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Integrating Circular Economy Practices in Aviation: Requirements Analysis for the Exchange of Material and Product Information to improve Circularity in the Aviation Industry

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Abstract

Sustainability remains a critical global challenge in global industries, particularly in aviation, where complex supply chains and strict regulations complicate the integration of the promising approach of circular economy. This study addresses these challenges by analysing the needs for sustainable product design and lifecycles of aircraft, components, and materials, focusing on digital continuity and uniform standards.
This paper presents the results of 27 qualitative expert interviews, developed roles to capture diverse perspectives and
key requirements for product lifecycle management and leveraging data ecosystems. This sets the basis for implementing data ecosystems and tools like digital product passports (DPPs) to embed circular economy into lifecycle management across complex aviation products.

Keywords: Circular Economy;Digital Product Passport; Material Information; Product Information; Aviation

1. Introduction

Aircrafts are the preferred mode of transportation for long-haul travel. According to forecasts, the global aircraft fleet will grow to around 35.700 aircrafts by 2030 [1]. Sustainable Development Goal No. 12 underscores the importance of sustainable production methods, making it highly relevant in the context of the aviation industry. In line with this, the European Green Deal and its goals for CO_2-neutral production by 2050, along with the push towards a circular economy, have intensified the focus on sustainability across the aviation industry. There are many levers to reduce the environmental impact of the aviation industry along the lifecycle. The largest environmental impact stems from the emissions caused by fuel combustion of aircrafts in operation. However, the design of aircraft plays a relevant role, as it influences the environmental impact over the entire life cycle - from construction and maintenance to the End of Life (EoL) phase [2]. The EoL treatment of aircraft presents a key sustainability challenge in aviation, which has so far been insufficiently researched [1]. Particular challenges arise from the global, highly complex supply chains, strict regulatory requirements regarding airworthiness and the pursuit of lightweight construction as well as the use of highly complex materials [1, 3, 4]. The long product life cycle of 25 to 30 years must also be considered [1]. These factors require a rethinking towards more sustainable product designs and circular strategies that cover the entire process from material procurement, production and usage to reuse and material recycling [1]. Digital technologies, such as Digital Product Passports (DPP) can provide an important approach as they can enable digital continuity, transparency and traceability of materials and products and provide the necessary

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Nomenclature

EoL	End of Life
DPP	Digital Product Passport
LCA	Life Cycle Assessment
TA	Thematic Analysis
OEM	Original Equipment Manufacturer
CSRD	Corporate Sustainability Reporting Directive Structure
ESPR	Ecodesign for Sustainable Products Regulation
MRO	Maintenance, Repair and Overhaul

information to make sustainable decisions along the entire product life cycle [5, 6]. In this context, this study addresses the following research questions:

- **RQ1:** What are the current challenges in implementing circular economy in the aviation industry?
- **RQ2:** What data requirements are necessary for the implementation of circular economy?
- **RQ3**: What are the requirements for the exchange of material and product Information, data ecosystems to support product lifecycle management and product design frameworks for a sustainable aviation industry?

To address these research questions, 27 semi-structured interviews with experts from across the entire aviation value chain are conducted as part of the publicly funded German research Project Aerospace-X [7]. The goal is to identify current challenges and requirements for implementing circular economy in aviation and to capture the needs of the industry.

2. Methodology

A qualitative, inductive research approach was chosen. Semi-structured expert interviews have been conducted with interview partners representing different focus areas along the entire value chain of aviation. The semi-structured approach to the interviews allows for specific questions based on an interview guide while also being flexible to respond to the answers of the interviewees, creating space for follow-up questions [8]. The interview guide covers topics such as the interviewee's background knowledge and current role in the company and aviation value chain, IT systems, data needs and access, digitalization and decision-making processes, as well as the circular economy, sustainability objectives, and the status quo of current processes and strategies. The interviews were conducted over a period of five months in 2024 and were subsequently comprehensively documented. A total of 27 interviews were evaluated.

2.1. Selection of Experts for the Interviews

Interview partners were selected to represent key roles within the value chain. Especially, experts from the area of sustainability and digitalization where involved. The interviewees therefore include representatives for material manufacturers, component manufacturers, Original Equipment Manufacturers (OEM), brokers and service providers for the repair and distribution of used parts and recycling companies. Criteria for selection included the participants' functional roles such as sustainability and LCA experts, procurement managers and also upper management functions, within their respective organization, as well as their involvement in relevant processes such as materials management, product development, procurement, quality assurance.

