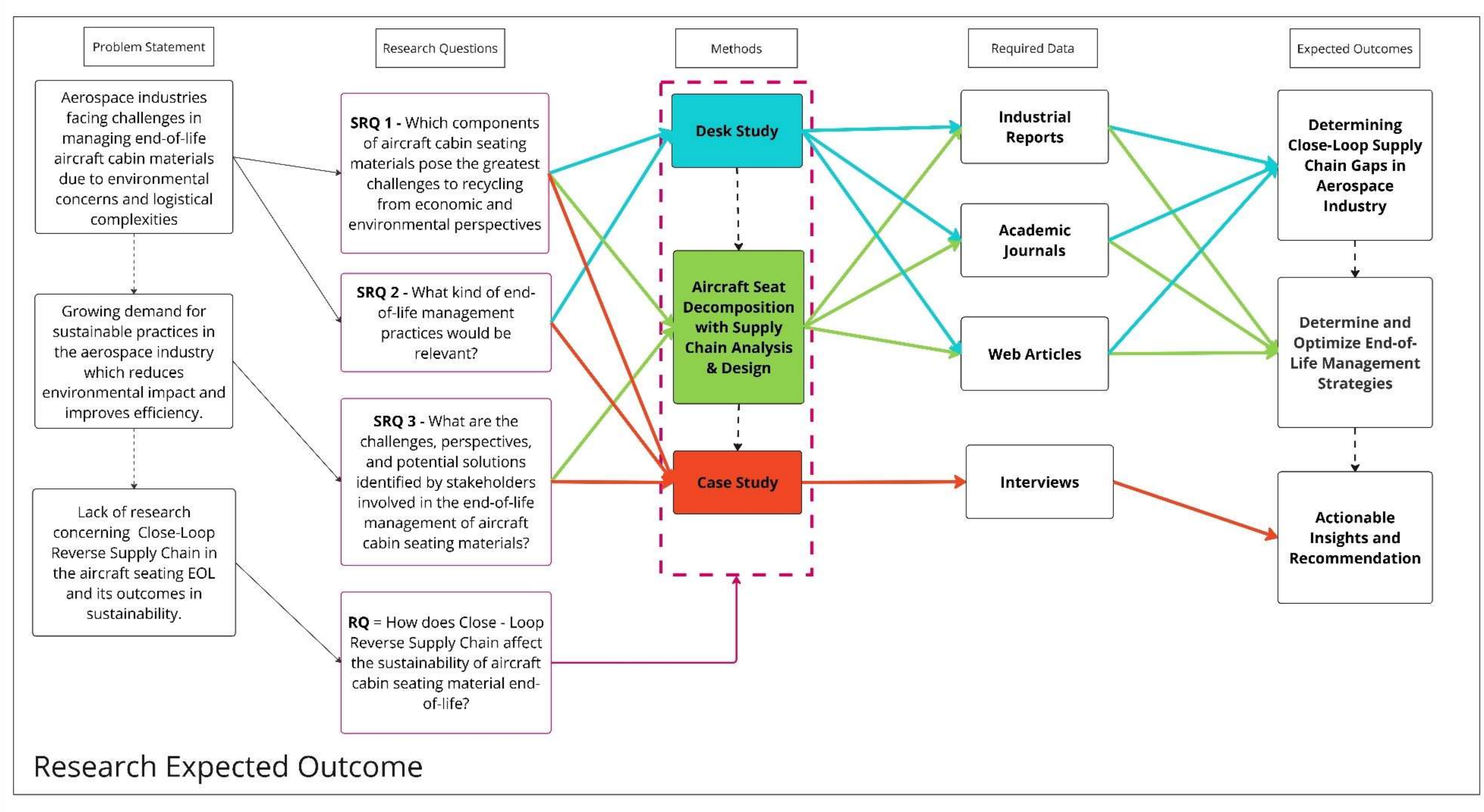
Appendix A – Research Outcomes



Appendix B – Preliminary Study: Relevant Literature Identification

Part I: Circular Economy

Search Strategy: {“Circular Economy”, “Aerospace”}, {“Circular Economy”, “Aerospace”, “Aircraft”}

Database: Web of Science

Total Papers Discovered: 70 {“Circular Economy”, “Aerospace”}, 5 {“Circular Economy”, “Aerospace”, “Aircraft”}

Total Relevant Papers Found: 1 {“Circular Economy”, “Aerospace”}, 4 {“Circular Economy”, “Aerospace”, “Aircraft”}

Year Published	Author(s)	Title	Key Findings	Limitation	Remarks	DOI
2022	Dias, VMR; Jugend, D; Fiorini, PD; Razzino, CD; Pinheiro, MAP	Possibilities for applying the circular economy in the aerospace industry: Practices, opportunities and challenges	• Financial benefits drive the adoption of circular economy (CE) strategies in the aerospace industry. • Ethanol and other alternative fuels are being used as renewable fuel sources. • Industry 4.0 technologies (AI, VR, drones, additive manufacturing) facilitate CE practices. • Reuse and recycling of materials in aerospace and other industrial sectors are significant.	• High costs associated with the development and use of environmentally friendly materials. • Technological challenges due to the complexity and long lifecycle of aerospace products. • Lack of incentives and regulatory support from agencies. • Limited empirical study scope with only three companies.	The study provides a framework for CE practices in the aerospace industry, highlighting the importance of financial and environmental benefits. It also emphasizes the role of technological advancements and regulatory support in promoting CE adoption.	https://doi.org/10.1016/j.jairtraman.2022.102227
2024	Vogiantzi, C; Tserpes, K	On the Definition, Assessment, and Enhancement of Circular Economy across Various Industrial Sectors: A Literature	• Detailed definitions and assessment methodologies for the circular economy (CE) across various sectors including aerospace, wind energy, transportation, automotive, and sports goods. • Identification of key challenges in implementing CE practices in these	• The study primarily relies on literature reviews and the EC-funded project RECREATE, which may limit the scope of practical, real-world applications. • Subjective nature of definitions and assessment criteria used in different studies. • Limited empirical data on	The study provides a comprehensive overview of CE definitions, assessment frameworks, and enhancement strategies across multiple industries. It highlights the role of digitalization and systemic approaches in promoting CE, while also addressing the challenges and opportunities	https://doi.org/10.3390/su152316532

