Life Cycle Assessment and Recycling Study on Aluminium and Polyamide 6 Materials

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Abstract: *Global awareness of the importance of environmental protection is driving the aviation sector to research, identify, and implement standards and practices throughout all stages of an aircraft's life cycle, with the aim of achieving sustainable aviation and reducing environmental impact. In this context, the aviation field is adopting an interdisciplinary approach known as Life Cycle Engineering (LCE) and the methodology called Life Cycle Assessment (LCA), with the purpose of harmonizing the design, production, operation, and end-of-life phases of components. This approach takes into account not only environmental, economic, and social concepts but also the systematic evaluation of the environmental impact of a component/product throughout its entire life span from raw material extraction to disposal, reuse, or transformation into a new product. This article conducts a study on comparative indicators related to LCA for alumnium and polyamide 6 materials using the OpenLCA software.*

Key Words: *LCA, composite materials, thermoplastics, PA6, polymer, recycle, OpenLCA*

1. INTRODUCTION

The identification of sustainable solutions for the components and products used in the aerospace industry is currently of major global interest, given the lifespan of aircraft and especially the materials from which they are made [10].

So far, there are no established standards or government regulations addressing aircraft and aircraft components that have reached the end of their operational phase. Most are stored in areas known as aircraft graveyards, with a few donated for educational purposes or to dedicated museums.

However, each year, dozens of transport aircraft are retired from service. While in the past aircraft were predominantly made from metallic materials, which allowed for conventional recycling and reuse, in the current century, it is necessary to develop methods and technologies that enable the reuse of composite materials, which are increasingly used in the aerospace industry.

Both strategies aim to optimize the entire life cycle of products or systems in order to ensure sustainability and compliance with environmental standards.

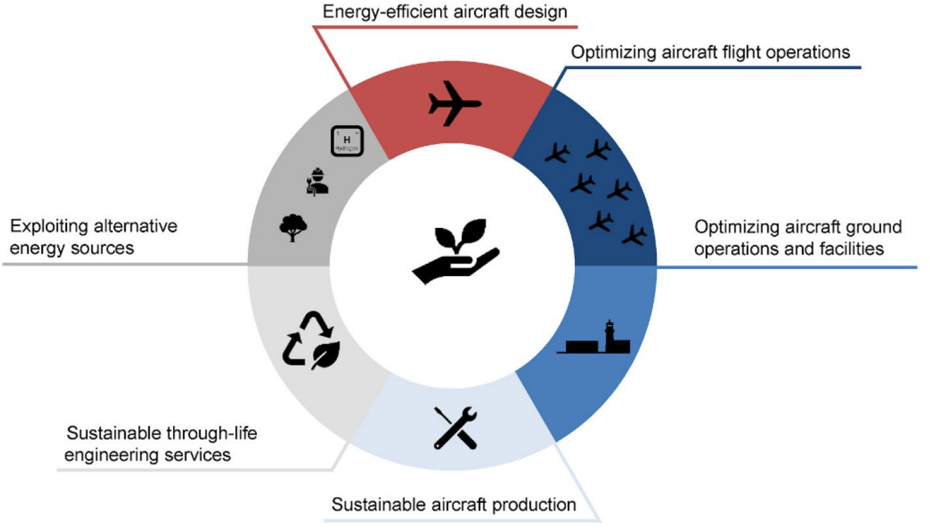

Fig. 1 Sustainability research priorities in the aviation industry as outlined by the Aerospace Technology Institute [1]

In addition to the significant carbon emissions generated by the aviation sector, emissions throughout the entire life cycle of commercial aircraft are also taken into account, including those arising during component maintenance and repair.

Alongside improving efficiency across all aviation sectors to reduce environmental impact and in anticipation of continued industry growth, the International Air Transport Association (IATA) announced in 2021 a carbon emissions goal - namely, achieving net-zero carbon emissions by 2050 [1].

To support the achievement of IATA's stated objective, the Aerospace Technology Institute (ATI) proposed a framework comprising six research areas focused on sustainability (see Fig. 1). The proposal begins with the design of energy-efficient aircraft, targeting both current aircraft and the development of new structural and propulsion concepts, and culminates in research focused on alternative propulsion sources - specifically, finding sustainable alternatives to replace kerosene, the conventional fossil fuel [1] [18].

Jörg Feldhusen et al. mentioned in 2011 that approximately 2,000 decommissioned civil aircraft were awaiting final disposal or recycling, with an additional 250 aircraft expected to reach the end of their operational phase annually over the following two decades. Military aircraft were not included in this estimation [2]. In the reality of 2025, however, the actual number of aircraft has exceeded the figures shown in Fig. *2*.

Currently, in aviation, the end of an aircraft's service life is considered solely the social responsibility of the owner.

