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Study – Assessment of the environmental sustainability status in the Aviation Maintenance and Production Organisation (M&P) Domain

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Executive Summary

This report presents the outcome of the research study mandated by EASA to perform an **Assessment of the environmental sustainability status in the Aviation Maintenance and Production Organisation (M&P) Domain.** The study has been structured into three parts[1]:

- **Overview of the status quo**
- **Aviation M&P elements and technical culture which could support the implementation of sustainability**
- **Initiatives and recommendations to enhance sustainability in the aircraft lifecycle**

The **introduction chapter** includes the task background and objectives, as well as information regarding the concept of sustainability, its evolution, how it is handled in the EU, possible methods to measure it, and its link to aviation through the different aviation sustainability challenges.

After the introduction, the **overview of the status quo of environmental sustainability in the aviation maintenance and production organisation domain** is analysed. In this analysis, the identification and description of the different **areas, units, and processes** that are interlinked with the M&P domain are included.

Sustainable development refers to the development that takes account of social and ecological factors, as well as economic ones, and which can meet the needs of the present generation without compromising the ability of future generations to meet their own needs. An important concept to be considered when addressing sustainability is **circular economy**, which tries to achieve an improved resource management throughout the lifecycle of systems, and which is characterised by closed loops of material flows, promoting maintenance, reuse, remanufacturing, and recycling. Sustainability and the achievement of sustainable development have become major goals at international and EU levels.

Aviation has a crucial role to play to contribute to the overall sustainability of our society and has its own related challenges. While, undoubtedly, emissions generated by fuel burn cause by far the largest impact to environmental sustainability in an aircraft's life, design, maintenance, and production phases also have an important role to play in the sustainability of the aviation sector, since they are by themselves influencing environmental, social, and economic impacts, as well as the end-of-life (EoL) phase, which is strongly connected with the circular economy in aviation. Aircraft EoL is therefore a crucial element among the aviation sustainability challenges, which has not yet been studied in depth in the past. More than 15,000 commercial aircraft had been retired worldwide in the period from 1980 to 2017. During the years before the beginning of the Covid pandemic, around 700 aircraft were being retired annually, having an average age of 27 years. In addition, it was estimated that 12,000 aircraft would be retired in the next two decades (IATA, 2018)[2]. Due to the pandemic, this trend has been altered and only around 420 aircraft were officially retired in 2021, which represents the lowest level since 2007. Also, as a consequence of the pandemic, parts of the airline fleets keep grounded with little chance to be put back into service, therefore speeding up the process of aircraft retirement. Thus, there is an important need to optimise the aircraft EoL phase as much as possible, to reduce environmental impacts, reduce costs and produce a positive net social impact.

The following diagram indicates the **areas, units, and processes** that have been identified as part of the scope of this study, and for which the status quo is described.

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[1] For each of the three parts of the study, a separate internal report has been produced as deliverable to EASA. The present overall report constitutes a merged version of these three deliverables.
[2] IATA (2018). Best Industry Practices for Aircraft Decommissioning (BIPAD).

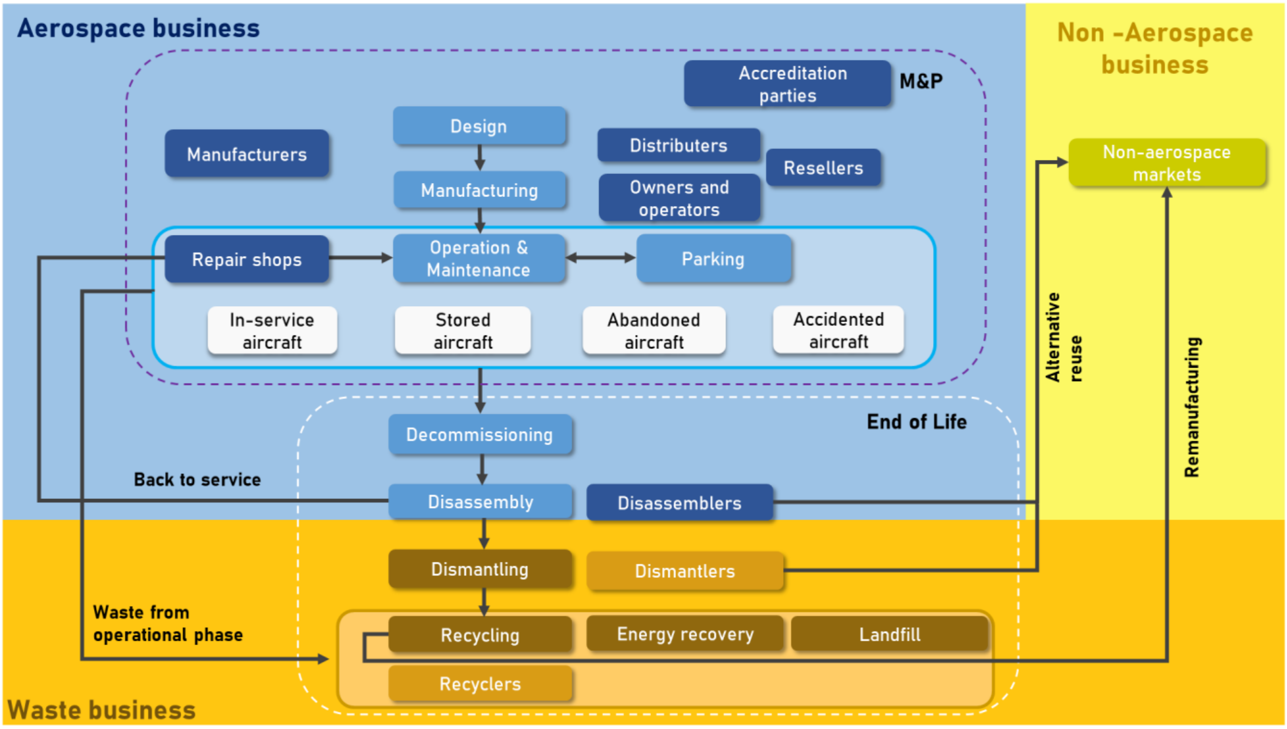

Figure 1. Main areas and units of the aircraft lifecycle

The **aerospace business** (blue section of the diagram) is constituted by all units in which the aircraft and their parts keep being utilised with their original purpose, serving air traffic operations. In this area, aircraft components are still certified for airworthiness. At some point of the aircraft lives, when the continuation of their use is not economically viable or due to safety issues, aircraft owners take the decision to **decommission** them and prepare them for disassembling. After disassembling, parts can be reused and employed as spare parts for other aircraft (still in the aerospace business) or taken to the non-aerospace business for **alternative reuse** (yellow area). After disassembling, aircraft enter the waste sector (orange part of the diagram), starting with the **dismantling**, where they are shredded and their materials are prepared to be either recycled, used for energy recovery, or sent to landfill if none of the previous options are available any longer. More details on all these areas, units and processes can be found in this report.