		Review and Recent Findings	industries. • Exploration of digital tools and Industry 4.0 technologies (IoT, AI, Big Data) in enhancing CE. • Highlighting the necessity of a holistic and systemic approach that engages all stakeholders across the value chain. • Mention of 3 assessment of circular economy, namely LCA, MFA, and IO analysis.	the effectiveness of proposed CE strategies in each industry. • Varying levels of technological adoption and regulatory support across different sectors.	for future research and practical implementation.	
2023	Ashraf, F; Lodh, A; Pagone, E; Castelluccio, GM	Revitalising Metallic Materials: A Path towards a Sustainable Circular Economy	• Introduction of preventive maintenance techniques to revitalize metallic materials and extend their lifespan. • Emphasis on coating, mechanical, and thermal treatments as effective maintenance strategies. • Comparison of environmental impact of primary and secondary (recycled) production of key aerospace alloys. • Development of a taxonomy of maintenance techniques based on mechanisms.	• Focus on a limited number of mainstream maintenance strategies. • The study is based on hypothetical case studies and selected materials. • The current state of recycling technologies may not generalize the findings. • Need for further empirical validation and real-world application.	The study provides valuable insights into the potential of preventive maintenance in promoting a sustainable circular economy. It highlights the importance of material revitalization and provides a ranking of techniques based on environmental impact, suggesting future directions for research and practical implementation.	https://doi.org/10.3390/su151511675
2016	Sabaghi, M; Mascle, C; Baptiste, P	Evaluation of products at design phase for an efficient disassembly at end-of-life	• Introduced a hybrid Design of Experiments (DOE) and TOPSIS method to evaluate disassemblability at the design phase. • Identified five critical disassemblability parameters: accessibility,	• The study relies on a specific case study (Bombardier Regional Jet) which may limit generalizability. • The model assumes controlled conditions that may not reflect real-world variability in disassembly	The study provides a robust framework for evaluating product disassemblability at the design phase, emphasizing the importance of considering end-of-life processes early in product development. Future	https://doi.org/10.1016/j.jclepro.2016.01.007

			mating face, tools type, connection type, and quantity and variety of connections. • Developed a disassembly scoring model to calculate disassemblability index for components, achieving 94.30% reliability. • Application of the model on Bombardier Regional Jet aircraft indicated improved end-of-life disassembly efficiency.	environments. • Limited empirical validation of the proposed methodology across different products and industries. • Some disassembly parameters and their interactions may require further exploration for comprehensive applicability.	research should focus on validating the model across diverse industries and products, and exploring additional disassembly parameters.	
2021	Krauklis, AE; Karl, CW; Gagani, AI; Jorgensen, JK	Composite Material Recycling Technology-State-of-the-Art and Sustainable Development for the 2020s	• Identified sociotechnical drivers for composite recycling technology development, such as landfill bans and increased decommissioning of wind turbines and aircraft. • Presented a cutting-edge review of recycling technologies for fiber-reinforced composites (FRCs), including mechanical, thermal, and chemical recycling methods. • Highlighted the importance of selecting optimal recycling methods based on composite type (e.g., E-glass vs. carbon fiber) to ensure economic and environmental sustainability. • Emphasized the need for technology readiness level (TRL) assessments to guide	• The study is based on a literature review and lacks extensive empirical data. • Focused mainly on technological aspects without in-depth economic analysis of recycling processes. • The feasibility and scalability of proposed recycling methods need further validation through real-world applications. • Limited exploration of the regulatory and logistical challenges associated with implementing recycling technologies in different regions.	The study provides a comprehensive review of composite recycling technologies, emphasizing the need for tailored approaches based on composite type and application. It underscores the importance of advancing recycling technologies to meet the growing demand for sustainable composite disposal solutions. Future research should focus on empirical validation, economic analysis, and addressing regulatory and logistical challenges.	https://doi.org/10.3390/jcs5010028

			the development and implementation of recycling technologies.			

Part IIa: Supply Chain

Search Strategy: {“Supply Chain”, “Aerospace”}, {“Supply Chain”, “Aerospace”, “Interior”}

Database: Scopus

Total Papers Discovered: 104 {“Supply Chain”, “Aerospace”}, 5 {“Supply Chain”, “Aerospace”, “Interior”}

Total Relevant Papers Found: 3 {“Supply Chain”, “Aerospace”}, 2 {“Supply Chain”, “Aerospace”, “Interior”}

Year Published	Author(s)	Title	Key Findings	Limitation	Remarks	DOI
2023	Cunha, N. F.; Gan, T.-S.; Curcio, E.; Amorim, P.; Almada-Lobo, B.; Grunow, M.	Robust supply chain design with suppliers as system integrators: an aerospace case study	• Developed a mathematical programming model for supply chain design (SCD) that includes integrators and considers integration risk. • Proposed new measures for integration risk, building on current risk assessment practices and utilizing robust optimization to account for uncertainty. • Demonstrated the model using both randomly generated instances and real data from a large European OEM in the aerospace industry. • Identified that sourcing flexibility can mitigate	• Relied on case studies and hypothetical scenarios, which may not cover all possible real-world complexities. • Assumed certain fixed parameters and cost structures that may not reflect real-world variability. • Limited empirical validation and practical application of the proposed model. • The computational efficiency of the model may be sensitive to input data variations.	The study provides a robust framework for supply chain design that incorporates integration risk, emphasizing the need for a balanced approach to managing risk and complexity. Future research should focus on empirical validation and exploring different industry settings to enhance the generalizability of the findings.	https://doi.org/10.1080/00207543.2022.2099769

			integration risk and emphasized the trade-off between integration risk exposure and supply chain complexity.			
2023	Schmelzle, U.; Mukandwal, P.S.	The impact of supply chain relationship configurations on supplier performance: investigating buyer–supplier relations in the aerospace industry	• Analyzed the performance impacts of suppliers forming shared relationships with the buyer's competitors • Better inventory efficiency and asset turnover are demonstrated by suppliers with fewer shared ties to the buying firm's competitors, as found in the study • Fostering relationships that are relatively focused, strong, and dependable, rather than broadly shared and shallow, is found to enhance operational efficiency for suppliers, as emphasized in the study. • Utilized secondary data and a seemingly unrelated regression approach to analyze the impact on supplier performance.	• Based on secondary data, which may not capture all relevant variables influencing supplier performance. • Focused on the aerospace industry, potentially limiting generalizability to other sectors. • Assumes that relationship configurations are the primary determinant of operational efficiency without considering other potential factors. • The study may not fully address the dynamic nature of supply chain relationships over time.	The study provides valuable insights into how supply chain relationship configurations affect supplier performance in the aerospace industry. It underscores the importance of exclusive, trust-based relationships in enhancing operational efficiency. Future research should explore additional industries and consider longitudinal data to capture the dynamic nature of supply chain relationships.	https://doi.org/10.1108/IJLM-12-2020-0465
2021	Manville, G.; Papadopoulos, T.;	Twenty-first century supply chain	• Investigated Lean Supply Chain Management (SCM) and Performance	• 1. Based on case studies from five organizations, limiting the generalizability	The study provides valuable insights into the effectiveness of the SC21	https://doi.org/10.1080/14783363.2019.164210