Aircraft recycling requires expertise not only in relation to the aircraft itself, but also in complying with safety regulations concerning both human and environmental factors, as well as applicable procedures and legal requirements.

Once the decision is made to recycle an aircraft, the responsibility for carrying out the recycling process must be assumed by a specialized entity, which is responsible for managing its decommissioning.

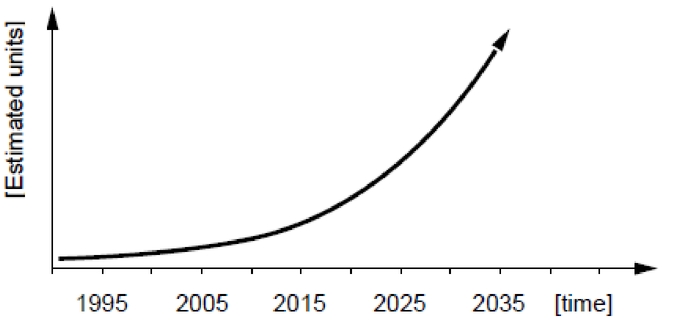

Fig. 2 The number of aircraft reaching the end of their estimated service life in the coming decades [2]

The disposal of an aircraft is a complex process that involves the owner, potential brokers, maintenance, repair and overhaul (MRO) organizations, dismantling and recycling specialists. The first step typically involves identifying, selecting, and dismantling components that can be repaired, maintained, and recertified for reuse as spare parts. The dismantling of aircraft components and equipment is carried out by qualified personnel trained for the specific aircraft type from which the parts are recovered [9].

After dismantling, parts are inspected, repaired, refurbished (if applicable), and recertified before being sold on the aftermarket, as spare parts. Finally, the fuselage is sectioned and recycled after all components, equipment, and systems (electrical, hydraulic, etc.) have been removed. This final stage requires careful handling, accurate documentation, and strict adherence to procedures [3].

2. POLYMERS IN AVIATION INDUSTRY

The aviation industry consistently prioritizes the development and integration of materials that are lightweight, mechanically robust, and durable, in order to enhance efficiency, optimize performance and promote long-term sustainability.

In this context, polymers have emerged as essential engineering materials, owing to their exceptional strength-to-weight ratio, inherent corrosion resistance and versatile design capabilities.

The integration of polymer-based materials into aircraft design offers a range of significant advantages.

Notably, polymers contribute to weight reductions of up to 50% compared to traditional metallic components, which directly translates into improvement of weight ratio and fuel efficiency.

Additionally, these materials aid in dampening operational noise, thereby enhancing acoustic comfort. Their inherent durability supports extended component lifespan, while the use of flame-retardant polymer formulations enhances safety standards, particularly in cabin interiors and critical structural elements.

Plastics are synthetic materials engineered to substitute natural ones such as metal and wood. Recent advancements, largely driven by additive technologies, have significantly enhanced their performance [16].

Additives play a critical role in improving key properties - including mechanical strength, corrosion resistance, flammability, and smoke suppression - which are essential in aerospace applications.

From a thermal behavior point of view, plastics are divided into two main categories:

- Thermoplastics – they soften when heated and can be reshaped multiple times.
- Thermosets – they harden permanently after heating and cannot be remelted.

Structurally, plastics are made of long molecular chains (macromolecules), usually based on carbon atoms. These chains can have different arrangements:

- Linear structure: Carbon atoms form continuous chains, where each carbon is bonded to two others. These chains can align to form ordered regions.
- Cross-linked structure: Chains are connected in multiple directions, forming a three-dimensional network, which increases strength and heat resistance.

Based on the arrangement of the molecular chains, plastics are:

- Crystalline (or semi-crystalline) – the chains are partially ordered, giving better strength and stability.
- Amorphous – the chains are randomly arranged, resulting in different physical properties.

Polymers utilized in the aviation industry are broadly categorized into thermosetting polymers, thermoplastics, and elastomers, each offering distinct properties tailored to specific aerospace applications [14].

Table presents an overview of the primary categories of polymers used in aviation - thermosetting polymers, thermoplastics, and elastomers - along with representative examples and their specific applications [14].

Each polymer type is selected based on its mechanical, thermal, and chemical properties, which are critical in meeting the stringent performance requirements of aerospace components [17]. The use of polymers in aviation encompasses a wide range of materials, each selected for its specific mechanical strength, thermal stability, and chemical resistance - key attributes required to meet the rigorous demands of aerospace environments. The main categories include thermosetting polymers, thermoplastics, and elastomers, each serving distinct functional roles in aircraft systems [14].

A classification of these polymer types, along with representative examples and their applications, is provided in the Table 1 below.