2.2. Methodological Framework of the study

As methodical framework, Thematic Analysis (TA) [9,10, 11] was chosen to identify, analyze, and report patterns within the data collected. Is is a qualitative approach and due to its flexibility suited for the deriving of specific requirements related to data exchange, regulatory compliance, and other organizational needs.

2.3. Evaluation Methodology

Interview data was collected, documented, and analyzed. The initial step was data coding, leading to entries based on 13 questions from 27 interview partners. Figure 1 presents the described evaluation methodology on the basis of the methodical framework. The first-order coding phase recorded interviewees' statements verbatim, while the second-order phase identified categories like Data Management. Similar codes within these categories were grouped to identify themes. A cross-category analysis was performed to find overarching themes to identify key challenges.

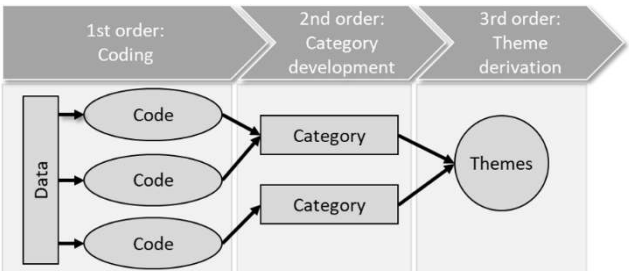

Figure 1: Evaluation method, own representation on basis of [9,10, 11]

2.4. Development of Roles

The analysis resulted in the formulation of roles and requirements for sustainable product design and lifecycle management, providing a user-centered approach. Roles were developed using qualitative criteria from interviews, such as participants' value chain roles (e.g., OEM, Tier 1 supplier), responsibilities, lifecycle focus, and key pain points. This ensures the roles reflect stakeholder experiences and challenges, enabling the creation of tailored user stories and requirements [12].

3. Analysis and Results

The nine categories that highlight recurring challenges, objectives with regards to circular economy and needs with regards to current pain points and stakeholder collaboration, employed for the second-order thematic analysis and cross-category analysis are: (1) Stakeholders, (2) roles and the focus of the (3) product lifecycle phase represented. Specific themes emerged within each category in the third-order thematic analysis, (1), (2), and (3) are discussed specifically in chapter 3.1. Under (4) Data Management, themes like data integration challenges and data quality were key themes, encompassing

aspects such as material traceability and data sharing willingness and ability of the stakeholders involved. In the (5) sustainability & compliance category, critical themes highlighted regulatory compliance needs with focus on material and substances (e.g. REACH regulatory obligations) and sustainability reporting obligations today and considered in the future (for instance from the Corporate Sustainability Reporting Directive (CSRD) and the Ecodesign for Sustainable Products Regulation (ESPR)). The calculation and tracking of sustainability KPIs apart from reporting obligations in general, including insights on environmental impact data, were also amongst the critical themes within the sustainability and compliance theme derived. Themes within the defined category for (6) IT systems ranged from the usage of general office applications (e.g. Excel was mentioned a number of times) to more specialized product lifecycle management applications. (7) Materials & Processes themes included discussions on material usage and recycling. (8) Communication & Collaboration themes pointed towards issues with manual data exchange and stakeholder-specific collaboration. Lastly, (9) pain point themes identified challenges like the lack of standardization and difficulties in supplier engagement for data exchange and LCA. These themes provided a comprehensive overview of the recurring patterns and shared concerns in the collected data. The identification of themes within each category served as input for the development of roles.

3.1. Roles and user stories

Table 1 presents the distribution of interview partners across their roles within the aviation value chain and their focus on the respective product lifecycle phases, noting that each may represent more than one role or product lifecycle phase depending on the organization and business function.

Table 1: Distribution of interview partners

Role in Supply Chain	Number of Interviewees
OEM	9
Tier 1 Supplier	8
Tier 2 Supplier	6
Tier 3 Supplier	5
Logistics Service Provider	1
MRO Service Provider	4
Broker used parts	1
Dismantler	1
Recycler	1
Consultancy	1
Focus Product lifecycle phase	
Begin of Life	23
Operational Phase	7
End of Life	4

The following role groups reflect perspectives from the entire value chain while playing crucial roles in sustainable product design, product lifecycles, and the integration of circular economy;

(1) **Top Management & Strategy** group, comprising business functions like Global CEO, and Head of Business Development. They focus on high-level strategic decisions and share common user stories around improving data quality, enhancing transparency, standardizing processes for circular economy objectives.
(2) **Sustainability & Environmental Compliance** group, including business functions such as Sustainability Manager, LCA experts and environmental protection department. They oversee the company's sustainability and compliance efforts, emphasizing the assessment and improvement of sustainability KPIs in addition to common user stories shared with the Top Management group.
(3) **Procurement & Supply Chain** group, with business functions like Procurement and Supply Chain Managers as well as logistic functions, manage the company's supply chain operations and sourcing of materials and components. They share common user stories around data quality, transparency, and standardization, emphasizing the importance of improving supplier engagement and sustainability KPIs in the procurement and supply chain context. Here, also procurement functions in Dismantling and Recycling companies are considered.
(4) **Engineering & Technical Development** group, including Aerospace Engineers and Material Scientists, focus on the technical aspects of product design, development as well as maintenance, repair and dismantling. Their user stories highlight the need for improved data quality, transparency, standardization, and supplier engagement specific to material and component information and sourcing activities.