	Garengo, P.	management: a multiple case study analysis within the UK aerospace industry	Measurement Systems (PMS) challenges in the UK aerospace industry through the SC21 programme. • Identified that SMEs with SC21 accreditation showed significant performance improvement by adopting Lean SCM and PMS practices. • Highlighted the importance of collaboration between supply chain partners, especially between SMEs and Prime contractors, to enhance supply chain performance. • Emphasized the role of SC21 performance awards (bronze, silver, gold) in bridging the gap between differing agendas of supply chain partners.	of the findings. • Focused mainly on the aerospace industry, potentially limiting applicability to other sectors. • Relied on qualitative data, which may not capture all nuances of supply chain dynamics • The study did not deeply explore the economic implications of Lean SCM and PMS adoption.	programme in improving supply chain performance in the UK aerospace industry. It underscores the importance of strategic planning, performance measurement, and collaboration among supply chain partners. Future research should include more diverse case studies and a deeper exploration of the economic impacts of Lean SCM and PMS.	1
2005	Voordijk, H.; Meijboom, B.	Dominant supply chain co-ordination strategies in the Dutch aerospace industry	• In the Dutch aerospace industry, coordination strategies that improve data-handling capability—by investing in cross-functional connections, strategic foresight, and shared data platforms among companies within the	• Based on case studies from six Dutch aerospace firms, limiting the generalizability of the findings. • Assumes that information processing is the primary determinant of co-ordination efficiency without considering other potential factors.	This study offers important insights into the key supply chain coordination strategies prevalent in the Dutch aerospace industry, emphasizing the importance of information processing. It highlights the need for strategic planning and collaboration among supply	https://doi.org/10.1108/00022660510585938

			supply chain—dominate supply chain management. • Lateral relations and information systems are substitutes for co-ordination strategies like keeping stock or slack resources and self-contained tasks. • The study employs an information processing perspective, drawing from the work of Galbraith, to understand co-ordination strategies.	• Limited empirical validation and practical application of the proposed strategies. • The study may not fully address the dynamic nature of supply chain relationships over time.	chain partners. Future research should explore additional industries and consider longitudinal data to capture the dynamic nature of supply chain relationships.	
2017	Roehrich, J.K.; Hoejmose, S.U.; Overland, V.	Driving green supply chain management performance through supplier selection and value internalisation	• The impact of green supplier selection (GSS) on the performance of green supply chain management (GSCM) is examined by utilizing self-determination theory (SDT). • Discovered that enhanced GSCM performance depends on the SDT mechanisms of autonomy, competence, and relatedness. • Emphasized the importance of GSS for both new and legacy suppliers. • Highlighted that motivation and value internalisation at second-	• Utilizing secondary data from a single focal company and its suppliers, along with semi-structured interviews, limits generalizability. • Focused on the aerospace industry, potentially limiting applicability to other sectors. • Relied on qualitative data, which may not capture all nuances of supply chain dynamics. • The study did not deeply explore the economic implications of SDT mechanisms in GSCM.	The study provides valuable insights into the role of GSS and SDT in driving GSCM performance. It underscores the importance of considering supplier motivation and value internalisation in supply chain management. Future research should include more diverse case studies and a deeper exploration of the economic impacts of SDT mechanisms in GSCM.	https://doi.org/10.1108/IJOPM-09-2015-0566

			tier suppliers are crucial for driving GSCM performance.			

Part IIb: Reverse Supply Chain

Search Strategy: {“Reverse Supply Chain”, “Aerospace”}

Database: Web of Science

Total Papers Discovered: 7

Total Relevant Papers Found: 2

Year Published	Author(s)	Title	Key Findings	Limitation	Remarks	DOI
2015	Keivanpour, S; Kadi, DA; Mascle, C	End of life aircrafts recovery and green supply chain (a conceptual framework for addressing opportunities and challenges)	• Examined the various challenges associated with end-of-life (EOL) aircraft and their impact on the supply chain of the original manufacturer. • Competency, along with supply chain relationships in the aerospace industry and governance policy, are encompassed in a conceptual framework that was created in this paper. • Identified challenges in EOL aircraft recovery that are unique to the aerospace industry and	• The study is based on literature reviews and limited empirical data. • The research area regarding EOL aircraft is relatively new, leading to incomplete literature in some respects. • The conceptual framework proposed needs further validation through practical application and empirical studies. • Lack of regulations in the aerospace industry requiring manufacturers to consider EOL aircraft treatment.	The study provides an important foundation for future research on green supply chains in the aerospace sector. It assists practitioners in understanding the opportunities and challenges associated with implementing long-term strategies for EOL (end-of-life) aircraft. The proposed framework facilitates the systematic evaluation of various aspects of the EOL aircraft issue.	https://doi.org/10.1108/MRR-11-2014-0267

			cannot be addressed by solutions from other industrial sectors. • Highlighted the importance of incorporating environmental thinking into supply chain management.			
2022	Liu, B; Papier, F	Remanufacturing of multi-component systems with product substitution	• Developed a hybrid manufacturing/remanufacturing system with controlled two-way substitution between new and remanufactured products. • Utilized Markov decision processes for both product-level and component-level management. • Demonstrated that the optimal policy on product-level has a switching-curve structure under the assumption of identical lost sales costs. • Proposed an efficient, close-to-optimal heuristic for general product-level and component-level models. • Showed that two-way substitution on the component level significantly reduces total cost.	• Based on hypothetical scenarios and selected case studies, which may not cover all possible remanufacturing options. • Assumes certain fixed parameters and cost structures that may not reflect real-world variability. • Limited empirical validation and practical application of the proposed models. • Sensitivity to changes in input parameters such as substitution costs and environmental impact weights.	The study provides a comprehensive framework for optimizing manufacturing and remanufacturing systems with controlled substitution, highlighting significant cost benefits. It emphasizes the need for empirical validation and practical application in diverse settings, as well as the consideration of environmental impacts in strategic cost analyses.	https://doi.org/10.1016/j.ejor.2021.11.029

			• Analyzed the impact of strategic costs, including environmental aspects, finding that substitution benefits profit-oriented firms more than sustainability-oriented firms.			

Part IIc: Close-Loop Supply Chain

Search Strategy: {“Close-Loop Supply Chain”, “Aerospace”}

Database: Web of Science

Total Papers Discovered: 5

Total Relevant Papers Found: 4

Year Published	Author(s)	Title	Key Findings	Limitation	Remarks	DOI
2023	Aydinliyim, T; Cil, E; Murthy, NN	Input material reduction incentives versus scrap recycling for closed-loop supply chains	• Evaluated the impact of two strategies for enhancing supply chain performance: offering incentives for reducing input materials through contracting and promoting the recycling of scrap materials. • Supply chain should utilize both approaches complementarily for complex geometry components but limit recycling for simpler components. • Developed mathematical	• Based on hypothetical scenarios and selected materials, which may not cover all possible material options and combinations. • Subjective nature of contract design and supplier’s effort. • Assumes linear, expected cost sharing, and nonlinear contract forms without empirical validation. • Focuses on a specific aerospace industry setting, limiting generalizability to other sectors.	The study provides a comprehensive analysis of input material reduction and recycling strategies in a closed-loop supply chain context. It offers valuable insights into optimal contracting and recycling decisions, emphasizing the need for integrated approaches and highlighting potential supply chain inefficiencies.	https://doi.org/10.1111/poms.14039