Table 1: Classification and applications of polymers in the aviation industry [14]

Category	Polymer Type	Description and applications in aviation
Thermosetting Polymers	Epoxy Resins	Used in composite materials such as carbon fiber-reinforced epoxy for excellent adhesion and structural integrity.
	Phenolic Resins	Employed in aircraft interiors due to high flame resistance and low smoke generation.
	Polyimides	Known for exceptional thermal stability; used in high-temperature engine components.
Thermoplastics	PEEK (Polyether ether ketone)	High-performance thermoplastic for structural and load-bearing components with excellent mechanical and chemical properties.
	Polycarbonate	Transparent, impact-resistant material used in cockpit canopies and aircraft windows.
	Nylon (including PA6) & PAI	Used in bearings, bushings, connectors, and mechanical parts; PA6 valued for toughness, chemical resistance, and processability.
Elastomers	Silicone, Viton, Fluoroelastomers	Used for seals, gaskets, and insulation due to thermal resistance, chemical stability, and durability in dynamic conditions.

Polymers play a fundamental role in the development of composite materials used in the aerospace industry.

In particular, polymer matrix composites, such as carbon fiber-reinforced epoxy, are widely employed due to their high strength-to-weight ratio, durability, and resistance to environmental degradation. These materials form the structural basis for many modern aircraft components.

The classification of composite aircraft can be made based on several factors, such as the extent of composite material usage, the type of aircraft, and its intended purpose.

Below is a relevant classification for aircraft manufactured using composite materials:

By the extent of composite material usage

a) Fully composite aircraft

Fully composite aircraft are those in which the primary structure (fuselage, wings, empennage, fairings) is made almost entirely of composite materials instead of metals. These materials—such as carbon fiber, glass fiber, or Kevlar—are combined with resins to form a lightweight yet extremely strong structure.

b) Partially composite aircraft

This category includes aircraft that have certain structural components made from composite materials.

Examples of aircraft in this category include the Airbus A380, which features composite materials in parts of the empennage and other auxiliary components, and the F-16 Fighting Falcon, which incorporates composite materials in fairings and access panels.

By type of aircraft

The following types of aircraft fall under this classification:

a) Commercial aircraft:

Modern passenger aircraft that make extensive use of composite materials to reduce weight and improve efficiency.

Examples include: Boeing 787 and Airbus A350.

b) Military aircraft:

Fighter jets or bombers that use composite materials for stealth capabilities and performance.

Examples include: F-22 Raptor, B-2 Spirit.

c) Light aircraft:

Private planes, sport aviation aircraft, or small utility aircraft such as: Pipistrel Virus, Cirrus SR22, Diamond DA40.

d) Drones (UAVs):

Most modern drones use composite materials for reduced weight and improved aerodynamics.

Examples in this category include: MQ-9 Reaper, Bayraktar TB2.

By type of composite material used

Carbon Fiber (CFRP) – high strength and low weight

Glass Fiber (GFRP) – more affordable, but less strong than carbon fiber

Kevlar / Aramid – impact resistance, often used in critical areas

Hybrid Composites – combinations designed for optimized performance

The classification of aircraft types that use composite materials in their structures, along with their composite content, can be found in Table 2 below.

Table 2: Classification of composite aircraft/UAVs and identification of composite material content in their construction

Aircraft Type	Composite Material Content (%)	Composite Structures
Boeing 787 Dreamliner (transport aircraft)	50%	Fuselage, wings, empennage, fairings
Airbus A350 (transport aircraft)	54%	Fuselage, wings, empennage, fairings, interior components
Diamond DA42 (general aviation)	90%	Fuselage, wings, empennage
Pipistrel Velis Electro (general aviation)	95%	Fuselage, wings, empennage, propeller
MQ-9 Reaper (UAV)	80%	Fuselage, wings, load-bearing structures
Lancair Evolution (general/experimental aviation)	95%	Fuselage, wings, fairings, interior
Bayraktar TB2 (combat UAV)	65%	Wings, upper fuselage, empennage
F-22 Raptor (fighter aircraft)	24%	Empennage, fairings, control surfaces
Cirrus SR22 (general aviation)	37%	Wings, empennage, fairings
B-2 Spirit (stealth strategic military aircraft)	80%	Fuselage, wings, control surfaces
Airbus A220 (commercial transport aircraft)	25%	Wings

The most commonly used types of CFRP are thermoset and thermoplastic composites. While thermoset materials are currently the most widely used in the aerospace industry, thermoplastic composites are gaining popularity due to their recyclability—an important aspect of the life cycle that has long been a drawback in the widespread adoption of CFRPs [16].

The main difference between thermoset and thermoplastic materials lies in what happens during the curing process. When cured in an autoclave, a thermoset material undergoes a chemical reaction that permanently changes its structure. A thermoplastic part, however, can be re-melted while retaining its original composition.

