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Evaluating the Environmental Impact of End-of-Life Management in Aircraft Components: A Life Cycle Assessment Approach

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Abstract

The aviation industry has traditionally focused on in-flight emissions, but has often overlooked the environmental impacts of the end-of-life (EoL) phase of aircraft and its components. However, the EoL phase not only has environmental impacts but also presents opportunities for material recovery and recycling, potentially reducing energy consumption associated with the production of new materials from raw extraction. This study presents a Life Cycle Assessment (LCA) of an A321 aircraft's single cabin interior panel. Mechanical recycling is shown to reduce climate change impacts by 3.3 times compared to landfill, while thermal recycling achieves the highest reduction in resource use (minerals and metals, by 172.7 times. However, chemical recycling increases ionizing radiation impacts by 21.9 times. This work contributes by providing a detailed assessment of the environmental impact of a cabin interior panel relative to the whole aircraft and demonstrates that comprehensive EoL management strategies yield significant environmental benefits.

Keywords: life cycle assessment; end-of-life; aircraft; cabin interior panel

1. Introduction

The number of aircraft retirements has been steadily increasing over the past few decades and is projected to continue rising in the coming years [1, 2]. Currently, over 20% of the global aircraft fleet is more than 20 years old and likely to be decommissioned soon, with an average retirement age of 26.5 years [1]. Despite this, End-of-Life (EoL) scenarios for aircraft have been largely neglected for a long time for a long time [3]. Indeed, landfill disposal remains the most common EoL scenario for decommissioned aircraft today [3]. However, this approach is raising environmental concerns due to the risks of hazardous material leakage and contamination of surrounding soils and water [1]. In response to these concerns, alternative EoL scenarios such as incineration, recycling and reuse are gaining attention. This shift is driven by emerging environmental regulations for aircraft recycling [2] and the increasing global demand for raw and secondary materials, which contrasts with the valuable resources present in decommissioned aircraft [3].

Understanding the environmental impacts of these emerging EoL scenarios is crucial. Currently, most aircraft reaching EoL are from the 1980s to 1990s and contain high levels of metallic components [4]. However, newer aircraft models like the Airbus 350 and Boeing 787 have significantly increased their use of composite materials, which now make up to 50% of their total structural weight [2, 4]. The technological options for recycling these composite parts and materials represent one of the major challenges and drivers of the aircraft EoL industry [2, 4].

This study aims to assess the environmental impact of sandwich composites used in aircraft cabin interiors over their entire life cycle and compare the impacts of different EoL scenarios, including landfill, incineration and recycling. The chosen method for this assessment is Life Cycle Assessment (LCA), as defined by the DIN 14040/14044 standards, which is used to evaluate the environmental impact of a product or system across its entire life cycle [5]. The LCA process includes four key steps: Goal and Scope definition, Life Cycle Inventory (LCI) Analysis, Life Cycle Impact Assessment (LCIA) and Interpretation.

This paper is structured as follows: Section 2 outlines the LCA methodology, inventory, and impact assessment methods. Section 3 presents and interprets the results. Finally, Section 4 provides the conclusion and recommendations.

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2. Materials and Methods

This section outlines the LCA methodology used in this study: Section 2.1 defines the goal and scope, Section 2.2 covers the LCI preparation, and Section 2.3 details the LCIA methodology and impact categories.

2.1. Goal and Scope

The primary objective of this study is to evaluate the environmental impact of an A321 cabin interior panel across various life cycle stages and various EoL scenarios. Initially, the assessment will consider landfill disposal as the baseline scenario. Subsequently, the study will explore four alternative EoL options: incineration, mechanical recycling, thermal recycling via pyrolysis and chemical recycling via solvolysis. Additionally, a side analysis will consider a fifth scenario, which involves reusing the panel. The environmental assessment will focus on both the cabin interior panel ((using specificities given in Table 1) and the entire aircraft, considering the full life cycle to determine the panel's cumulative environmental impact.

Table 1: Aircraft specifications.