In addition, the current situation regarding the end-of-life impact of **new aircraft technologies** is commented as part of the report, in particular for: composite materials, which are experiencing a much wider use in newer aircraft types in comparison with previous ones, the evolution of hybrid and electric aircraft, and the use of Structural Health Monitoring.

After presenting what sustainability means, its connection with the aviation industry, and the scope of areas units and processes relevant to sustainability in M&P, with a particular focus on aircraft EoL, the different **sustainability initiatives** within that scope are presented. Firstly, standards and regulations are presented (EU regulations, ISO schemes, etc.), followed by the relevant industry handbooks, other aviation sustainability projects, and other relevant studies. In addition, the implementation of these sustainability initiatives is presented. The categories of the sustainability initiatives included in this study as well as some examples are provided in the next diagram.

Standards and regulations

- EU taxonomy
- ISOs 9001, 14001, 19011, 5001
- EMAS
- ASA-100
- EU Waste Directive
- REACH

Handbooks

- AFRA BMP
- IATA BIPAD

Sustainability projects

- PAMELA-LIFE
- Upcycling projecs
- AFRA Aircraft EoL KPIs
- Design for decomissioning

Other studies

- Circular economy indicators for the aviation industry
- SENASA's white paper on aviation sustainability

Figure 2. Examples of sustainability initiatives described in Chapter 2

Following the description of the existing sustainability initiatives, an **overview of the aircraft lifecycle** is provided, first focusing on the aerospace business and alternative re-use, and then moving to the description of the steps of the cycle that occur within the waste business.

After the presentation of the status quo of the sector, a **description of the technical and cultural elements and day-to-day practices in the sector that can support the implementation of sustainability** initiatives is provided. This analysis is performed considering the different areas, units, and processes that are interlinked with this domain and which are introduced in Chapter 2 of this report.

The **operational phase** is the source of the largest proportion of impacts, such as noise, air pollution and climate change, as well as the production of waste. However, in this report we focus on the rest of the areas of the aircraft lifecycle, targeting M&P, aircraft EoL and alternative reuse, which have traditionally been targeted less than the operational phase of the aircraft lifecycle.

The elements of the aviation system and technical cultural are divided into the following groups:

- **General elements**, which include management and planning, cooperation among organisations and legal elements.
- **Elements within the aerospace industry and alternative reuse**, which include maintenance and production, decommissioning and disassembling, and alternative reuse.
- **Elements within the waste business**, which comprises dismantling, energy recovery and landfill activities.

As part of the **General elements**, **Sustainability management** is performed by almost all organisations that constitute the aerospace business, including sustainability reporting and monitoring, training, etc. However, in the field of dismantling and recycling of aircraft and their parts and materials, even though an increasing number of sustainability projects and initiatives have been launched, there is still room for improvement. In fact, many of the currently existing best practices are not broadly implemented across the industry, especially those that constitute smaller organisations. Thus, there is still potential to expand sustainability considerations in planning and management activities.

Cooperation among organisations is a crucial element to ensure the sustainability of the sector. Two main groups of stakeholders can be established for this area: those belonging to Maintenance and Production, and those belonging to aircraft EoL. Within these two main groups, the cooperation actions are widespread. For example, within the aircraft EoL area, intense cooperation happens between disassemblers, dismantlers, and recyclers to work with the different aircraft parts and materials and allow their reuse or recycling. However, there are less interactions between the M&P and the EoL actors. Although MRO organisations can also perform part-out and EoL activities, these activities are carried out in general without their involvement by dismantling companies. However, parts removed from decommissioned aircraft need to be handled and recertified by M&P organisations before being reused in other aircraft. In addition, cooperation currently exists with research centres and universities to develop new reuse and recycling technologies improving the sustainability of the aviation lifecycle.

Regarding the **legal elements**, there is currently no regulation worldwide about EoL specifically targeting aircraft (note that for example the EU vehicle EoL Directive[3] is applicable to road vehicles, but not to aircraft). There is, however, regulation which indirectly impacts aircraft recycling. Once an aircraft has irreversibly lost the ability to fly, it is considered an assembly of pieces of waste, therefore being affected by the general waste regulation. Depending on the materials used, different existing regulations apply. These, however, make no distinction whether the materials originate from aircraft or other previous uses.

The first element affecting the aerospace industry is **maintenance and production**. Manufacturers have made efforts over decades to increase the operational efficiency of their models, leading to lower fuel consumption, and have started in the last years to improve aircraft design to enhance the dismantling process and increase the recyclability of parts and materials in the aircraft EoL phase ("design for decommissioning"). In this report, we focus on the influence of the eco-design activities on the sustainability in the M&P and EoL areas of the aircraft lifecycle. In particular, the efforts from Airbus and Boeing with PAMELA/TARMAC and AFRA, respectively, are presented in the report, as well as the creation of the Environmental Product Declaration of the Bombardier C-series (currently renamed to A220).

The **environmental impacts from the aircraft manufacturing phase** are originated from different steps, such as the extraction of raw materials, their transportation, production and casting, and their use to produce the different components until the final assembly. During each of these steps, energy and water is consumed, as well as waste is produced. Aircraft manufacturers **work on reducing the environmental impacts of their manufacturing processes**. These strategies involve better waste management, as well as the reduction in the energy consumption at their facilities and health and safety aspects.