This distinction makes thermoplastics attractive, especially considering that Airbus and its suppliers generate hundreds of tons of composite waste each year. While thermoset resin cannot be reused, thermoplastic waste can be repurposed in various ways and across multiple industries, beyond aerospace.

While composite materials now constitute a significant portion of modern aircraft structures - as shown in Table 2 - the integration of thermoplastics and metallic materials remains essential to overall airframe performance and design versatility. Thermoplastics, such as PEEK and polyamides, are increasingly used in both structural and interior components due to their lightweight, impact-resistant, and easily moldable properties [13] [16] [17]. In some aircraft, thermoplastic composites are employed for parts that require rapid manufacturing cycles and modular integration, particularly in UAVs and light general aviation aircraft where thermoplastics help reduce weight and allow faster, more flexible manufacturing.

Meanwhile, metallic materials - particularly aluminum, titanium, and high-strength steel alloys - continue to play a dominant role in areas subjected to high mechanical loads, extreme temperatures, or requiring electrical conductivity. Even in highly composite-based designs like the Boeing 787 or Airbus A350, metals are retained for critical components such as landing gear, engine mounts, and fasteners. The strategic combination of composites, thermoplastics, and metals reflects a multi-material design philosophy aimed at optimizing performance, manufacturability and lifecycle costs in both manned and unmanned aircraft systems [16] [18].

3. RECYCLING METHODS AND PROCESSES FOR POLYMERS

Composite materials are defined as materials formed by combining two or more components. They are divided into three main categories polymer matrix composites (PMCs), metal matrix composites (MMCs), and ceramic matrix composites (CMCs). Each of these types has its own advantages as well as disadvantages or weaknesses specific to their class. Depending on the types of reinforcement, composite materials can be classified as particle-reinforced composites, fiber-reinforced composites, and structural composites [4].

There are three types of recycling: **mechanical, thermal, and chemical**.

The mechanical recycling method is based on the shredding and grinding of materials, followed by sieving or sorting to separate fiber-rich fractions from resin-rich ones for reuse. To carry out this recycling process, the following equipment can be used a grinding mill for components and a high-voltage impulse fragmentation machine.

This method requires a relatively high energy consumption, and the cost of crushing to obtain micro powder is quite significant, while the quality of the recycled materials is relatively low. The more micro powder is used as an additive in composite materials (FRP – fiberglass reinforced plastic), the lower the strength of the resulting product. Composite material waste obtained through mechanical recycling is reused, but not for its original purpose; instead, it undergoes downcycling, meaning the value created through reuse is diminished.

Thermal recycling includes several methods such as combustion, incineration, pyrolysis, etc. The thermal recycling method uses high temperatures (ranging from 300 to 1000 °C, or around 700 °C without the use of oxygen in the pyrolysis process [5]) to break down the resin and separate the reinforcing fibers and filler materials. Clean fibers or inorganic fillers are regenerated, and secondary fuel or thermal energy can be produced through pyrolysis, gasification, or combustion. However, the quality of the recovered fibers or fillers degrades to varying degrees during thermal processing [4].

The temperature used in the thermal recycling process depends on the type of resin, and improper control of this parameter can lead to a reduction in the length of the recovered fibers.

Heating produces carbon and syngas or oil as by-products [6]. Although the recovered fibers can be reused, the options are limited and they may be severely damaged depending on the heating temperature.

Chemical recycling is defined as the process by which polymers are chemically converted into monomers [7].

Chemical recycling is a method of fiber recovery by dissolving the matrix of fiber-reinforced composites in a fluid through a chemical reaction between the matrix and the solution. Acid solvolysis falls under the category of chemical recycling. For low-temperature solvolysis, the temperature at which the solution is handled must be below 200 °C [8].

This method targets chemical depolymerization or matrix removal and the release of fibers for subsequent recycling, using an organic or inorganic solvent. The lack of flexibility and the generation of chemical waste, along with environmental concerns related to chemical recycling, have led to a situation where no active development is currently taking place.

The possible ways of reusing and applying the recovered products obtained through different recycling methods are summarized in Table 3.

Table 3: Reuse and application of recovered products obtained through different recycling methods [6]

Recycling Method	Reuse and Application
Mechanical	Composites reinforced with recycled fibers Concrete reinforced with crushed CFRP pieces
Thermal – Pyrolysis	Composites reinforced with short recycled fibers Organic liquid fuels Pyrolytic gas or oil
Fluidized Bed	Bulk molding compound (BMC) Electromagnetic shielding materials High-modulus composites
Microwave pyrolysis Supercritical fluid Solvolysis	Chemically recycled short fiber-reinforced composites Short fiber-reinforced recycled composites Fuel gas

Regardless of the recycling technique used, the second stage of composite recycling technology relies on the re-impregnation of the recovered fibers. The main limitation in reusing recycled fibers lies in their discontinuous, non-uniform, and fluffy morphology. As a result, it is very difficult to use these reinforcements for the development of structural composites. When recycled fibers are applied in direct molding techniques, they can be added to various polymer matrices through injection molding (for thermoplastics) and compression molding using bulk molding compounds (for thermosets).