			models for optimal decisions regarding final component geometry, costs, and control of recycling decisions. - Highlighted inefficiencies due to decentralized recycling and contracting decisions, and analyzed expected cost sharing and nonlinear contract alternatives.			
2014	Hashemi, V; Chen, MY; Fang, LP	Process planning for closed-loop aerospace manufacturing supply chain and environmental impact reduction	- Development of a mixed integer linear programming (MILP) model to maximize profit considering manufacturing, remanufacturing set-up, refurbishing, and inventory carrying costs. - Identified various waste reduction options including direct reuse, repair, refurbishing, cannibalization, and remanufacturing. - Highlighted the importance of remanufacturing in reducing environmental impacts and material scraps in aerospace manufacturing. - Sensitivity analysis showed the effects of certain factors on	- The study is based on hypothetical scenarios and selected materials, which may not cover all possible material options and combinations. - Assumes deterministic defect rates and lead-times, which may not reflect real-world variability. - Limited empirical validation and real-world application of the proposed model. - The computational time for the MILP model can be long and is sensitive to input data.	The study provides a comprehensive MILP model for closed-loop supply chain management in aerospace manufacturing. It emphasizes the importance of remanufacturing and transforming defective components to increase profit and reduce environmental impact. Future work could extend the model to include stochastic factors and improve computational efficiency.	https://doi.org/10.1016/j.cie.2014.06.005

			inventory carrying cost, profit, amount of scrap, and inventory turnover ratio.			
2019	Desai, P; Saremi, R; Hoffenson, S; Lippizi, C	Agile and Affordable: A Survey of Supply Chain Management Methods in Long Lifecycle Products	• Defined supply chain management (SCM) and surveyed existing models for long lifecycle products in aerospace, shipbuilding, and automotive industries. • Categorized SCM methods into seven approaches: traditional, fuzzy, closed-loop, economic impact, supplier risk, green supply chain, and sustainability. • Highlighted the main factors considered in each approach and compared these across the three industries. • Emphasized the importance of integrating different SCM methods to address unique challenges in long lifecycle products.	• Relied heavily on literature review with limited empirical validation • Focused on specific industries, limiting generalizability to other sectors. • The comparison may not cover all possible SCM methods and factors comprehensively. • Some approaches, like fuzzy and green supply chain, were less explored compared to traditional and closed-loop methods.	The study provides a comprehensive review of SCM methods for long lifecycle products, offering valuable insights for managers in aerospace, shipbuilding, and automotive industries. It highlights the need for a strategic and integrated approach to SCM, considering the unique challenges and requirements of long lifecycle products. Future research should focus on empirical validation and the exploration of underrepresented approaches.	https://doi.org/10.1109/SYSCON.2019.8836861
2016	Hashemi, V; Chen, MY; Fang, LP	Modeling and analysis of aerospace remanufacturing systems with scenario analysis	• A network for closed-loop aerospace remanufacturing processes is structured using a mathematical programming model in this paper.	• The study is based on hypothetical scenarios, which may not reflect real-world complexities. • Assumes deterministic defect rates and lead-times, potentially	The study offers a comprehensive model for closed-loop supply chain management in aerospace remanufacturing. It emphasizes the importance of considering variability in defect rates and lead times, and provides insights into	https://doi.org/10.1007/s00170-016-8566-8

			- Identified remanufacturing as a strategy to reduce negative environmental impacts of disposal. - Conducted scenario and sensitivity analyses to evaluate the effects of variations in defect rates, remanufacturing lead time, and input factors on profit margins and scrap quantities.	overlooking real-world variability. - Limited empirical validation and practical application of the proposed model. - Computational time for the model can be lengthy and is sensitive to input data variations.	optimizing remanufacturing processes to reduce environmental impacts and increase profitability. Future work could incorporate stochastic factors and enhance computational efficiency.	

Part III: Product End-of-Life

Search Strategy: {“Product End-of-Life”, “Aerospace”, “Aircraft”}

Database: Web of Science

Total Papers Discovered: 11

Total Relevant Papers Found: 5

Year Published	Author(s)	Title	Key Findings	Limitation	Remarks	DOI
2016	Sabaghi, M; Mascle, C; Baptiste, P	Evaluation of products at design phase for an efficient disassembly at end-of-life	- Introduced a hybrid Design of Experiments (DOE) and TOPSIS method to evaluate disassemblability at the design phase. - Identified five critical disassemblability parameters: accessibility, mating face, tools type, connection type, and quantity and variety of connections.	- The study relies on a specific case study (Bombardier Regional Jet) which may limit generalizability. - The model assumes controlled conditions that may not reflect real-world variability in disassembly environments. - Limited empirical	The study provides a robust framework for evaluating product disassemblability at the design phase, emphasizing the importance of considering end-of-life processes early in product development. Future research should focus on validating the model across diverse industries and products, and exploring additional disassembly parameters.	https://doi.org/10.1016/j.jclepro.2016.01.007

			• Developed a disassembly scoring model to calculate disassemblability index for components, achieving 94.30% reliability. • Application of the model on Bombardier Regional Jet aircraft indicated improved end-of-life disassembly efficiency.	validation of the proposed methodology across different products and industries. • Some disassembly parameters and their interactions may require further exploration for comprehensive applicability.		
2020	Zhao, XJ; Verhagen, WJC; Curran, R	Disposal and Recycle Economic Assessment for Aircraft and Engine End of Life Solution Evaluation	• Proposed an economic indicator to evaluate aircraft End of Life (EoL) strategies, focusing on disposal and recycling (D&R) scenarios. • Developed a method to estimate D&R costs and values, integrating product, process, and cost properties. • Demonstrated that disassembly and dismantling of aircraft engines provide more economic gains compared to whole aircraft. • Highlighted the significant impact of salvage value and D&R costs on the economic efficiency of D&R processes.	• Based on hypothetical scenarios and selected case studies, which may not cover all possible D&R options. • Assumes certain fixed parameters and cost structures that may not reflect real-world variability. • Limited empirical validation and real-world application of the proposed economic indicator. • The study's results are sensitive to changes in input parameters such as salvage value and D&R costs.	The study provides a robust framework for evaluating the economic performance of aircraft EoL strategies, emphasizing the importance of considering both disposal and recycling processes. It suggests that optimizing D&R processes can lead to significant economic and environmental benefits. Future research should focus on empirical validation and exploring additional D&R scenarios.	https://doi.org/10.3390/app10020522
2007	Thimm, G; Ma, YS; Lee, SG; Liu, D; Chua, K	An investigation into the early and retirement life-cycle stages: tools,	• Discussed integration of conceptual design and end-of-life stages in product lifecycle management (PLM).	• Relied on case studies and existing PLM solutions, which may not cover all possible PLM functionalities.	The study provides valuable insights into the integration of conceptual design and end-of-life stages in PLM. It highlights the importance of compliance with	