During **aircraft maintenance**, environmental impacts are produced due to the energy use, the production of maintenance materials, as well as the waste and wastewater produced. These impacts are in essence very similar to those that happen during aircraft decommissioning and disassembling. In the MRO business, which is driven by time pressure, safety and reliability concerns, sustainability is usually not yet a main topic being addressed. The MRO organisations comply with the regulations for waste management but additional measures to increase sustainability are still not broadly extended. An important practice during the aircraft maintenance is the traceability of parts, which is still largely a manual process that can lead to a higher frequency of mismatches or failures to update the records. Therefore, this important element of the maintenance activities has a big potential to be improved with the inclusion of electronic databases to keep track of all the documentation.

Decommissioning and disassembling constitute the entry into the EoL phase, being this decision made mainly by economic and safety factors. During decommissioning, aircraft cleaning and decontamination of hazardous substances, draining of tanks and piping, and the implementation of safety procedures take place. In addition, the list of aircraft parts which could be disassembled and re-used is prepared. In some cases, young aircraft (less than 15 years old) are decommissioned to obtain a higher economic value than continuing to operate the aircraft. These cases are becoming more frequent but are still not the norm. Prior to receiving an aircraft in a

[3] European Parliament and Council (2000). Directive 2000/53/EC on end-of life vehicles

storage facility, a risk assessment and a method statement which outlines where the potential hazards are and what/how it is planned to mitigate those risks might be performed.

The **steps of disassembling** before dismantling can be summarised as follows:

- Removal and disposal of Hazardous materials and components
- Removal of interior and insulation and further re-use, recycling, or disposal
- Removal of parts list, identifying with tags showing part number, etc.
- Individual packaging for each component
- Shipping of waste (including hazardous materials) to places where it is recycled or disposed of.

As a **result of the disassembling process**, the following parts and materials categories can be differentiated:

- **Main parts to be reused (Engines, APU, Landing Gears and Components).** These equipment and parts that need (re-) certification for use as spare parts. This reuse is influenced by the availability of the parts records, which determines the value of the part and the possibility to be reincorporated to the aerospace sector.
- **Parts and materials not to be reused** (alternative reuse, recycling, and landfill):
    - **Consumables/expendables (with limited life expired)**, such as fluids, nuts, and bolts (lubricants, hydraulic fluids, chemicals, etc..).
    - **Components for alternative (non-aerospace) use**. For instance, the composite parts of the aircraft, including the fuselage and interior parts, could potentially be employed in other industries. Even the whole aircraft or large sections could be used for demonstrators and exhibitions in shows and museums.
    - **Materials for recycling**.
    - **Unrecyclable materials**, which either destinated to energy recovery or sent to landfill.

The process of recovering all the valuable airworthy is known as "parting out.," Only after this has been done, aircraft will be dismantled. Dismantling organisations usually take care of the **disassembling** of the various parts that the aircraft owners require them to take out for reuse as spare parts, which are included in a harvest list. The aircraft parts removed as part of the disassembling process are intended to be returned to the aviation market, when possible, to maximise the recoverable value. As part of the full disassembling and dismantling process, checklists are created for reference. Electronic platforms are created by some disassembling organisations to keep track of the various parts recovered and to properly inform their customers.

Alternative reuse refers to operations by which products or components that are not waste are used for different purposes from the ones they were conceived for. Aircraft materials and parts can take this pathway at their EoL and be used as part of different activities, such as training and education, filmmaking, TV productions, furniture manufacturing, etc. Alternative reuse provides much higher added values to those parts and materials that could not be recovered for aviation use and that would otherwise be sent to recycling facilities to recover the materials. A small number of companies work with dismantled aviation materials and parts and the volume of materials required are therefore small. In addition, when these activities happen, they are usually restricted to a very local scope, with organisations using alternative reuse activities contacting nearby dismantling facilities to get the materials they need. Thus, there is a potential for increasing the importance of this pathway, which would require increasing the awareness of the benefits of these activities to both sellers (dismantlers) and buyers (any organisation creating the alternative reuse products, such as designers, furniture manufacturers, etc.).

Aircraft **dismantling** constitutes the entry of the aircraft parts and materials into the waste business, meaning that they cannot be reused in the aerospace sector, are considered as waste, and are under the general regulations covering waste treatment. Aircraft dismantling consists of the following steps: the final draining of the systems, the categorisation of the materials that are left and the end-of-life fates that they will follow, the removal of hazardous materials, removal of non-recyclable materials, shredding, and transportation to recycling and recovery facilities. Most of the value from the parts and materials that enter the aircraft EoL comes from the reuse of parts in the aerospace business. Therefore, the pure dismantling is performed once all that potential value was already recovered. Materials above the cabin floor are usually very neat, so these are relatively easy to be used efficiently in recycling. Insulation materials in the cabin can be separated to be reused either in aviation or in other industries. Regarding the engines' parts and components, these follow a particular process, considering their remarkably high value. Safety and Quality initiatives come from national legislation which apply as well to the aviation industry. When parts are not to re-enter the aerospace business, they need to be properly destructed. These initiatives get complemented with the use of toolbox talks and on the job trainings.

Following dismantling, the **recycling, energy recovery, and landfill** steps take place. After having removed all valuable components, the remaining fuselage is broken up into small pieces and processed by a metal recovery company. Those materials that allow for energy recovery are taken to incineration facilities to extract energy from the combustion of the materials. Finally, materials that cannot be either recycled or used for energy recovery, are sent to landfill.

High **recovery** rates are reported by manufacturers for the case of aircraft that have been retired in the last decade. For aircraft types currently being retired (and which usually have a high share of metals in their structure), various recyclers can reach recovery rates of around 95%. These high recovery rates involve the use of downcycling and dealing with aircraft that have a high percentage of metallic parts. Thus, for the case of recent aircraft models containing a large percentage of composite structural parts, which will enter the EoL phase in the future, new recycling technologies will be required to keep the high reusability and recyclability rates. In the case of engines, these are a source of rare earths and other precious materials. However, not all these elements are recycled, due to the difficulties to separate them.

Energy recovery is defined as a form of resource recovery in which the organic fraction of waste is converted to some form of usable energy. Waste incineration itself is as well a carbon-intensive process and undermines the general efforts of carbon emissions reductions in aviation and which can also lead to LAQ issues. Therefore, even though energy recovery is still a better path than landfilling, it still has related issues and should not be the focus to increase circularity and sustainability.