Most recycled composites (especially rCFRPs) are used in non-structural components, such as aircraft interiors in the aerospace industry. Recycled FRPs can also be widely used to develop automotive components, thereby replacing more traditional materials, as well as in the construction industry, sports and household goods, and certain components for wind turbines [4].

Thermoplastics are advanced polymers known for their lightweight, high-strength properties and ability to be repeatedly reshaped through heating and cooling without degradation of their chemical structure. Unlike thermoset composites, they eliminate the need for curing, allow for welding instead of riveting, simplifying assembly and offer full recyclability, making them a more sustainable alternative to traditional materials like aluminum [12]. Recycling typically involves mechanical processes, such as shredding, melting and remolding into new products. In aerospace and other high-performance sectors, recycled thermoplastics are increasingly used in non-critical components or blended with virgin material to reduce waste and production costs. Advanced methods like chemical recycling are also being developed to recover high-purity monomers for reuse in high-performance applications.

Metallic materials—such as aluminum, titanium, and steel - are among the most widely recycled engineering materials. Unlike polymers, metals do not degrade during melting, which means they can be recycled repeatedly without loss of performance.

In the aviation industry, aluminum alloys are especially valued for their high recyclability, contributing to significant energy savings (recycling aluminum uses ~95% less energy than producing it from ore). Recycled metals are used in the manufacture of new structural components, supporting sustainability goals and reducing raw material demand and reduces greenhouse gas emissions.

Among these, aluminum alloys are the most efficiently recycled due to their low melting point, widespread use, and established recycling infrastructure.

The process typically involves collection, sorting, shredding and melting, followed by recasting into billets or ingots for reuse in new aerospace parts or secondary industries. Importantly, aluminum retains its properties indefinitely during recycling, making it highly sustainable.

To better understand the performance benefits of thermoplastics, it's useful to compare them directly with traditional materials such as aluminum and thermoset composites. Key differences across critical properties, illustrating why thermoplastics are increasingly favored in high-performance applications like aerospace and automotive manufacturing are highlighted in the Table 4 [12].

Table 4: Performance comparison of thermoplastics vs. aluminum and thermoset composites [12]

Property	Aluminum	Thermoset Composites	Thermoplastics
Weight	Moderate	Light	Very Light
Strength-to-Weight Ratio	Medium	High	Very High
Recyclability	Medium	Low	High
Production Speed	Slow	Moderate	Fast
Assembly Method	Riveting	Curing & Adhesives	Welding & Molding

A brief comparison of the recyclability, common recycling methods, and main challenges associated with thermoplastics, thermoset composites, and metallic materials used in the aerospace industry is provided in Table 5.

Table 5: Comparison of recycling methods for aerospace materials

Material Type	Recyclability	Recycling Method	Challenges
Thermoplastics	High	Mechanical (melting & remolding), Chemical (monomer recovery)	Degradation after multiple cycles (for some types), quality control
Thermoset Composites	Low to moderate	Pyrolysis, Solvolysis, Grinding for fillers, Mechanical, Fluidized Bed	Difficult to separate fibers from resin; high energy cost
Metallic Materials	Very high	Melting and re-alloying, solid-state recycling	Contamination control, alloy-specific separation

4. STUDY ON COMPARATIVE INDICATORS RELATED TO LCA FOR ALUMNIUM AND POLYMIDE 6

This study compares aluminum and POLYMIDE 6 (PA6) plates to evaluate their suitability for aerospace applications. Given PA6's growing use in lightweight aircraft components, such as trolley parts, trays, armrests and seat track covers; it offers a promising alternative to traditional aluminum in terms of weight, cost and manufacturing efficiency [15].

For life cycle analysis, there are several indicators used to assess the environmental impact throughout the entire lifespan of materials from the extraction of raw materials to recycling or disposal.

A series of commonly used indicators in such studies are presented in Table 6 below.

Table 6: Examples of life cycle assessment (LCA) indicators

Indicator	Unit of Measurement
Carbon footprint (CO_2-eq)	kg CO_2-eq
Soil acidification	kg SO_2-eq
Energy consumption	MJ
Abiotic resource depletion	kg Sb-eq

For the present study, the software OpenLCA 2.0 was used a product developed by the company GreenDelta, widely employed in environmental research, sustainability consulting, product development, and corporate decision-making. It is a free and open-source program designed for conducting Life Cycle Assessment (LCA). The software is used to analyze the environmental impact of a product, process, or service throughout its entire life cycle from raw material extraction, production, and use, to final disposal ("cradle to grave") [11] [20] .