Paramter	Value	Reference
Aircraft type	A321	MaTiC-M project
Lifespan	25 years	Rahn et al. [5]
Operational empty weight	48.5 t	Airbus [6]
Cabin length	34.44 m	Airbus [6]
Panel count in cabin	26	Own calculations
Panel weight	10.1 kg	MaTiC-M project
Panel surface	7.9 m^2	MaTiC-M project
Heavy maintenance	9 years	From [7]

The subject of this study is the A321 cabin interior panel, which includes two sidewall panels, two overhead storage compartments and a ceiling panel. This panel is made from a sandwich composite structure comprising a core, skins and a decorative foil [8]. It is important to note that other components, such as windows and brackets, are excluded from this assessment. The cabin interior panel considered in this study is produced in Germany. Consequently, a German electricity mix is used for the production process to accurately reflect the local energy conditions.

The functional unit for this study is defined as one complete cabin interior panel, including all components listed above. The system boundaries cover the cabin panel's life cycle from raw material extraction to transportation, manufacturing, and final EoL disposal, excluding the use phase, assumed to have identical impacts across scenarios. This comprehensive approach ensures a thorough understanding of the environmental impacts associated with each stage of the product's life cycle.

2.2. Inventory Analysis

The LCI analysis forms the backbone of this study, capturing essential inputs like raw materials and energy as well as outputs such as emissions and waste. For this analysis, data was primarily gathered from the MaTiC-M (Methods and Technologies for an intelligent Circularity of Materials) project, an internal initiative at DLR focused on developing a holistic approach for design-for-circularity. When field data was not available, additional information was sourced from scientific literature, the ecoinvent database version 3.9.1 [9] and ESA LCA databases [10]

Raw materials The interior panel analyzed in this study is built using a sandwich composite structure consisting of several layers: a decorative film made of tedlar foil, a honeycomb core with a thickness of 5 mm composed of 20% aramid fibres and 80% phenolic resin and outer skins on each side of the core made from Glass Fibres Reinforced Prepeg (GFRP), with a composition of 60% glass fibres and 40% phenolic resin. Other components, such as windows and brackets, are excluded from this assessment. The mass breakdown of the materials used in the panel, as shown in Table 2, was primarily obtained from the internal MaTiC-M project and supplemented with data from the literature. The LCI data for glass fibres, phenolic resin and polyvinyl fluoride were sourced from the ecoinvent 3.9.1 database and enriched with additional literature data [9]. For aramid fibres, due to a lack of specific LCI data, nylon 6-6 was used as a proxy [8] with further data adjustments made using relevant literature.

Table 2: Material composition and mass breakdown of a cabin panel.

Materials	Mass (*kg*)	Distribution (%)
Glass fibres	5.01	49
Aramid fibres	0.42	4
Phenolic resin	4.32	44
Polyvinylfluoride	0.36	3
Total	**10.1**	**100**

Manufacturing The manufacturing process for the cabin interior panel consists of several key steps as described in Figure 1: producing the GFRP and honeycomb core, forming the sandwich composite and applying the tedlar foil. The GFRP is made by combining glass fibres with a resin matrix. The LCI data for this process comes from studies [11–14], which cover the production of glass fibres and prepreg. The honeycomb core is manufactured with aramid paper using the expansion process, where sheets of aramid paper with adhesive lines are cured, expanded into various cell shapes and trimmed to the desired dimensions [15]. The LCI data for this was obtained from [8, 11, 16, 17] and the ESA database. The sandwich composite is then formed by combining the GFRP with the honeycomb core. LCI data for this process was sourced from [8], detailing the material combination and curing steps needed for a lightweight composite. Finally, tedlar foil is applied to the sandwich composite to provide a protective and decorative layer. The LCI data for this step was sourced from [17].