As it is the case for energy recovery, the process of sending aviation waste to **landfill** is not aviation-specific, since at this point of the aircraft lifecycle, this waste has no specific legislation and follows the same steps as waste from other industries and sectors. Sending waste to landfill implies costs for aircraft dismantlers. It has been proven that aircraft that currently go through the EoL process can reach close to zero landfill.

It is expected that the **aircraft annual production and deliveries** will experience a continuous rise over the following years. Moreover, the global fleet is forecasted to steadily increase, reaching 35,700 aircraft in 2030 (Oliver Wyman, 2022). These forecasts imply higher demand for aircraft manufacturing and maintenance.

An average of 800 aircraft per year are expected to retire at the end of the current decade, increasing from an average of 650 (Oliver Wyman Fleet and MRO Forecast, 2022). In addition, more than 30% of the current fleet in Europe is expected to retire over the next decade, therefore increasing **the demand of aircraft disassembling, dismantling, and the recycling of aircraft materials**.

In Chapter 4 of this report, **ways, solutions, and methods to implement sustainability** in the aircraft lifecycle are identified. This chapter considers the information from the current situation of sustainability in the aviation M&P sector (Chapter 2) and the description of the technical and cultural elements in the sector setting the framework for the implementation of sustainability initiatives in the real world (Chapter 3). It considers the different units, processes, and key stakeholders, the sustainability initiatives, and the different elements which could help to enhance the sustainability of the sector. The initiatives and recommendations incorporate feedback from aviation stakeholders.

Initiatives and recommendations are listed by three main groups (General elements, aerospace sector and alternative re-use, and waste business), **and by several subgroups**:

General elements

- Regulation aspects
- Work on incentives
- Use of charges
- Increasing collaboration among stakeholders
- Promotion and implementation of sustainable management practices
- Training of personnel in sustainability and circular economy
- Communication activities to increase the visibility of the sector

Aerospace industry and alternative reuse

- Regulation aspects
- Best practices
- Industry policy
- Standards
- Publication of materials and components of the aircraft
- Decommissioning registry
- Aircraft decommissioning decision recommendations

Waste business

- Improving recyclability and reuse of parts and materials
- Increase of aero grade metals upcycling
- Enhancement of current best practice handbooks and their application
- Set the aspirational goal to eventually reach zero landfill

Figure 3. Groups of initiatives and recommendations

Each subgroup contains one or more **initiatives** that are explained in their respective subchapters, indicating the rationale for them and the expected benefits. In addition, a **qualitative analysis of the initiatives and recommendations** is presented. In this analysis, a set of characteristics are described for each of the suggested recommendations. The **categories** proposed for the analysis are environmental benefits, economic benefits, social benefits, technical benefits, geographical scope, ease to implement, and speed to implement.

For these categories, a **rating system** ranging from 1 to 3 has been proposed. For each of the initiatives, scores have been given to each of the categories in order to estimate the impacts derived from its application. The ratings have been established in a way that, the higher the score, the more interesting (in terms of benefit and/or implementability) the application of the recommended measures is expected to be. A general matrix can be found in Subchapter 4.5 with all the ratings assigned to each of the initiatives. In addition, at the end of Chapter 4, the average ratings per group, subgroup and assessment category are presented, as well as the list of those initiatives that are expected to be the easiest to implement.

The information from this document serves to provide a **general overview of the sustainability of the aircraft lifecycle, its status, and options to improve it**. After obtaining this information, additional steps could be taken forward to analyse in detail which initiatives would be preferential to implement and the details on this process.

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Abbreviations

ACRONYM	DESCRIPTION
AFRA	Aircraft Fleet Recycling Association
BMP	Best Management Practices
APU	Auxiliary Power Unit
AR	As Removed
ASA	Aviation Suppliers Association
BER	Beyond Economical Repair
BIPAD	Best Industry Practices for Aircraft Decommissioning
CBA	Cost Benefit Analysis
CE	Conformité européenne (European Conformity)
CFRP	Carbon-Fibre-Reinforced Polymers
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
CSR	Corporate Social Responsibility
D1a	Deliverable 1a
D1b	Deliverable 1b
D1c	Deliverable 1c
D2	Deliverable 2
D3	Deliverable 3
DTD	Damage Tolerant Design
EASA	European Aviation Safety Agency
EAER	European Aviation Environmental Report
ECHA	European Chemicals Agency
EEA	European Environment Agency
EIA	Environmental Impact Assessment
EMAS	Eco-Management and Audit Scheme
EoL	End of Life
EPD	Environmental Product Declaration
ESAP	EASA Sustainability Aviation Programme
EU	European Union
EU-ETS	European Union – Emissions Trading Scheme
eVTOL	Electric Vertical Take-off and Landing
FAA	Federal Aviation Administration
FN	Factory New
FOCA	Swiss Federal Office of Civil Aviation
GAMA	General Aviation Manufacturers Association
GHGs	Greenhouse Gases
GPP	Green Public Procurement
IATA	International Air Transport Association
ICS	Incident Clearance Statement
ICT	Information and Communications Technologies

IEA	International Energy Agency
IMO	International Maritime Organization
IPBES	Intergovernmental Science – Policy Platform on Biodiversity and Ecosystem Services
ISO	International Organisation for Standardisation
IUCN	International Union for Conservation of Nature
KPI	Key Performance Indicator
LAQ	Local Air Quality
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LTO	Landing and Take-Off Cycle
MCA	Multi Criteria Analysis
M&P	Maintenance and Production
MRO	Maintenance, Repair and Overhaul
NB	Narrow Bodies
NE	New Equipment
NLR	Royal Netherlands Aerospace Centre
NS	New Surplus
NSA	National Supervisory Authority
OEM	Original Equipment Manufacturer
OH	Overhauled
PAMELA	Process for Advanced Management of EoL of Aircraft
PAO:TO	Paperless Aircraft Operations in Technical Operations
PCB	Printed Circuit Board
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals
RJ	Regional Jets
R&D	Research and Development
RTK	Revenue tonne kilometres
SAC	Sustainable Aviation Committee
SAF	Sustainable Alternative Fuels
SEA	Strategic Environmental Assessment
SENASA	Servicios y Estudios para la Navegación Aérea y la Seguridad Aeronáutica
SDG	Sustainability Development Goal
SHM	Structural Health Monitoring
SMS	Safety Management System
SV	Serviceable
TP	Turboprops
UN	United Nations
UNEP	United Nations Environment Programme
WB	Wide Bodies
WCED	World Commission on Environment and Development
WWF	World Wildlife Fund