To perform a Life Cycle Assessment (LCA) of a component using OpenLCA, the following steps are followed to obtain a complete and meaningful analysis [11] [19]:

- Import relevant databases that include both materials and specific processes related to the studied components.
- Create a new process for the manufacturing of the panel, including all necessary inputs (e.g., PA6, carbon fiber, epoxy resin, electricity, heat) and a defined output (e.g., 1 kg or 1 m² of PA6 panel);
- Model end-of-life treatments appropriate to the studied product;
- Add impact assessment methods, such as ReCiPe, CML, or other suitable models;
- Build and analyze scenarios involving different recycling or disposal options;
- Compare product systems and interpret the results to draw environmental conclusions and support decision-making.

For the purpose of this study, aluminum and polyamide PA6 were selected as reference materials.

The environmental impact of producing an aluminum plate was analyzed in comparison to a PA6 plate. The life cycle was modeled and the product systems were compared in OpenLCA, using flows, processes, product systems, and projects [20].

The first step was the creation of material, product, and service flows for the study comparing an aluminum plate to a PA6 plate. The stages considered included raw material extraction, the final product, and its transport to the location where it will be processed or installed on the aircraft. The types of flows and the reference properties of the flows created for the purpose of this study are presented in Table 7.

Table 7: Name, Types, and Reference Property of the flows

Flow Name	Flow Type	Reference Property
Raw Material Aluminium	Product	Mass
Final Product Aluminium Plate	Product	Mass
Aluminium Plate Transport	Product	Number of items
Raw Material for Composite (PA6) Plate	Product	Mass
Final Product Composite (PA6) Plate	Product	Mass
Composite Plate Transport	Product	Number of items

The creation of processes is the next step in modeling within the OpenLCA software. For each process created, there are both input and output data.

A detailed overview of the inputs and outputs for each process, tracing the transformation from raw material to the final product, is illustrated in Table 8÷Table 11.

Table 8: Input data for the aluminium sheet system

Process	Quantitative Reference	Input Data	Quantity
Aluminium Production	Aluminium production	Aluminium sheet	1 kg
Aluminium Transport	Aluminium sheet transport	Aluminium sheet	1 kg
Final Product – Aluminium Sheet	Final aluminium sheet product	Transport kg*km	1 kg*500 km
		Aluminium sheet transport	1 item

Table 9: Output data for the aluminium sheet system

Flow	Category	Amount	Unit
Final Product – Aluminium Sheet	Al vs PA6	1	1 kg

Table 10: Input data for the PA6 sheet system

Process	Quantitative Reference	Input Data	Quantity
Raw material production- PA6	PA6 sheet raw material production	Nylon 6 granulate (PA6)	1 kg
PA6 Transport	PA6 sheet transport A	Nylon 6 granulate (PA6)	1 kg
Final product- PA6 sheet	Final PA6 sheet product	Transport kg*km	1 kg*500 km
		PA6 sheet transport A	1 item

Table 11: Output data for the PA6 sheet system

Flow	Category	Amount	Unit
Final Product – PA6 Sheet	Al vs PA6	1	1 kg

The next step in the modeling process is the creation of product systems, which include all the processes under study. In the software, environmental impacts can be calculated for a product system.

The reference process of the product system is used to calculate the impact for all upstream connected processes within the system. Product systems can be created either automatically or manually.

For this study, the systems were generated automatically.

Product systems were created for:

a) 1 kg aluminum sheet

b) 1 kg PA6 (Nylon 6) sheet

The selected impact assessment method was CML-IA baseline, with the "Lazy/On-demand" calculation type. The impact categories associated with this method are shown in Table 12 below.

Table 12: Impact categories of the CML-IA baseline method

Category of impact	Reference unit
Abiotic depletion	kg Sb eq
Abiotic depletion (fossil fuels)	MJ
Acidification	kg SO2 eq
Eutrophication	kg PO4 eq
Fresh water aquatic ecotoxicity	kg 1,4-DB eq
Global warming (GWP100a)	kg CO2 eq

Human toxicity	kg 1,4-DB eq
Marine aquatic ecotoxicity	kg 1,4-DB eq
Ozone layer depletion (ODP)	kg CFC-11 eq
Photochemical oxidation	kg C2H4 eq
Terrestrial ecotoxicity	kg 1,4-DB eq

The final stage in the modeling process is the creation of projects, where the CML-IA baseline method was also selected for configuration. Within the projects, the production of both the aluminum sheet and the PA6 sheet were compared.

For each product system and corresponding project, two types of results can be obtained: depending on the impact category and on the flows/emissions.

5. LIFE CYCLE ASSESSMENT RESULTS

As stated at the outset, the assessment was carried out for 1 kg of aluminium plate and 1 kg of PA6 plate.

The results were obtained based on both impact categories and flow categories.