		requirements	• Examined influences of end-of-life on product costs and identified links between conceptual design and end-of-life stages. • Identified gaps between current and ideal PLM functionalities regarding these stages, focusing on compliance with regulations and environmental impact. • Evaluated PLM solutions by UGS and Autodesk, highlighting their strengths and limitations in supporting early and retirement lifecycle stages.	• Assumed certain fixed parameters for evaluating PLM solutions, potentially overlooking real-world variability. • Limited empirical validation and practical application of the proposed evaluation criteria. • Focused on specific PLM solutions, potentially limiting generalizability to other PLM systems.	regulations and environmental considerations. Future research should focus on empirical validation and exploring additional PLM solutions to enhance the generalizability of findings.	
2012	Yang, YX; Boom, R; Irion, B; van Heerden, DJ; Kuiper, P; de Wit, H	Recycling of composite materials	• Discussed various recycling technologies for composite materials, focusing on mechanical, thermal, and chemical recycling. • Highlighted the challenges of recycling composite materials due to their heterogeneous nature, especially thermoset-based composites. • Identified mechanical recycling as energy-intensive with lower quality recyclates, thermal recycling with some fiber recovery but quality degradation, and chemical	• The study is largely based on literature review and lacks extensive empirical data. • Focused mainly on the technological aspects without in-depth economic analysis of recycling processes. • Current recycling methods have limited commercial application and face high costs and market barriers. • Environmental and regulatory aspects were discussed but need more detailed exploration and	The study provides a comprehensive overview of the challenges and technologies associated with recycling composite materials. It underscores the importance of developing new composite materials that are easier to recycle and advancing separation technologies. Future research should focus on practical applications, cost reduction, and compliance with environmental regulations.	https://doi.org/10.1016/j.cep.2011.09.007

			recycling as promising but with environmental concerns. - Emphasized the need for extensive R&D to develop better recyclable composites and efficient separation technologies.	empirical validation.		
2021	Yakovlieva, A; Boichenko, S; Kale, U; Nagy, A	Holistic approaches and advanced technologies in aviation product recycling	- Analyzed existing policies, methods, and technologies for handling decommissioned aviation transport means. - Highlighted the ecological and economic benefits of introducing recycling programs in the aviation industry. - Identified the importance of the recycling associations such as AFRA (Aircraft Fleet Recycling Association) and recycling initiatives such as PAMELA, or Process for Advanced Management of End-of-Life Aircraft, in setting industry standards. - Discussed the necessity of integrating new recycling technologies for composite materials, including mechanical, thermal, and chemical methods.	- Relied on existing policies and methods which may not be universally applicable. - Limited empirical validation of proposed recycling methods. - The study focused on technological aspects without a comprehensive economic analysis. - The research may not fully address the logistical and regulatory challenges in different regions.	The study provides a thorough overview of the current state and future prospects of aviation product recycling. It emphasizes the need for standardized practices and advanced recycling technologies to handle the increasing number of decommissioned aircraft. Future research should focus on empirical validation and economic feasibility studies of the proposed methods.	https://doi.org/10.1108/AEAT-03-2021-0068