Definitions

NAME	DESCRIPTION
Aircraft (in the context of this report)	When describing statistics, processes, initiatives, and recommendations for the aircraft lifecycle, these have been based on commercial aircraft information. However, the information portrayed in this document can be extrapolated in most of the cases to general aviation.
Aircraft End-of-Life	In aviation, the aircraft end-of-life refers to the steps in the aircraft lifecycle that occur after the decommissioning decision, thus including disassembling, dismantling, recycling, energy recovery and landfill.
Alternative reuse	Any operation by which products or components that are not waste are used for a different purpose from the one they were conceived for.
Assembly	An Assembly is a functionally integrated group of Parts that together make up a component required for the certified operation of a commercial aircraft (e.g., engines, landing gear, etc.) (AFRA BMP).
Asset	In the context of aircraft disassembly, the Asset means an item that is being disassembled, such as an aircraft, engine, or any Assembly of commercial aircraft Parts, thereof. (AFRA BMP[4]).
Circular economy	Model that aims to maintain the value of products, materials, and resources for as long as possible by returning them into the product cycle at the end of their use, while minimising the waste generation. (Eurostat[5]).
Decommissioning	Process that comprises the retirement of an aging aircraft from operational service, including the inspection, cleaning, and decontamination steps.
Disassembly	When used in reference to an Asset, means to take apart or dismantle constituent parts from a given Next Higher Assembly. It is not intended to address disassembly that occurs incidental to maintenance (e.g., a teardown that is a step in an overhaul). NOTE: Facilities desiring to be accredited for Disassembly must have the auditable means to perform disassembly as described, at a fixed, remote, or contracted area. (AFRA BMP).
Dismantling	Step of the aircraft end-of-life in which the aircraft materials are prepared to be treated as waste, either via recycling, energy recovery or sent to landfill. The dismantling process include the following steps: final draining of the systems, categorisation of materials to waste treatment routes, removal of hazardous materials, removal of non-recyclable materials, shredding, and transportation.
Downcycling	Recycling of waste where the recycled material is of lower quality and functionality than the original material. (Cambridge Dictionary).
Energy Recovery	A form of resource recovery in which the organic fraction of waste is converted to some form of usable energy. Recovery may be achieved through the combustion of processed or raw refuse to produce steam through the pyrolysis of refuse to produce oil or gas; and through the anaerobic digestion of organic wastes to produce methane gas. (EEA[6])
Ferry flight	Non-revenue-generating flight typically used for delivery. In the context of this report, it refers to the flight that takes the aircraft to the facility in which the decommissioning takes place.
Ferrous 3b	Fragmentised, old light steel arisings fragmentised into pieces not exceeding 200mm in any direction. Must be free from dirt, free non-ferrous metals and foreign material and

[4] AFRA (2022). The AFRA BMP
[5] European Commission (2022). EUROSTAT
[6] EEA (2022). Energy recovery

	exclude excessive moisture, introduced loose cast iron, incinerator material, grindings, swarf, turnings, and borings. Should also be free from tin cans. Must conform to the following specifications: • Density: 0.8 tonne per cubic metre minimum • Sn content: 0.03% max • Cu content: 0.25% max (letsrecycle.com)
Hazardous waste	Waste which displays one or more of the hazardous properties listed in Annex II of the EU Waste Framework Directive. (EU Waste Framework Directive[7]).
Key Performance Indicators	Those that measure the behaviour and performance of a system. It is a set of quantifiable measurements that a Facility uses to gauge its performance over time. (AFRA BMP).
Landfill	Site for disposal of waste materials. (EU Waste Framework Directive).
Part	Part means any component, part, sub-part, assembly, sub- assembly, or other item removed from the Asset. (AFRA BMP).
Recertification	The process of being certified again, in the context of this report related to aircraft parts and equipment that have lost their airworthiness certification but are intended to be used again in an aircraft.
Recovery	Any operation the principal result of which is waste serving a useful purpose by replacing other materials which would otherwise have been used to fulfil a particular function, or waste being prepared to fulfil that function, in the plant or in the wider economy. (EU Waste Framework Directive). The difference between reuse & recycling in comparison with recovery is the incineration fraction ("energy recovery").
Recycling	Any recovery operation by which waste materials are reprocessed into products, materials, or substances whether for the original or other purposes. It includes the reprocessing of organic material but does not include energy recovery and the reprocessing into materials that are to be used as fuels or for backfilling operations. (EU Waste Framework Directive).
Remanufacturing	Use of recycled aircraft materials in non-aerospace markets.
Reuse	Any operation by which products or components that are not waste are used again for the same purpose for which they were conceived (EU Waste Directive)
Sustainability	Goal of the process of sustainable development, which is achieved when the material and social conditions for human health and the environment are maintained or improved over time without exceeding the ecological capabilities that support them. (UN[8])
Sustainable development	Development that takes account of social and ecological factors, as well as economic ones, and which can meet the needs of the present generation without compromising the ability of future generations to meet their own needs. (UN)
Waste	Any substance or object which the holder discards or intends or is required to discard (EU Waste Framework Directive).
Waste producer	Anyone whose activities produce waste (original waste producer) or anyone who carries out pre-processing, mixing or other operations resulting in a change in the nature or composition of this waste. (EU Waste Framework Directive).

[7] European Parliament and Council (2008). Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives
[8] UN (2022). Sustainability

Waste management	Collection, transport, recovery (including sorting), and disposal of waste, including the supervision of such operations and the aftercare of disposal sites, and including actions taken as a dealer or broker. (EU Waste Framework Directive)
Zorba	A form of nonferrous scrap metal consisting mainly of aluminium, especially that which is left behind after an automobile is shredded and the iron and steel is removed. (Wiktionary)

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1. Introduction

1.1 Task background and objectives

Sustainability has become a crucial topic following environmental developments over the last decades. The EU has recognised that action is required, which has led to the establishment of the EU Green Deal[9]. Within this framework, EASA has taken its responsibility in the field of aviation and has installed the EASA Sustainability Aviation Programme (ESAP), overseen by the Sustainable Aviation Committee (SAC). The SAC agreed to establish initiatives to encourage and support the sustainability of the aviation sector. Amongst many other initiatives, the SAC has decided to launch the **present study to assess the current state of environmental sustainability in the Maintenance and Production (M&P) domain, targeting aircraft lifecycle aspects and aircraft EoL**.