Transport This life cycle phases for this study includes several stages. First, the materials used for manufacturing the

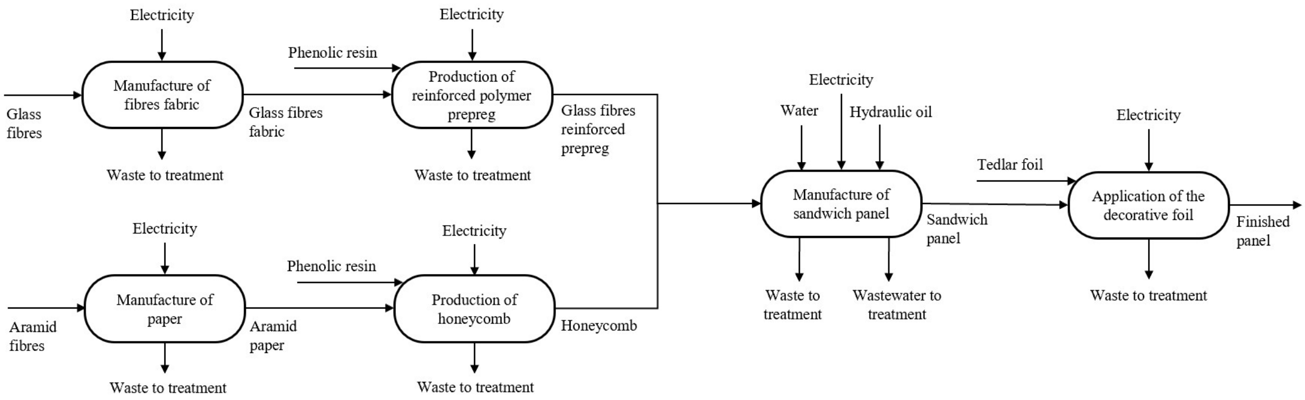

Fig. 1: Manufacturing process diagram adapted from [8].

cabin interior panel are transported by road from the suppliers to the manufacturing plant, with an estimated distance of 200 km. Additionally, waste generated throughout the manufacturing process and at the EoL stage of the panels is also transported by road. The estimated distances for waste transport, based on [18], are 100 km for landfill, 200 km incineration and 300 km for each of the three recycling scenarios. The reuse scenario is the only EoL option that does not require transportation. To model the transport of materials and waste, freight transport was assumed to be conducted using a lorry with a gross vehicle weight of 16–32 metric tons and meeting the Euro III emissions class.

End-of-Life Cabin panels are replaced every 6–12 years during heavy maintenance or when the aircraft is decommissioned (after 25 years) [7, 5]. Four EoL scenarios are analyzed:

a) **Landfill (Baseline)**: this is the most common method for disposing of decommissioned aircraft materials, where the panels are buried in a landfill.
b) **Incineration with energy recovery (scenario 1)**: panels are burned in a controlled environment to reduce waste volume and recover energy. Credits are given for avoiding energy production by recovering energy from the incineration process.
c) **Recycling scenarios**: given that both the GFRP and aramid honeycomb components of the panels are made with phenolic resin, a thermoplastic resin, several recycling methods are explored:
   - **Mechanical recycling - Scenario 2**: this method involves physically grinding the composite materials into smaller particles that can be reused in other applications. A credit is assumed for avoiding virgin material production, with recycled fibers considered at 70% of virgin fiber quality.
   - **Thermal recycling via pyrolysis - Scenario 3**: in this method, the panels are subjected to high temperatures in an oxygen-free environment, breaking down the materials into basic compounds that can be reused. Here too, credits are assumed for avoiding virgin material production.
   - **Chemical recycling via solvolysis Scenario 4**: this process uses chemical solvents to break down the composite materials into their constituent components, which can then be separated and reused. Here too, credits are assumed for avoiding virgin material productions.
d) **Reuse - Scenario 5**: panels that are still in good condition are reused after replacing the decorative foil, extending their life cycle.