Part IV: Circularity of Aircraft Cabin Seating Material

Search Strategy: {“circular”, “aircraft”, “interior”}

Database: Web of Science

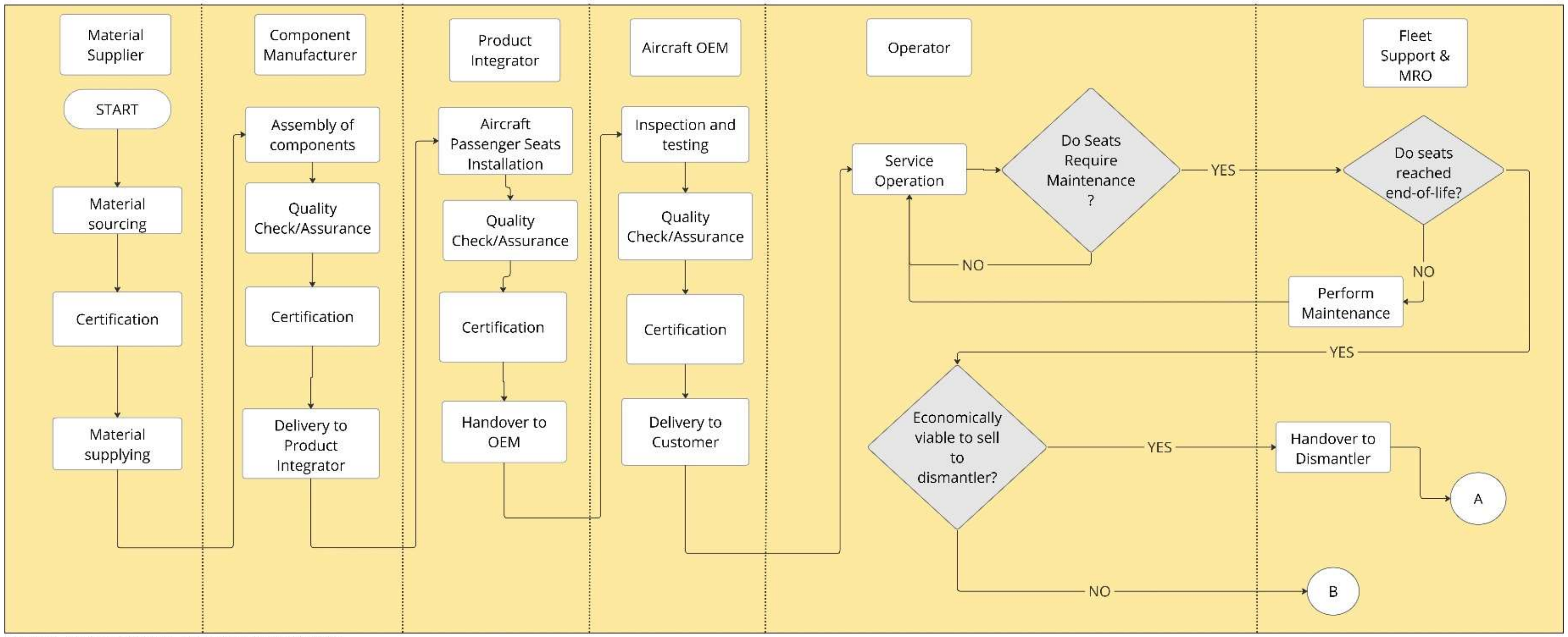
Total Paper Discovered: 17

Total Relevant Papers Found: 3

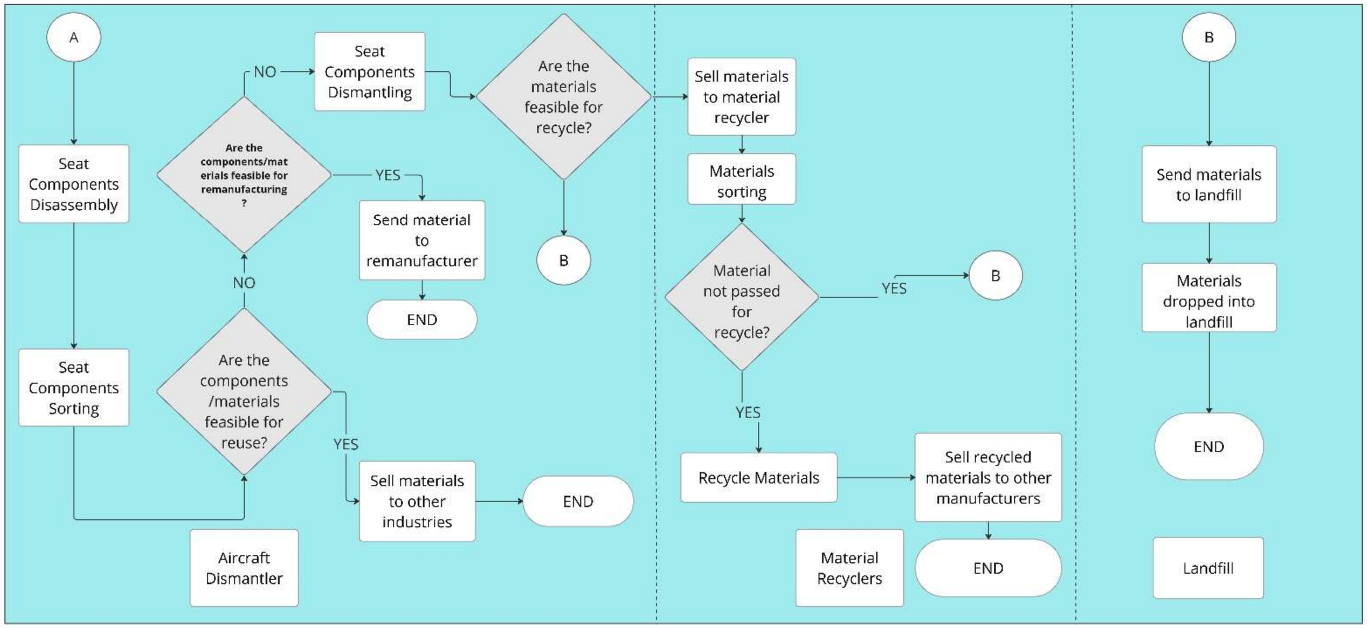
Year Published	Author(s)	Title	Key Findings	Limitation	Remarks	DOI
2021	Bachmann, J; Yi, XS; Tserpes, K; Sguazzo, C; Barbu, LG; Tse, B; Soutis, C; Ramon, E; Linuesa, H; Bechtel, S	Towards a Circular Economy in the Aviation Sector Using Eco-Composites for Interior and Secondary Structures. Results and Recommendations from the EU/China Project ECO-COMPASS	• Assessed different eco-materials, including bio-based and recycled composites, for application in aircraft interiors and secondary structures. • Highlighted the ecological and economic benefits of eco-composites in reducing environmental impacts and resource consumption. • Developed new eco-composites combining bio-based epoxy resins, natural fibers, and recycled carbon fibers. • Demonstrated the feasibility of eco-composites for aviation through life cycle assessment (LCA) and environmental impact evaluations.	• The study is based on preliminary assessments and requires further empirical validation. • Focused mainly on interior and secondary structures, not primary load-bearing components. • The current eco-composites need further optimization to meet stringent aviation safety and performance standards. • Economic feasibility and market adoption of eco-composites are not fully explored.	The study provides a promising outlook for the use of eco-composites in aviation, emphasizing the need for further research and development to optimize material properties and ensure compliance with aviation standards. It highlights the potential of international collaborations to advance eco-material technologies and promote sustainable practices in the aerospace industry.	https://doi.org/10.3390/aerospace8050131
2022	Dias, VMR; Jugend, D; Fiorini, PD; Razzino, CD; Pinheiro,	Possibilities for applying the circular economy in the aerospace	• Financial benefits drive the adoption of circular economy (CE) strategies in the aerospace industry. • Ethanol and other	• High costs associated with the development and use of environmentally friendly materials.	The study provides a framework for CE practices in the aerospace industry, highlighting the importance of financial and environmental benefits. It also	https://doi.org/10.1016/j.jairtraman.2022.102227

	MAP	industry: Practices, opportunities and challenges	alternative fuels are being used as renewable fuel sources. • Industry 4.0 technologies (AI, VR, drones, additive manufacturing) facilitate CE practices. • Reuse and recycling of materials in aerospace and other industrial sectors are significant.	• Technological challenges due to the complexity and long lifecycle of aerospace products. • Lack of incentives and regulatory support from agencies. • Limited empirical study scope with only three companies.	emphasizes the role of technological advancements and regulatory support in promoting CE adoption.	
2020	Kim, NK; Mao, NT; Lin, R; Bhattacharya, D; van Loosdrecht, MCM; Lin, YM	Flame retardant property of flax fabrics coated by extracellular polymeric substances recovered from both activated sludge and aerobic granular sludge	• Developed a bio-based flame retardant using extracellular polymeric substances (EPS) extracted from activated sludge (EPSflocs) and aerobic granular sludge (EPSgranules). • Coated flax fabrics with EPSflocs and EPSgranules, demonstrating significant improvement in flame retardancy. • EPSgranules coated fabrics met US Federal Aviation Regulation (FAR) flame retardancy requirements for aircraft interiors. • Identified the presence of carbonated hydroxyapatite in EPSgranules char residue, contributing to self-extinguishing properties.	• Based on preliminary tests and limited real-world application. • Focused primarily on flax fabrics, not exploring other potential materials. • The study did not provide a comprehensive economic analysis of scaling up the EPS-based flame-retardant production. • Limited investigation into long-term durability and environmental impact of EPS coatings.	The study offers promising insights into the use of bio-based flame retardants derived from wastewater treatment processes. It highlights the potential for sustainable flame-retardant solutions in the textile industry, particularly for aviation applications. Future research should focus on broader material applications, scaling up production, and comprehensive economic and environmental impact assessments	https://doi.org/10.1016/j.watres.2019.115344

Appendix C – Existing Supply Chain Flow (After Evaluation)