The EASA Basic Regulation (regulation (EU) 2018/1139)[10] Article 87 point 4 requires that "*the Agency shall, at least every three years, publish an environmental review, which shall contain recommendations aiming to improve the level of environmental protection*". As of this moment, there is no Implementing Rule available, based on M&P Department recommendations, the SAC has agreed to initiate a project to achieve the main objective defined in the initial sustainability analysis and decided to first start with a **research study to determine the status quo**. Envisa has been assigned to develop this study.

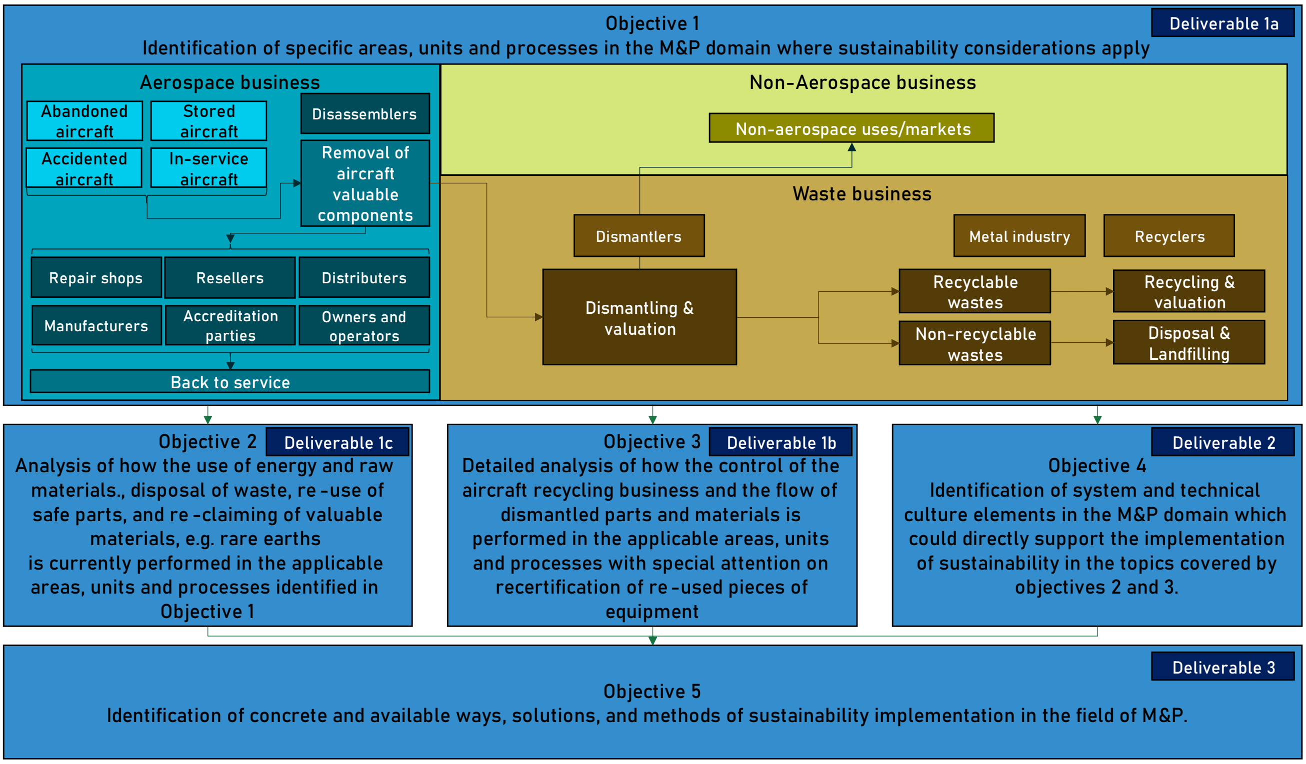

Figure 4. Objectives and Deliverables Diagram (Envisa, 2022)

The **study aims** at providing a clear picture concerning the current attention paid to environmental aspects by EASA approved M&P organisations in their culture, policy, and systems. This includes in practical terms the management of reduction of waste and energy consumption, the disassembly of aircraft and the subsequent redistribution of aircraft parts and the re-use or recycling of materials, and the application of life cycle assessment and/or circular economy concepts in general. Furthermore, other co-related areas/activities in

[9] EU Commission, (2022). A European Green Deal
[10] EC (2018), Regulation EU 2018/1139

maintenance, such as proper awareness, technical culture management, procedures, and oversight are considered.

The **goal of this project** is to provide guidelines to EASA to react to and improve the situation in Europe regarding the sustainability of the aviation M&P sector.

The first step of this project was to gather information about the current situation of sustainability in the aviation M&P sector. This information is presented in **Chapter 2**, followed by a description of the technical and cultural elements in the sector that can support the implementation of sustainability initiatives (**Chapter 3**). Once this information was obtained, the third project step, described in **Chapter 4**, focused on the Initiatives and recommendations to enhance sustainability in the aircraft lifecycle.

The structure of the report can be consulted in the diagram below.

1. Introduction

- Task background and objectives
- The concept of sustainability and its evolution
- Sustainability in the EU
- How to measure sustainability?
- Aviation sustainability challenges

2. Overview of the status quo

- Key areas, units , and processes in the M&P Domain
- New technologies
- Composite materials and SHM
- Sustainability initiatives affecting aviation
- Analysis of the aircraft lifecycle outside the waste business
- Analysis of the aircraft lifecycle within the waste business

3. Elements of the aviation system and technical culture which could support the implementation of sustainability

- General elements
- Elements within the aerospace industry and in the alternative reuse
- Elements within the waste business

4. Initiatives and recommendations to enhance sustainability

- Summary of the initiatives and recommendations
- General elements
- Elements within the aerospace industry and in the alternative reuse
- Elements within the waste business

5. Conclusions

6. Next steps

Figure 5. Structure of the report

The **introduction** of this report focuses on defining what the meaning of sustainability is, its importance in aviation in the EU, and how it can be measured. This is a key chapter since it helps to set the scope of the sustainability initiatives.