The themes where also analyzed cross-category. Figure 1 presents the most prevalent pain points across all interview

Figure 2: Pain Points across Interview Participants

partners and respective Role groups. The analysis highlights pain points in the area of data management and collaboration in the aviation industry. Majority of the interviews mention data quality issues, manual data exchange, lack of standardization, and transparency issues. Difficulties in supplier engagement for information exchange and achieving sustainability KPIs were also noted, along with challenges in information exchange and communication in general. Based on the interviews, key challenges in achieving sustainability KPIs include data quality and measurement issues, as well as a lack of regulatory obligations and economic incentives. The use of individual platforms and portals and stakeholder-specific collaboration were among further issues raised by the interview

partners. Regulatory and contractual constraints that hinder the information exchange, as well as difficulties in implementing sustainability assessment platforms at supplier side, were less prevalent but still notable in this context.

When examining the pain points cross-category by role in the value chain, OEMs, Tier 1 and Tier 2 suppliers all mention lack of standardization and data quality issues, which are also among the top concerns across product lifecycle phase. Other stakeholders such as dismantlers, brokers, and recyclers also highlighted challenges regarding traceability, transparency, dependency on manual processes, and challenges in recycling and waste management.

Cross-category themes, such as the lack of standardization and Collaboration Barriers, were frequently mentioned by participants across different roles and lifecycle phases, underscoring their significance as top pain points affecting multiple facets of the product lifecycle. These findings provide a structured basis for deriving targeted requirements for data exchange, compliance, and enhanced collaboration.

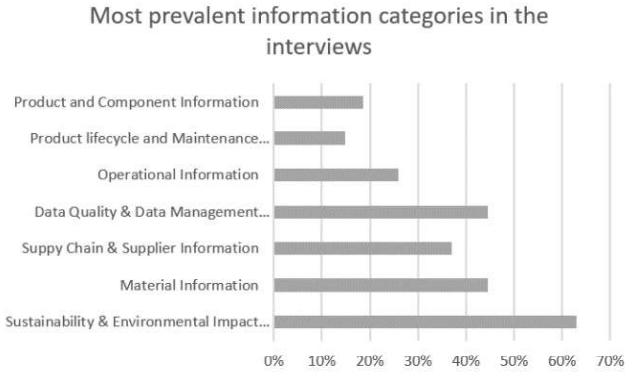

Figure 3: Most prevalent Information Categories in the Interviews

Based on the thematic analysis approach, information categories where derived from the second order category for data. Figure 2 presents the most prevalent information categories from the interviews. According to the interviews, material Information encompasses material details such as material composition, secondary material content, and traceability, which are necessary to enable effective resource recovery and circularity of materials. Sustainability and Environmental Impact covers data related to decarbonization targets, recycling, and CO_2 emissions of products and components. Regulation and Compliance information includes regulatory and audit data, ensuring alignment with EU supply chain laws and EoL obligations. Product and Component Information includes information on the product and its composition, along with repair and maintenance manuals and other documentations relevant for the customer. Data Quality and Management addresses the importance of data accuracy, sharing willingness, and platform integration for seamless data exchange. Here, interview participants specify especially the need for data quality indicators with regards to data sources, calculation methods and assumptions used, so that data can be interpreted accordingly. Supply Chain and Suppliers information category summarizes data about the suppliers and orders with regards to materials, components and products purchased. The Operational Data category captures real-time data like flight information, essential for product and component performance tracking. This typically includes data points such as actual flight cycles and hours of the individual components in an operational aircraft. Product Lifecycle and Maintenance is closely linked to the previously described information category, as it describes the information relevant for the maintenance and repair of products and includes data on maintenance cycles and component longevity, critical for ensuring product reliability and monitoring activities over time.

By analyzing the categories across one another, the analysis further reveals information needs and their variation depending on stakeholder and product lifecycle phase concerned. Here, the analysis reveals data needs applicable to most stakeholders and product lifecycle phases as well as data needed by specific roles within the value chain. Recyclers, MRO service provider and dismantler highlighted the need for material traceability, recycling and reuse data, end-of-life obligations. They also emphasized the necessity of primary data share, data exchange.