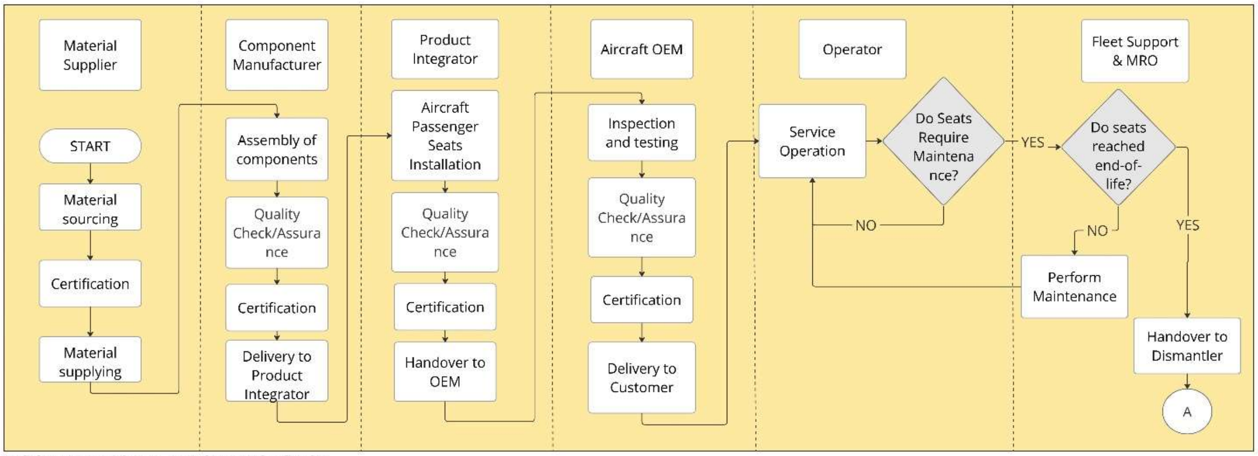


DESIGN, MANUFACTURE, AND OPERATION STAGE

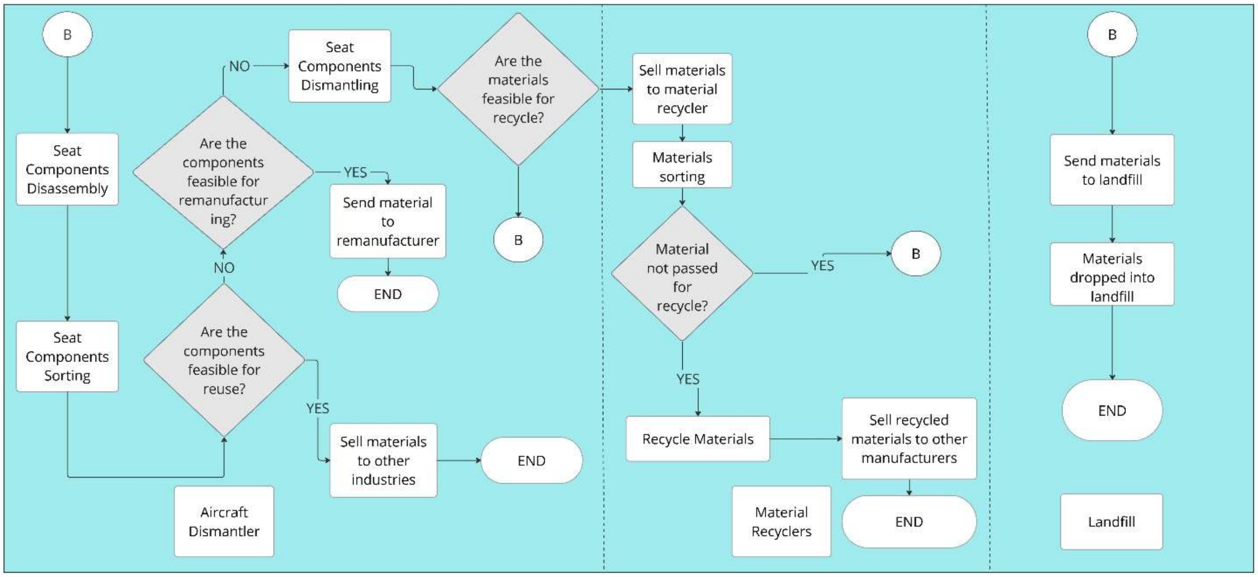


END-OF-LIFE STAGE

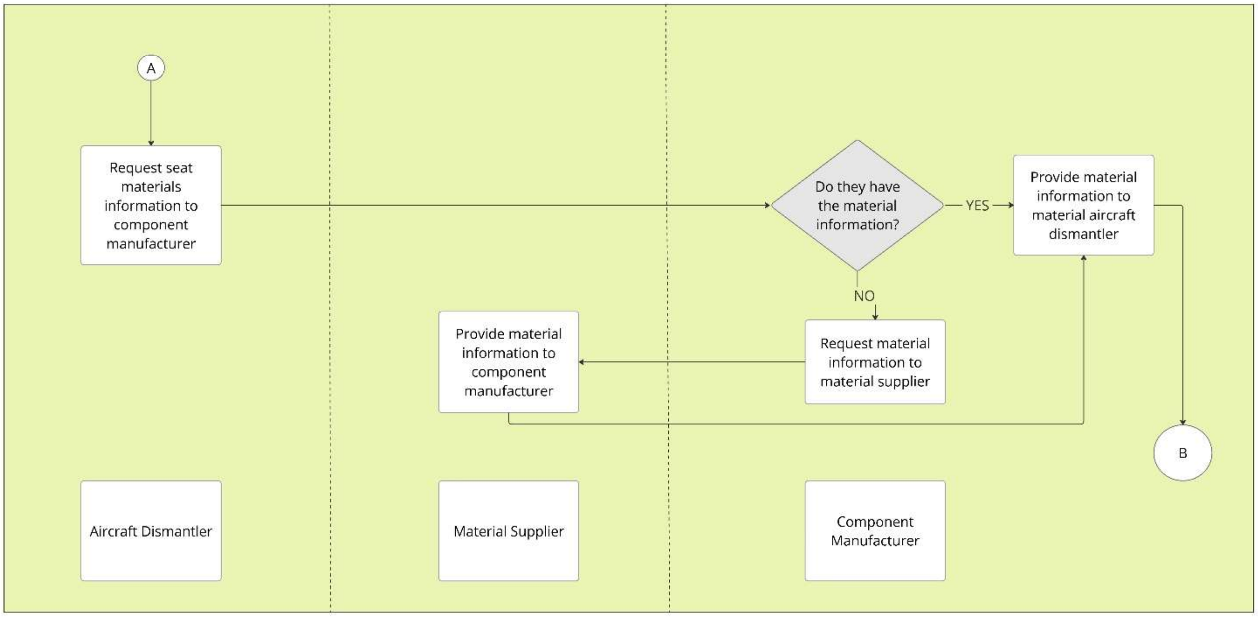
Appendix D – Proposed Supply Chain Flow: Communication Line During EOL Phase (After Evaluation)