After the introduction, an **overview of the status quo**, with a description of the key areas, units, and processes in the aviation M&P domain, and the sustainability initiatives that exist within it is provided. In addition, a focused analysis of the aerospace business is given, which focuses on the reuse part, including the parts recovery, recertification, and put back into service. The following subchapter focuses on the waste business area of the aircraft lifecycle, thus providing more information concerning dismantling, recycling, energy recovery, and landfill aspects of the domain.

Following the overview of the status quo, a **description of the different elements of the aviation system and of the technical culture which could support the implementation of sustainability** is provided. This analysis is performed over the areas, units and processes that were identified as part of the overview of the status quo. This chapter expands on those identified areas and includes information on how the day-to-day practices are carried out, and on the related technical culture elements. The analysis of these elements is supported by several interviews and feedback obtained from stakeholders involved in the aircraft lifecycle, such as manufacturers, MRO companies, aircraft owners, national aviation institutions, dismantlers, and recyclers. As part of the description of the current practices in the defined scope, relevant sustainability initiatives are also included.

After the description of the aviation system and technical culture elements, Chapter 4 describes the different **initiatives and recommendations to enhance sustainability in the aircraft lifecycle**. In addition, a qualitative analysis of these recommendations is included, providing an orientation of the benefits that they would produce.

Finally, the **conclusions** of the different Chapters are summarised in Chapter 5, followed by some recommendations regarding **next steps** in Chapter 6.

1.2 The concept of sustainability and its evolution

To clarify the concept of **sustainability**, it is first required to indicate what sustainable development represents. The origin of the discussions that led to the definition of sustainable development was the publication of "Silent Spring"[11] in 1962, which can be considered the origin of the widespread concern about environmental degradation due to industrial activities. This concern evolved in the following years, leading to the creation of the term "sustainable development," that was defined by the IUCN's 1980 World Conservation Strategy[12]. It stated that "for development to be sustainable it must take account of social and ecological factors, as well as economic ones."

The report "Our Common Future" (Brundtland Report) (WCED, 1987)[13], expanded the concept and gave future directions to try to find global solutions. It defined **sustainable development** as the one which "meets the needs of the present generation without compromising the ability of future generations to meet their own needs." This has since become an often-quoted definition. Currently, the term has become widespread and well-known by most of the society. As indicated in the WCED report, sustainable development implies that natural resources belong to all humans, not limiting their aspirations to higher standards of living. The present lifestyle of the developed nations is not sustainable, resulting in environmental degradation and societal inequity. Sustainable development is meant to be a balance between economic, environmental, and social elements, which are known as the "triple bottom line." In addition, especially for the case of aviation, safety and security are important aspects imposing mandatory requirements alongside the sustainability pillars. Aviation safety refers to the efforts taken to ensure that aircraft and flight operations are free from factors that may end up producing injuries or losses. Aviation security on the other hand focuses on the protection

[11] Rachel Carson (1962). Silent spring
[12] IUCN, UNEP, and WWF (1980). World Conservation Strategy
[13] World Commission on Environment and Development (1987). Our Common Future.

against illicit acts with the aim to cause intentional harm to aviation infrastructure, including passengers, workers, property, infrastructure, and overall continued operations. The three "sustainability pillars," and the influence of safety and security in the case of aviation are illustrated in the figure below.

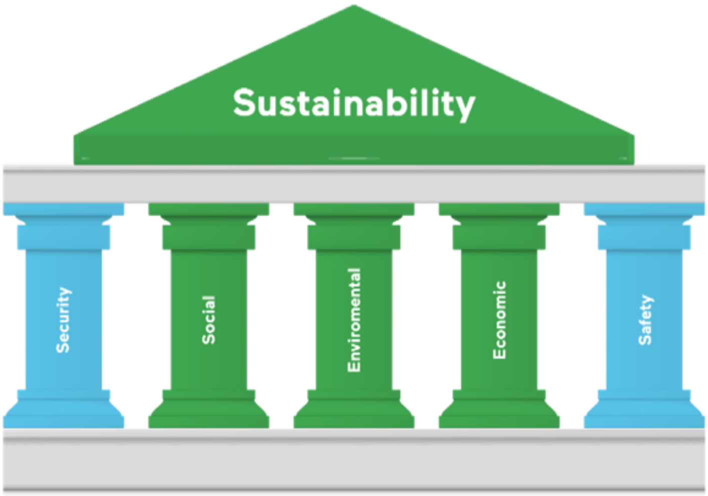

Figure 6. Pillars of sustainability (Envisa, 2022)

Another important concept in the domain of sustainability is **circular economy**. There is no standard definition of the circular economy concept. However, as pointed out by Saidani et al. (2017)[14], the definitions used so far agree that circular economy is opposed to the linear model "make-take-waste". This concept tries to achieve an improved resource management throughout the lifecycle of systems, and it is characterised by closed loops, promoting maintenance, reuse, remanufacturing, and recycling. In addition, an important attribute shown by the authors is the compatibility and consistency of the circular economy concept with sustainable development, through its three associated pillars, as it aims to improve economic, environmental, and social benefits. A characterisation of the concept can be consulted in the figure below.

Figure 7. A characterisation of circular economy (Envisa, 2022)

[14] Saidani et al. (2017). How to Assess Product Performance in the Circular Economy? Proposed Requirements for the Design of a Circularity Measurement Framework

Another way to represent the concept of circular economy is the "**butterfly diagram**," which illustrates the continuous flow of materials in the economy. There are two main cycles: the technical cycle and the biological cycle. As part of the technical cycle, products are kept in circulation in the economy through reuse, repair, remanufacture and recycling. This way, materials can be kept in the cycle and never become waste. In the biological cycle, nutrients from biodegradable materials return to Earth via processes such as composting or anaerobic digestion. In the case of the aviation sector, the technical cycle can be used as reference system. An important aspect to be considered from the diagram, is that the loops located closer to the middle, for instance maintenance and reuse, keep a higher value than those located on the sides, such as recycle. This concept is linked with the waste hierarchy, which indicates that after prevention of waste, priority should be given to reuse, recycling, recovery, and disposal, in this order, and trying to reduce the disposed amount as much as possible.