The LCI for each scenario was modeled to assess the environmental impacts of EoL processes. For landfill, incineration and recycling, the initial step is grinding the sandwich composite panels for size reduction, as described by [19]. In recycling and reuse scenarios, the tedlar foil is dismantled first, as per Vidal et al. [8] methodology. Incineration is modeled using methods from [18, 20, 21], while recycling follows the approaches of [18, 20–22]. The reuse scenario is based on Vidal et al. [8] approach.

2.3. Impact Assessment

The LCA calculations in this study were performed using the open-source, python-based Brightway2 framework [23], with the Environmental Footprint (EF) 3.1 method [24] applied for the LCIA. Table S1, in the supplementary material, lists the selected impact categories of this methodology as well as their indicators and units.

3. Results

This section presents the environmental impacts of the cabin interior panel across its life cycle stages: Section 3.1 evaluates a single panel, Section 3.2 compares EoL scenarios, and Section 3.3 examines its cumulative impact over the aircraft's life cycle.

3.1. Environmental Impact of a Single Cabin Panel

Figure 2 illustrates the environmental impacts of various life stages of the product, focusing on raw materials, manufacturing, transport, and landfill as the EoL scenario. The raw ma-

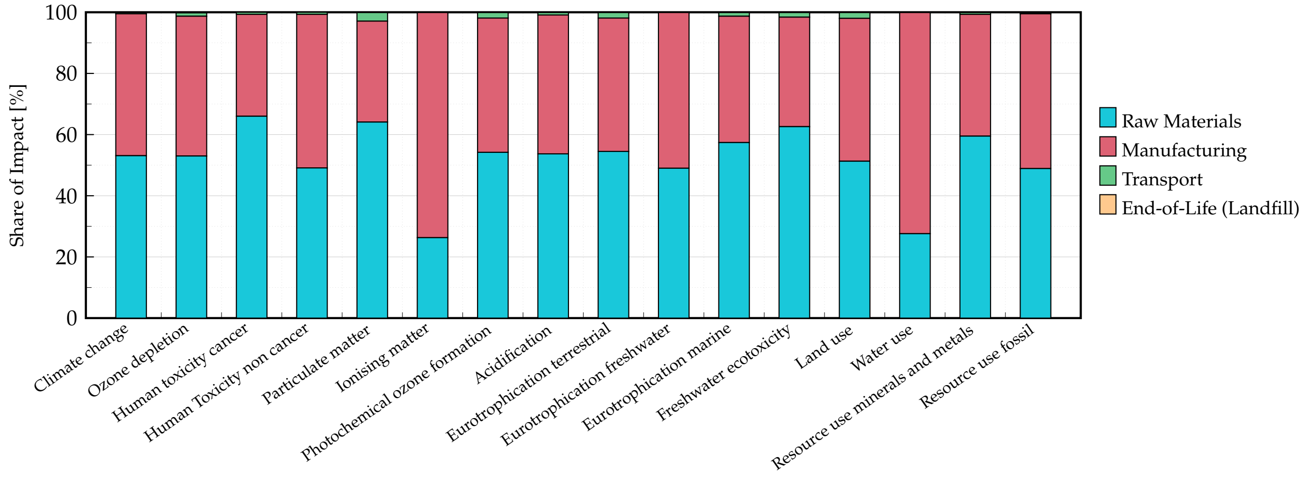

Fig. 2: LCA results for the cabin interior panel across all impact categories and life cycle phases.

terials phase is the primary contributor in categories such as Climate Change (CC) (53.1%), Resource Use, Minerals and Metals (MM) (59.5%), and Freshwater Ecotoxicity (FETP) (62.6%), highlighting the environmental burden of material extraction and processing. The manufacturing phase shows significant contributions across several categories, particularly Particulate Matter (PM) (73.6%) and Land Use (LU) (72.3%). These results emphasize the energy-intensive nature of composite production processes. The transport phase contributes minimally to the overall impact, with values below 2% in all categories, such as CC (0.4%) and Photochemical Ozone Formation (POF) (1.8%), reflecting its relatively minor influence. The EoL phase, represented by the landfill scenario, has negligible impacts, contributing 0.1% across most categories. Comparing these phases reveals that raw materials and manufacturing dominate the environmental footprint of the cabin interior panel. This underscores the importance of addressing these stages to reduce environmental impacts. Additionally, exploring alternative EoL scenarios, such as recycling or incineration, could further mitigate the environmental burden by promoting material recovery and reducing the need for virgin resources.