Both groups also identified the need for more comprehensive data relating to CO2 footprint, chemical composition, and secondary material content.

Finally, user stories are formulated based on the specific pain points and data needs per role group defined. Table 2 lists the user stories formulated for the most prevalent role groups based on the thematic analysis of pain points and data needs.

Table 2: User stories for the most prevalent role groups

User Stories
As a member of **Top Management & Strategy**, I need improved data quality and management tools to make informed strategic decisions and ensure the integration of sustainability into our core operations.
As a member of **Sustainability & Environmental Compliance**, I want to leverage accurate and timely sustainability and environmental impact data to track and achieve our sustainability KPIs effectively.
As a member of the **Procurement & Supply Chain** group, I need standardized processes and transparent supplier data to ensure the efficiency and sustainability of our supply chain operations, , ensuring our product development and supply chain operations comply with all relevant laws and regulations
As a member of the **Engineering & Technical Development** group, I need access to reliable and comprehensive material and product data, including composition, traceability, and usage information, to support key processes such as product design, repair, and dismantling, ensuring alignment with our sustainability goals across the product lifecycle.

The user stories describe the specific needs and objectives of the derived role groups. By grounding user stories in the derived roles and pain points identified during interviews, they serve as actionable insights that guide the development of targeted requirements for the implementation of circular economy objectives across the aviation value chain.

3.2. Requirements for Sustainable Product Design and Circular Economy

The interviews highlight the challenges and considerations related to material management and circular economy in the aviation sector. Market potential for aviation materials, both within and outside of the industry, is perceived, with emphasis

on the type of material determining open versus closed loop viability. In terms of materials, titanium and aluminum are predominantly used in various applications including machining, assembly, coating, painting, and heat treatment, according to the interviews.

For closed-loop systems, the implementation, particularly for high-performance materials, presents challenges. However, there are opportunities for implementing closed loops for specific materials. Open-loop systems seem viable for materials like aluminum and steel, and there is a positive outlook for their implementation, even for high-performance materials, in the aviation industry. Regarding the use of secondary materials, current practices in the aviation sector do not favor their use due to high safety and quality criteria. The percentage of recycled content often remains unknown due to missing traceability and data availability as well as lack of standards to calculate recycled content. Yet, the possibility of using recycled materials is present, although it may not be applicable for all materials and products. Scrap separation during production processes, especially for aluminum, is emphasized as critical for effective recycling during production.

The derived requirements from the analysis, roles, and user stories highlight the need for a comprehensive and reliable system to manage, track, and exchange data across various operations and parties involved. Key requirements include accurate data management tools, standardization features for process consistency, transparency features for detailed reporting, and efficient communication tools for supplier engagement. Furthermore, there's a need for tools aiding in tracking and achieving sustainability KPIs, managing regulatory and contractual constraints, and supporting the management of information flow for circularity and lifecycle management. Stakeholders, including Dismantlers, OEMs, Brokers, Recyclers, and Tier 1 and 2 Suppliers, have specific data needs, emphasizing the importance of standardization, data quality, transparency, supplier engagement, sustainability tracking, and compliance.

For different product lifecycle phases, requirements focus on standardization, data quality, transparency, supplier engagement, sustainability tracking, lifecycle management, and compliance. These requirements vary depending on the phase: Begin of Life, Use Phase, and End of Life. Brokerage and MRO service providers for used airplane parts need detailed records of components and aircraft, material information, and broker data. Recyclers require material and parts traceability, recycling data, substance data, end-of-life obligations, and audit data, among others. Requirements for implementing better recyclability and material reuse include improving design for disassembly, increasing material traceability, improving data exchange, implementing standards for recycled content, and improving end-of-life planning.

OEMs require regulatory data, decarbonization targets, material data, supply chain data, toxicity information, and information about material recovery. From these data needs, further requirements regarding material information exchange, information management for lifecycle phases, and circular economy strategies can be derived. These include improving tracking and reporting systems, standardizing data formats, enhancing data exchange platforms, and implementing strategies to increase recycling and reuse of materials.

In summary, this paper identified the following overarching requirements to support circular economy and product lifecycle management:

- **Data Management & Traceability**: Accurate, standardized data management and traceability across lifecycle phases.
- **Lifecycle Management**: Tools for managing product lifecycle, from design to end-of-life, with a focus on circularity.
- **Sustainability Tracking & Compliance**: Systems for tracking sustainability KPIs, managing regulatory requirements, and ensuring material reuse/recycling.
- **Standardization & Data Exchange**: Standardized formats and platforms for efficient data exchange across stakeholders and lifecycle phases to support communication and collaboration across suppliers, recyclers, and other stakeholders.