For the consolidation of the results, the following clarifications are necessary regarding the types of impact and flow categories: from the list available in the software, specific indicators were selected, see Table 13, considered to be the most relevant for the conducted study.

Table 13: Impact categories selected for the study

Impact Category	Unit of measurement in OpenLCA
Acidification	kg SO2
Eutrophication	kg PO4
Global warming (GWP100a)	kg CO2
Human toxicity	kg 1,4- DB
Ozone layer depletion (ODP)	CFC-11
Photochemical oxidation	kg C2H4
Terrestrial ecotoxicity	kg 1,4-DB

The results obtained for this study are presented in Table 14, where the following impact categories were taken into consideration:

Table 14: Impact categories selected for the study

Impact Category	PA6 Plate	Aluminium Plate
Acidification	$1,555^{-4}$	0,014
Eutrophication	$3,577^{-5}$	$6,819^{-4}$
Global warming (GWP100a)	0,033	3,216
Human toxicity	$1,031^{-3}$	1,778
Ozone layer depletion (ODP)	$6,655^{-11}$	$3,564^{-7}$
Photochemical oxidation	$1,120^{-5}$	$7,627^{-4}$
Terrestrial ecotoxicity	$1,419^{-6}$	$5,097^{-3}$
Carbon dioxide	$4,585^{-6}$	0,030
Carbon monoxide	$5,487^{-5}$	$1,473^{-3}$

In the software, it is also possible to model end-of-life (EoL) treatments for the materials used. These can include recycling methods, landfilling, energy consumption, types of technologies, and the residues generated during a material's life cycle.

The existing menu in OpenLCA, which includes sections related to End-of-Life (EoL) treatments, residues and types of energy and/or technologies, is presented in Fig. 3.

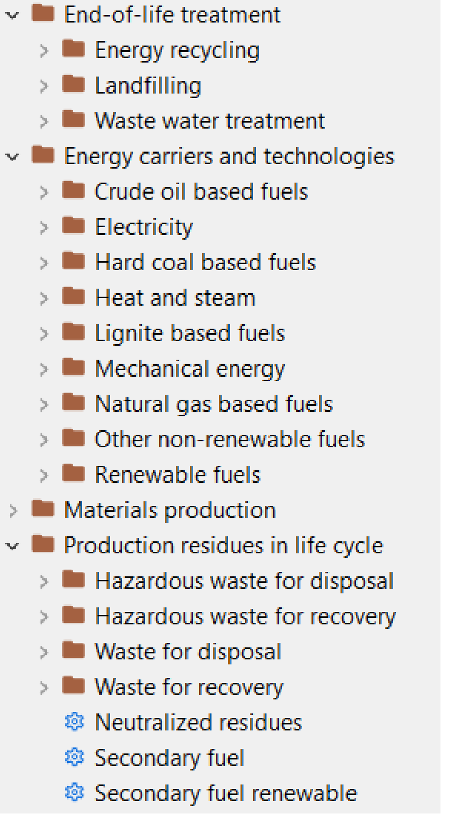

Fig. 3: Possibilities for modeling End-of-Life (EoL) [21]

As the End-of-Life (EoL) method for the conducted study, thermal recycling, specifically incineration of materials, was selected. Following the modelling and data processing, the results presented in Table 12 and Table 13 were obtained.

Table 15: Impact indicators for incineration / melting

Impact Category	PA6 Plate	Aluminium Plate
Acidification	0,030	0,053
Eutrophication	7,362^{-3}	6,819^{-4}
Global warming (GWP100a)	9,055	3,216
Ozone layer depletion (ODP)	1,331^{-10}	3,564^{-7}
Photochemical oxidation	1,873^{-3}	7,627^{-4}

Table 16: Flow indicators for incineration / melting

Flow	PA6 Plate	Aluminium Plate
Carbon dioxide	5,461^{-3}	2,865
Carbon monoxide	9,741^{-3}	1,473^{-1}

6. CONCLUSIONS AND FUTURE WORK

Based on the conducted studies and the results obtained, it can be observed that the carbon footprint is lower for composites or plastic materials compared to aluminium. However, in terms of recycling and emissions, they present greater challenges than aluminium.

The carbon footprint of aluminium is significantly higher in the production phase, but when the analysis is extended over the entire life cycle of the component, aluminium compensates due to its high recyclability.

The global warming potential indicators in the operational phase are lower for composites than for aluminium. However, at the end-of-life stage, particularly in incineration treatments, their impact is three times higher compared to aluminium melting.

From the obtained results, it can be concluded that composite and/or plastic materials become favourable only when used over a long period, benefiting from reduced weight and durability.

Based on recyclability levels, metals exhibit the highest efficiency with minimal quality loss, thermoplastics offer moderate recyclability but can degrade after repeated use, and composites - particularly thermosetting types - are the most challenging to recycle, though advancements are enhancing fiber recovery and reuse.