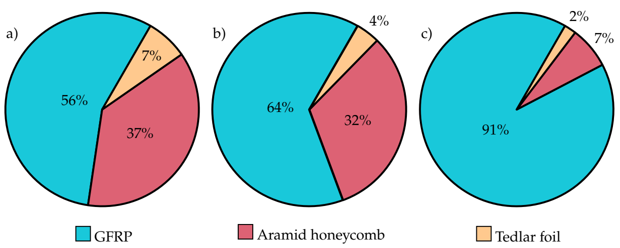

Fig. 3: Material impact share by category: (a) Climate Change, (b) Freshwater Ecotoxicity, and (c) Minerals and Metals.

Figure 3 compares the environmental impacts of the three materials used in the cabin interior panel — GFRP, aramid honeycomb, and tedlar foil — across three impact categories: CC, FETP, and MM. These categories were chosen for their broad relevance and implications [25, 26]. GFRP has the highest environmental impact in all three categories, accounting for 91% of the total impact in MM, 56% in CC, and 64% in FETP. Aramid honeycomb shows lower impacts, contributing 37% to CC, 32% to FETP, and 7% to MM. However, the LCI data for aramid honeycomb was incomplete, using a proxy from the ESA database. Consequently, its actual impact, particularly during the expansion stage, might be higher. Tedlar foil has the smallest impact, contributing 7% to CC, 4% to FETP, and 2% to MM. The mass breakdown of the panel — 7.9kg of GFRP, 2kg of aramid honeycomb, and 0.33 kg of tedlar foil — aligns with the impacts. GFRP, the heaviest component, drives most impacts, while aramid honeycomb and tedlar foil, with smaller masses, contribute less, reflecting their minimal usage.

3.2. *Comparison between End-of-Life Scenarios*

The results shown in Figure 4 compare the baseline scenario, which is landfill, with other EoL scenarios, including incineration, mechanical recycling, thermal recycling, and chemical recycling, across various environmental impact categories. In the baseline scenario, all impacts are normalized to 1, serving as the reference point for comparison. Incineration shows a mixed impact compared to the baseline. For instance, CC is slightly reduced by 2.1 times and Ozone Depletion Potential (ODP) by 2.3 times. However, certain categories like PM see a slight increase of 0.6, indicating that while incineration can reduce some environmental impacts, it may exacerbate others. Mechanical recycling demonstrates the most significant reductions across nearly all categories. For example, CC is reduced by 3.3 times and ODP by 32.0 times. In terms of resource conservation, MM sees a reduction of 86.7 times and Water Use (WS) by 35.0 times. These results highlight mechanical recycling as the most effective strategy for minimizing environmental impacts, particularly for pollutant emissions and resource usage. However, mechanical recycling of the sandwich composite can produce hazardous dust, requiring proper controls and further research to mitigate health risks. Thermal recycling shows substantial reductions in some categories, such as MM, which decreases by