A key finding is that, alongside material flow, information flow must also be addressed to enable greater circularity. This is particularly relevant for lifecycle management, where challenges in information availability and traceability persist, especially in the use phase and end-of-life stages, affecting MRO and dismantling processes.

4. Discussion

The interviews underline that the aviation supply chain is a complex network with diverse processes, material flows, and contract types, determining equipment provision and maintenance responsibilities. Component trading and reuse, facilitated by brokers, are pivotal during the aircraft's operational phase. The industry employs varied standards for material and scrap management, often using specific platforms, and key processes include leasing, reselling within company groups, and sorting production waste, with systematic scrap management spanning production, maintenance, and EoL phases. The thematic analysis of interviews revealed key challenges, objectives, and needs in relation to circular economy. The significance of digital continuity, especially with regards to material and product information for the aviation industry was emphasized for the integration of sustainable practices and circular economy strategies. The lack of information seems to be a common denominator across all interviews, resulting from different pain points such as data quality issues, lack of standardization and challenges in the information exchange and gathering sustainability data. The industry faces difficulties in material management, such as the recycling and reuse of materials, particularly in relation to high-performance materials. The use of secondary materials is currently limited due to high safety and quality criteria. According to the interview statements and analysis, scrap management is crucial for reducing manufacturing costs, minimizing environmental impact, and potentially reintroducing valuable materials back into the production cycle. The thematic analysis reveals that the improvement of the availability of relevant information is a key factor in integrating circular economy strategies.

In summary, the defined research questions can be answered based on the thematic interview analysis as follows;

RQ1: The current challenges in implementing the circular economy in the aviation industry are primarily associated with data management, collaboration, and material usage. Key issues include the lack of standardization, data quality issues, transparency issues, and difficulties in supplier engagement for data exchange and LCA. There's also a challenge in effectively reusing and recycling materials, particularly high-performance materials, due to rigorous safety and quality criteria.

RQ2: In terms of data requirements for the implementation of circular economy, the analysis identified several key areas. The need for improved data quality and management tools, particularly for accurate material information such as composition and traceability, was emphasized. Comprehensive regulatory data and digital product passport data are also essential to navigate regulatory and contractual constraints. Moreover, accurate and timely sustainability and environmental impact data are necessary to track and achieve sustainability KPIs effectively. Other critical requirements include supply chain data, operational data reflecting real-time product and component performance, and product lifecycle data focusing on maintenance cycles and component longevity.

RQ3: Several requirements were identified for data ecosystems supporting product lifecycle management and design. These include standardized processes, transparent supplier data, and advanced IT systems to manage data across lifecycle stages. The ability to handle diverse data types, from material to regulatory compliance information, is essential. Collaboration platforms for seamless data exchange and improved supplier engagement are also needed. Lastly, reliable systems for data management, tracking, and exchange are crucial for transparency, standardization, and effective decision-making.

The analysis provides valuable insights across product lifecycle phases but is limited by the number of interviews, potentially missing some complexities of the aviation industry. Evolving circular economy regulations are likely to have significant impacts, underscoring the need for future research to explore these themes in depth and include a broader range of stakeholders in the aviation value chain.

5. Conclusion and Outlook

The analysis reveals significant challenges in implementing circular economy in the aviation industry, including issues with data management, material reuse, and collaboration across the value chain. Addressing these challenges requires improved data quality, traceability, and management systems, as well as standardized processes, advanced IT solutions, and collaborative platforms to enable efficient and transparent data exchange.

Data ecosystems provide a foundational framework for addressing the aviation industry's challenges by enabling data exchange, and collaboration across stakeholders, fostering improved data quality and standardization. DPPs as a key tool within data ecosystems, could provide lifecycle transparency and traceability, enabling regulatory compliance, sustainability tracking. This paper highlights the requirements for such ecosystems and outlines the specific data and information needs including the integration of material, component and product information to support life cycle management.

Given the evolving regulatory landscape and the study's scope, future research is essential to deepen these insights and to fully address the complexities of the aviation value chain. In conclusion, the aviation industry is at a crossroads. To move towards a more sustainable and circular economy, it needs to address its current challenges, leverage digital tools like DPPs, and embrace new strategies and practices. Future research could explore the role of collaborative design, particularly how feedback from the use phase and processes like MRO can inform and optimize material and component design. In addition, future research should also consider that introducing recycled materials into the aerospace industry may alter material properties, making safety-critical verification and integration into existing quality assurance processes essential.

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