To conduct a complete and effective study, it is essential to analyse not only the input data but also various scenarios and comparisons for each life cycle stage of the material. This includes recycling scenarios specific to the aerospace industry. These scenarios should consider emissions, waste generation, materials, energy consumption, as well as transportation and cost estimation.

Life cycle assessment of a material becomes relevant only when combined with a life cycle cost analysis - from raw material extraction to recycling or final disposal; only in this way does the assessment become useful and realistic.

In conclusion, to carry out a thorough and realistic study, it is essential to combine life cycle assessment (LCA) with the life cycle cost (LCC) analysis, along with access to a comprehensive database capable of modelling processes at an advanced level and reflecting all potential real-world scenarios.

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REFERENCES

[1] D. Keiser, L. H. Schnoor, B. Pupkes, M. Freitag, Life cycle assessment in aviation: A systematic literature review of applications, methodological approaches and challenges, *Journal of Air Transport Management*, 2023.

[2] J. Feldhusen, J. Pollmanns, J. E. Heller, *End of Life Strategies in the Aviation Industry, Glocalized Solutions for Sustainability in Manufacturing*, Springer Link, 2011.

[3] * * * *End-of-life Reusing, recycling, rethinking*, https://aircraft.airbus.com/en/newsroom/news/2022-11-end-of-life-reusing-recycling-rethinking, accessed on April 20, 2024.

[4] Y. Yang, R. Boom, B. Irion, D.-J. van Heerden, P. Kuiper, H. de Wit, *Recycling of composite materials, Chemical Engineering and Processing: Process Intensification*, Elsevier, 2012.

[5] N. Ramawat, N. Sharma, P. Yamba, Madhavchary A. T. Sanidhi *Recycling of polymer-matrix composites used in the aerospace industry-A comprehensive review*, Materials Today: Proceedings, Elsevier, 2023.

[6] M. Blazso, *Pyrolysis for recycling waste composites*, DOI:10.1533/9781845697662.2.102, 2010.

[7] U. O. Ozaltay, A. Gunoz, M. Kara, *The Recyclability of Composite Materials*, All Sciences Proceedings, 2023.

[8] Y. Wei, S. A. Hadigheh, *Development of an innovative hybrid thermo-chemical recycling method for CFRP waste recovery*, Elsevier, Composites Part B, 2023.

[9] * * * International Civil Aviation Organization ICAO. Best Practices and Standards in Aircraft End-of-Life and Recycling, 2019 https://www.icao.int/environmental protection/Documents/EnvironmentalReports/2019/ENVReport2019_pg279-284.pdf, accessed on May 20, 2024.
[10] * * * Environmental responsibility, A lifecycle approach to environmental impact, https://www.airbus.com/en/sustainability/environment/environmental-responsibility#recycling, accessed on May 20, 2024.
[11] * * * Comprehensive manual for openLCA 2 (updated October 2024), greendelta.github.io/openLCA2-manual, accessed on November 2024.
[12] * * * Boeing and Airbus Embrace Thermoplastics - A New Era in Jet Design! https://engineerine.com/boeing-airbus-thermoplastic-design/ accessed on August 5, 2025.
[13] * * * 6 polymer technology trends in aerospace https://www.aerospacemanufacturinganddesign.com/article/6-polymer-technology-trends-in-aerospace/ accessed on July 27, 2025.
[14] A. P. Mouritz, *Introduction to Aerospace Materials-Chapter 13. Polymers for aerospace structures*, pp. 268-302, Woodhead Publishing, 2012.
[15]* * * Ultramid Polymides-Engineering Thermoplastics https://aerospace.basf.com/ultramid.html accessed on August 5, 2025.
[16] M. Pylkko, *Closed-loop recycling of polymeric aircraft parts*, Master's Programme in Mechanical Engineering, Master's Thesis, Lappeenranta–Lahti University of Technology LUT, 2022.
[17] A. Fertschej, P. Reithofer, T. Schaffranek, *Material Models For Thermoplastics In LS-DYNA® From Deformation To Failure*, 15th German LS-DYNA® USERS CONFERENCE, 2018.
[18] A. Johanning, D. Scholz, *A first step towards the integration of life cycle assessment into conceptual aircraft design*, Deutscher Luft- und Raumfahrtkongress, 2013.
[19] T. Ekvall, A. Björklund, G. Sandin, K. Jelse, J. Lagergren, M. Rydberg, *Modeling recycling in life cycle assessment*, Final project report, May 2020 - Gothenburg, Sweden.
[20] * * * OpenLCA Tutorial- Basic Modelling in openLCA, June 2020, GreenDelta.
[21] * * * OpenLCA- Software, Tools and Help menus.