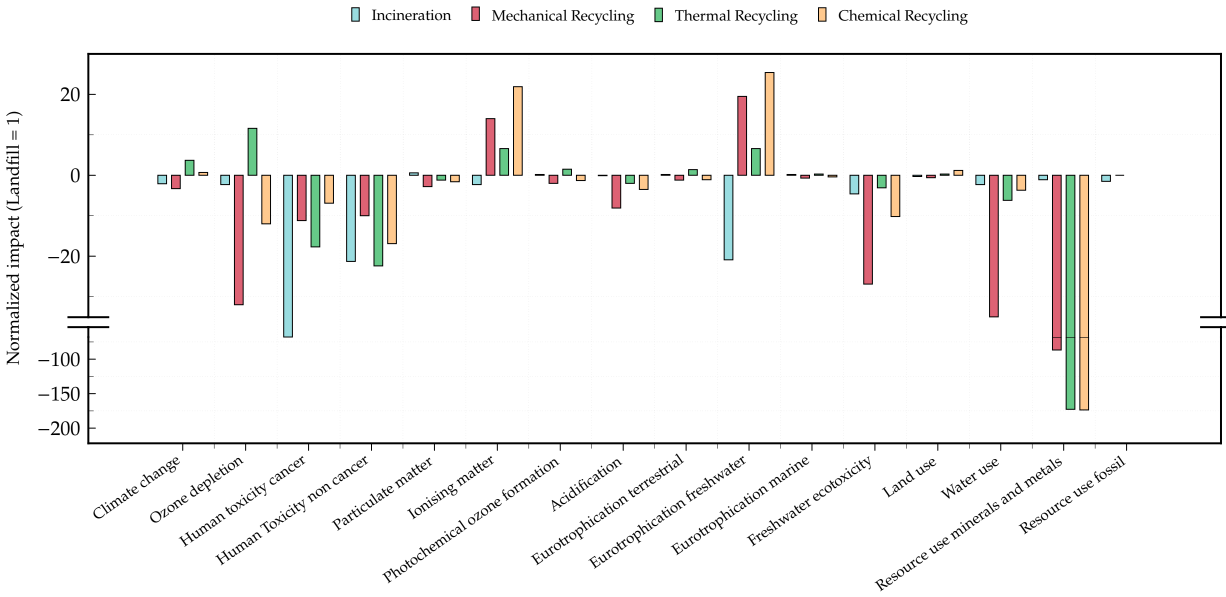

Fig. 4: Comparison of environmental impacts (normalized to 1) across EoL scenarios for cabin interior panel.

172.7 times, but it increases impacts in others, like ODP, which rises by 11.6 times. This suggests that while thermal recycling can significantly reduce resource-related impacts, it may increase emissions in other categories. Chemical recycling shows moderate reductions across most categories, such as a 6.9 times decrease in Human Toxicity, Cancer (HHC) and a 16.9 times reduction in Human Toxicity, Non-Cancer (HHNC). However, it causes a 21.9 times increase in Ionising Radiation, Human Health (IR), highlighting that while chemical recycling reduces certain impacts, it increases those related to energy consumption.

Table 3: Impact reductions for landfill and reuse scenarios.

Impact category	**Reduction (%)**
CC (kg CO_2-eq)	-58%
FETP (CTUe)	-68%
MM (kg Sb-eq)	-68%

Aircraft cabin panels are typically replaced every six to twelve years during heavy maintenance or when the aircraft is decommissioned after about 25 years. A fifth scenario, involving panel reuse, was considered in the study but analyzed separately since the reuse of composite materials has not been proven viable due to inspection and repair challenges. The reuse scenario is based on [8], where only the tedlar foil is dismantled and replaced. The focus is on three environmental categories: CC, FETP and MM. The results, presented in Table 3, show a reduction of 58% for CC, 68% for FETP and 68% for MM when switching from landfill to reuse. These significant improvements align with the expected reductions in resource extraction and waste generation through reuse.

3.3. Cumulative Impact Across Aircraft Life Cycle

The results, presented in Table 4, of the CC impact comparison between the aircraft cabin interior and the entire aircraft reveal that the cabin interior has a relatively small contribution to the overall environmental impact. The total climate change impact of a single cabin interior panel is approximately 457 kg CO_2-eq. When scaled up to account for the entire aircraft cabin interior over its full life cycle, this impact increases to 35,660 kg CO_2-eq. However, when compared to the total climate change impact of the entire aircraft, which amounts to 735,272,408 kg CO_2-eq as reported by Rahn et al. [5], the cabin interior's contribution represents only 0.005% of the overall impact. This indicates that while the cabin interior plays a role in the aircraft's environmental footprint, its impact remains marginal when viewed in the context of the entire aircraft's life cycle. Recycling cabin panels remains relevant, given their frequent replacement, as it supports circular economy principles, reduces waste, and mitigates resource burdens. Given that the cabin interior represents approximately 0.55% of the aircraft's total weight, this significant reduction in contribution to CC impacts is not surprising, as the flight operations of an aircraft accounts for over 99.70% [5] of its total environmental impacts in terms of climate change.