DESIGN, MANUFACTURE, AND OPERATION STAGE

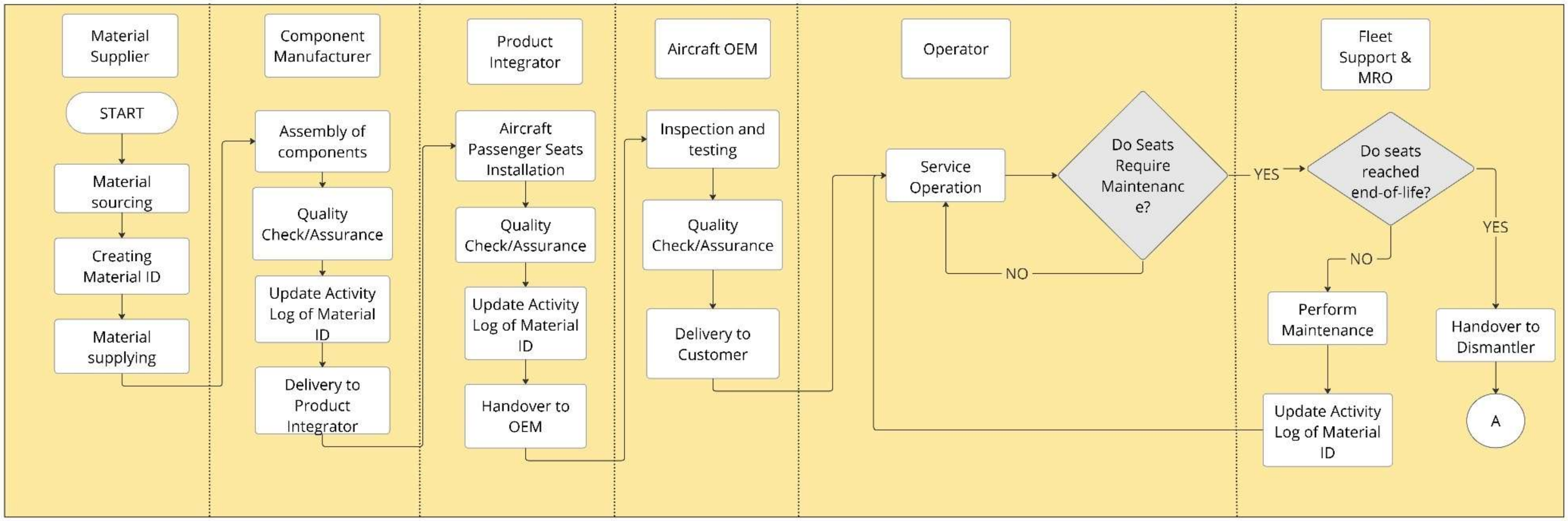


END-OF-LIFE STAGE

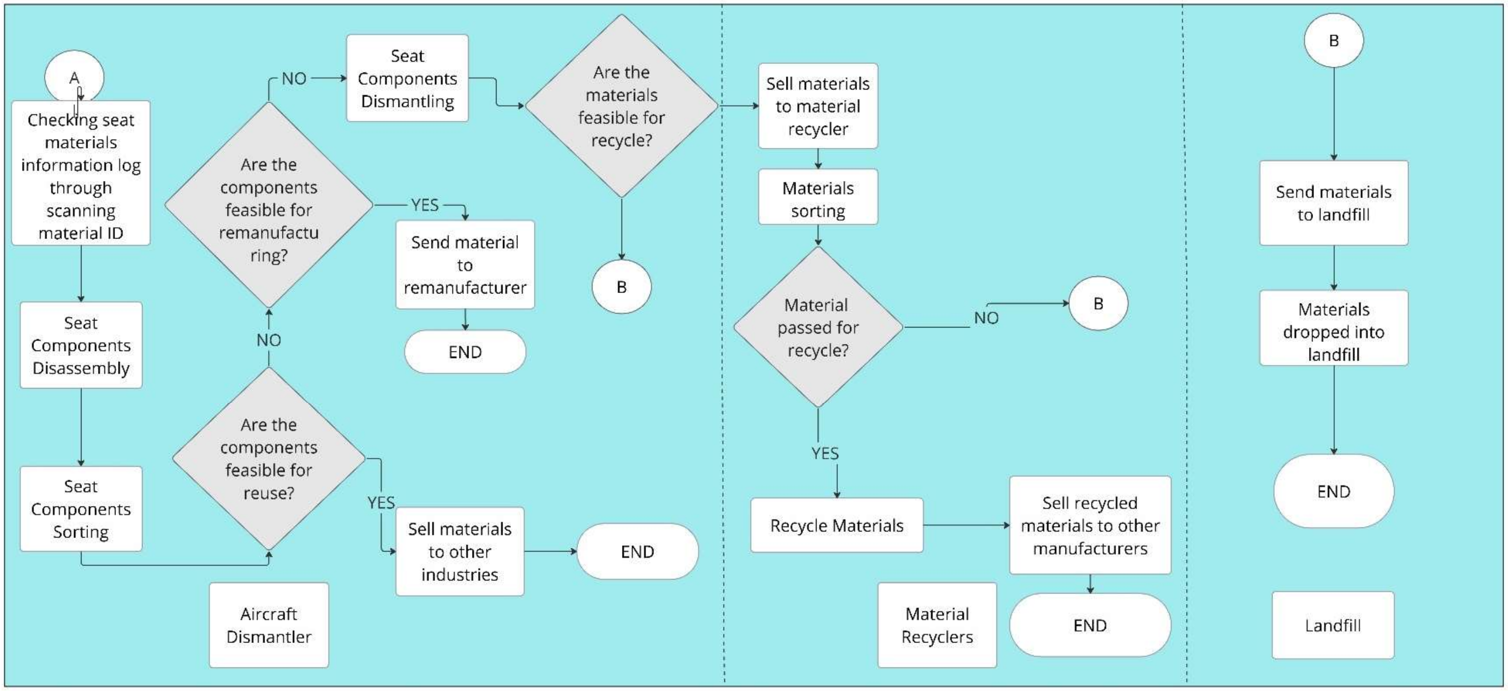


MATERIAL CHECKING STAGE

Appendix E – Proposed Supply Chain Flow: Material Passport (After Evaluation)



DESIGN, MANUFACTURE, AND OPERATION STAGE



END-OF-LIFE STAGE

Appendix F – Interview Question List

General Questions	1. What materials are primarily used in these seating designs, and why were they chosen? 2. Based on your industry role, how do you currently handle the end-of-life phase of aircraft seating materials? 3. What are the main challenges with the current materials and designs in recycling/remanufacturing? 4. How do environmental considerations influence your decisions regarding the end-of-life management of aircraft seating? 5. Do you have any ideas in place for recycling or reusing aircraft seating materials? 6. How do customer preferences influence the choice of materials and designs in aircraft seating? 7. How do regulatory requirements influence the choice of materials and designs in aircraft seating?
Specific Questions (Aircraft Seating Manufacturer)	8. In your role, what steps are you taking to ensure the recyclability of the seating materials you produce? 9. How feasible would it be to redesign your products to better accommodate end-of-life recycling?
Specific Questions (Operator)	10. From an operator's standpoint, what are the most important aspects of cabin seating design and material composition? 11. How do you assess the life cycle impact of seating materials in terms of maintenance and end-of-life management?
Specific Questions (Aircraft OEM)	12. What factors do you consider when choosing materials for your aircraft seating designs? 13. How do you balance performance, comfort, cost, and sustainability in your seating designs?
Specific Questions (Aircraft Dismantler)	14. Based on your experience, how do current seating materials and designs affect the dismantling process? 15. Which materials from aircraft seats are easiest and most difficult to recycle or dispose of?
Specific Questions (Research Institutes)	16. What research can you share about the environmental impacts of different materials used in aircraft seating? 17. Are there emerging materials or technologies that could revolutionize aircraft seating design?
Flow Question	**Flow 1 – Normal EOL Management Supply Chain Flow** 1. Could you confirm if the flowchart accurately represents the current procedures of end-to-end flow of aircraft seating components? 2. If there are any discrepancies or additional steps that need to be included, could you specify what these are? **Flow 2 – Usage of Material Identification (Barcode, RFID, etc.) in the Supply Chain Flow** 1. How effectively do you believe this flowchart could manage the recycling and minimizing waste objective? 2. Are there any stages in the process that could be optimized for better resource management? 3. Does the flowchart accurately reflect all the current procedures and decision-making processes involved in the end-to-end flow of aircraft cabin seating? 4. If there are any steps or paths missing or inaccurately represented, could you specify what these are?