Table 4: Climate change impacts: cabin interior vs. total aircraft.

Impact category	**CC (kg CO_2-eq)**
Single cabin interior panel	457
Entire aircraft cabin interior	11,887
Aircraft cabin over aircraft's lifetime	35,660
Total aircraft lifetime [5]	735,272,408
Cabin share over aircraft's lifetime	0.005%

4. Conclusion

Although the EoL phase under landfill shows low impacts, considering alternative EoL scenarios could address challenges such as emerging environmental regulations for aircraft recycling and the increasing global demand for raw and secondary materials. The environmental impact analysis reveals that mechanical recycling is the most advantageous for reducing the environmental footprint of aircraft cabin interior panels, significantly lowering emissions and conserving resources. Incineration also offers reductions, particularly in CC and ODP, although its effectiveness varies across other impact categories. Chemical and thermal recycling present mixed results. Chemical recycling reduces impacts in several areas but increases others, while thermal recycling shows both improvements and setbacks, primarily due to limited industrial implementation. Reuse of cabin panels shows benefits but faces challenges related to material inspection and repair. These findings align with previous studies, confirming the dominance of raw material and manufacturing phases while providing new insights into EoL scenarios for aircraft cabin panels. Although the cabin interior's overall impact is minor compared to the full aircraft life cycle, enhancing EoL strategies remains essential for improving sustainability. Moreover, the growing interest in biocomposites presents a promising opportunity. Biocomposites, with their sustainable material profiles, could simplify the management of EoL scenarios, offering more effective and environmentally friendly solutions. This study's limitations include excluding the operation phase and lacking comparison with existing EoL studies, highlighting the need for future research. Embracing these emerging materials and innovative recycling methods will be key to advancing aircraft component sustainability.

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References

[1] ICAO, Destination green the next chapter: Best practices and standards in aircraft end-of-life and recycling.
[2] J. Scheelhaase, L. Müller, D. Ennen, W. Grimme (Eds.), Economic and Environmental Aspects of Aircraft Recycling, 2022.
[3] J. S. Ribeiro, J. de Oliveira Gomes (Eds.), Proposed framework for End-Of-Life aircraft recycling, 2015.
[4] K. Wong, Rudd,Chris, Pickering, Steve, X. Liu, Composites recycling solutions for the aviation industry, Sci China Tech Sci Vol. 60 (No.9 : 1291-1300) (2017). doi:10.1007/s11431-016-9028-7.
[5] A. Rahn, K. Wicke, G. Wende, Using discrete-event simulation for a holistic aircraft life cycle assessment, Sustainability 14 (10598) (2022). doi:10.3390/su141710598.
[6] Airbus Aircraft, A321 the most succesful commercial aircraft family ever.
[7] Aircraft Commerce, Aircraft owner's & operator's guide: A320 family maintenance analysis & budget, Aircraft Commerce 44 (February/March 2006) 18–31.
[8] R. Vidal, E. Moliner, P. P. Martin, S. Fita, M. Wonneberger, E. Verdejo, F. Vanfleteren, N. Lapena, ˜, A. G. ´, Life cycle assessment of novel aircraft interior panels made from renewable or recyclable polymers with natural fiber reinforcements and non-halogenated flame retardants, Journal of Industrial Ecology 22 (1) (2017) 132–144. doi:10.1111/jiec.12544.
[9] G. Wernet, C. Bauer, B. Steubing, J. Reinhard, E. Moreno-Ruiz, B. Weidema, The ecoinvent database version 3 (part i): overview and methodology, The International Journal of Life Cycle Assessment 21 (9) (2016) 1218–1230.
[10] J. B. Pettersen (Ed.), ESA Life Cycle Assessment Database (Space LCA DB) - A guided tour, 2021.
[11] T. Suzuki, J. Takahashi (Eds.), Prediction of energy intensity of carbon fiber reinforced plastics for massproduced passenger cars, 2005.
[12] G. Tchana Toffe, S. Oluwarotimi Ismail, D. Montalvão, J. Knight, G. Ren, A scale-up of energy-cycle analysis on processing non-woven flax/pla tape and triaxial glass fibre fabric for composites, Journal of Manufacturing and Materials Processing 3 (4) (2019) 92. doi:10.3390/jmmp3040092.
[13] Y. S. Song, J. R. Youn, T. G. Gutowski, Life cycle energy analysis of fiber-reinforced composites, Composites Part A: Applied Science and Manufacturing (40) (2009) 1257–1265. doi:10.1016/j.compositesa.2009.05.020.
[14] H. Stiller, Material Intensity of Advanced Composite Materials: Results of Asudy for the Verbundwerkstofflabor Bremen eV., n°90 Edition, Wuppertal Institut für Klima, Wuppertal, Germany, 1999.
[15] Hexcel Composites, Hexweb honeycomb attributes and properties: A comprehensive guide to standard hexcel honeycomb materials, configurations and mechanical properties (1999).
[16] S. Dong, C. Li, X. Zhang, G. Xian, Environmental impact assessment for manufacture of plant fiber honeycomb core, China Plastics 36 (6) (2022) 108–115.
[17] Dupont, Tedlar polyvinylfluroride films adhesive and lamination guide (2013).
[18] S. Karuppannan Gopalraj, I. Deviatkin, M. Horttanainen, T. Kärki, Life cycle assessment of a thermal recycling process as an alternative to existing cfrp and gfrp composite wastes management options, Polymers 13 (4430) (2021). doi:10.3390/polym13244430.
[19] A. Hedlund-Astrom, Model for end of life treatment of polymer composite materials, Doctoral thesis, Royal Institute of Technology, Stockholm (2005).
[20] R. A. Witik, R. Teuscher, V. Michaud, C. Ludwig, J.-A. E. Manson, Carbon fibre reinforced composite waste: An environmental assessment of recycling, energy recovery and landfilling, Composit es: Part A 49 (2013) 89–99. doi:10.1016/j.compositesa.2013.02.009.
[21] A. van Oudheusden, Recycling of composite materials: Faculty of industrial design engineering, delft university of technology, the netherlands, master thesis.
[22] F. Meng, E. A. Olivetti, Y. Zhao, J. C. Chang, S. J. Pickering, J. McKechnie, Comparing life cycle energy and global warming potential of carbon fiber composite recycling technologies and waste management options, ACS Sustainable Chemistry & Engineering 6 (2018) 9854–9865. doi:10.1021/acssuschemeng.8b01026.
[23] C. Mutel, Brightway: An open source framework for life cycle assessment, Journal of Open Source Software 2 (12) (2017). doi:10.21105/joss.00236.
[24] S. Andreasi Bassi, F. Biganzoli, N. Ferrara, A. Amadei, A. Valente, S. Sala, F. Ardente, Updated characterisation and normalisation factors for the environmental footprint 3.1 method. doi:10.2760/798894.
[25] S. Fazio, F. Biganzoli, V. de Laurentiis, L. Zampori, S. Sala, E. Diaconu, Supporting information to the characterisation factors of recommended EF Life Cycle Impact Assessment methods, Publications Office of the European Union, Luxembourg, 2018. doi:10.2760/090552.
[26] A. Oestreicher, A. Rahn, J. Ramm, J. Städing, C. Keller, K. Wicke, G. Wende (Eds.), Sustainable engine maintenance: evaluating the ecological impact of life limited part replacement: Congress of the International Council of the Aeronautical Sciences, Florence, Italy, 9-13 September 2024.