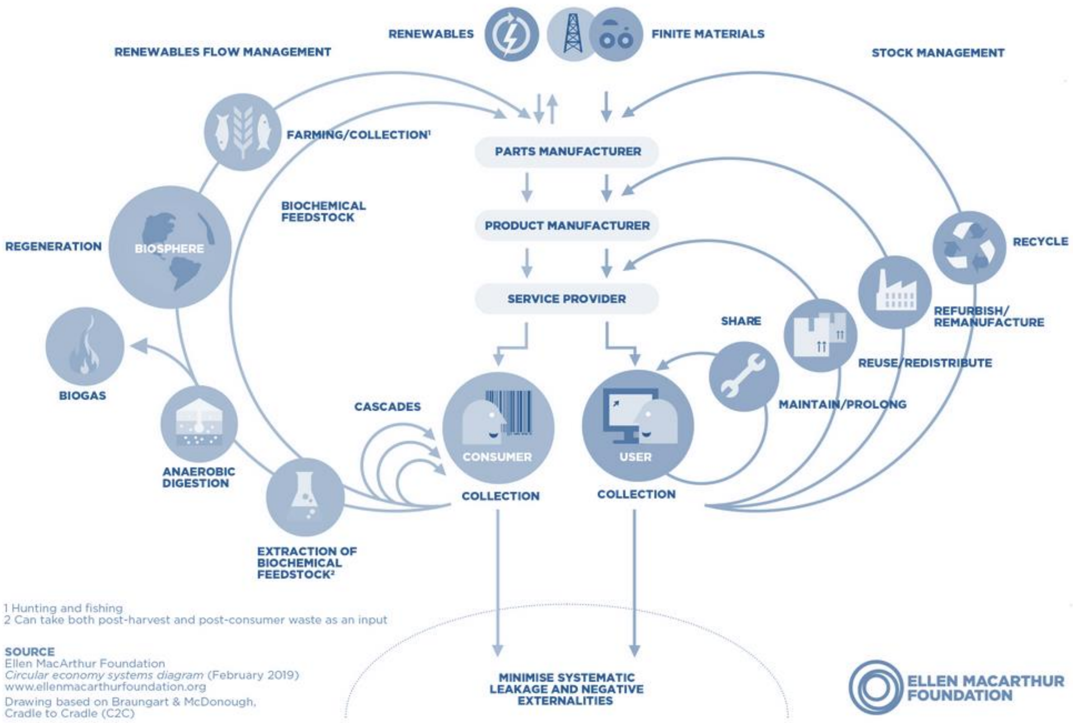

Figure 8. Circular Economy systems diagram[15]

Sustainability and the achievement of sustainable development have become major goals at international level. A reflection of this ambition has been the 2030 Agenda for Sustainable Development, adopted by all United Nations Members States in 2015. This Agenda includes the 17 **Sustainable Development Goals**, which are a call for action by all countries in a global partnership. The goals target all aspects of sustainability, have been designed to achieve a better and more sustainable future, and are intended to be achieved by the year 2030. Reports are published on a yearly basis covering the progress and challenges associated to each of them.

[15] Ellen McArthur Foundation (2019). Circular economy systems diagram

Figure 9. Sustainable Development Goals[16]

The global aviation sector has a role to play in 15 of the 17 SDGs, contributing to a safe, efficient, and cost-effective mobility strategy. Through increasing connectivity between nations, aviation is a crucial driver of economic and social development. In addition, aviation has wide ranging climate action plans, contributing to the environmentally focused SDGs. In the figure below, the connection and strength of the link between aviation and the SDGs is shown.

Figure 10. Aviation and SDGs (Based on ATAG, 2017[17])

As it can be seen in the figure, **aviation has a strong link with 7 out of the 15 SDGs**. Regarding Gender equality, aviation needs to work on encouraging young women to join technical areas, as well as men to join the frontline staff. When it comes to affordable and clean energy, aviation has a key role by developing SAF and renewable energies and their supply at airports. Aviation supports the decent work and economic growth as well, by providing skilled and high-value employment and supporting economic development through the connectivity it brings. Regarding industry, innovation and infrastructure, aviation is one of the most innovative industries in the world, continually developing new infrastructures and technologies. Aviation also greatly contributes to reducing inequalities between countries and individuals, since it creates trade links and provides access to goods and services for the people living in remote communities. The SDG number 12: "Responsible consumption and production" is linked to one of the main areas of this study, which is the EoL management.

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[16] United Nations (2022). Sustainable Development Goals

[17] Air Transport Action Group (2017). Flying in Formation

Finally, the strongest commitment from the aviation sector is found to achieve the goal of combatting climate change and its impacts. Examples of this commitment are the agreement on the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), and the long-term 2050 emissions goals.[18]

1.3 Sustainability in the European Union

The EU is at the forefront of the achievement of sustainable development, as it is a core principle of the Treaty on the European Union and constitutes a main objective for the Union's internal and external policies. The European Commission remains committed to the 2030 Agenda and has presented a policy programme to deliver on sustainability in the EU and beyond. The Commission has focused on delivering concrete actions that will bring tangible progress in the areas of the Sustainable Development Goals (SDGs). All 17 SDGs are represented at least in one or more of the European Commission Priorities for the period 2019-2024.

Figure 11. European Commission Priorities and SDGs[19]

Particularly relevant EU initiatives to enhance sustainability are the **European Green Deal and the Circular Economy Action Plan**[20]. The Green Deal is a set of proposals with the goal to overcome the challenges of climate change and environmental degradation. These proposals include the objective of reducing net greenhouse gas emissions by at least 55% by 2030 and by 100% (no net emissions) by 2050. The Green Deal proposals include actions in various sector, such as: climate change, energy, industry, transport, and research and innovation. In the case of transport, the proposals' objective is to put the sector on track to cutting its greenhouse gas emissions by 90%. Also, at the heart of the European Green Deal, and in line with the commitment of the Paris Agreement, the EU aims to be climate-neutral by 2050, having set out its vision in November 2018 and the first European Climate Law on 4 March 2020. An example of the proposals taken

[18] Such as the ATAG Waypoint 2050, European industry's Destination 2050, the ICAO LTAG task group, and Roadmap for climate neutrality in aviation

[19] EU Commission (2021). EU holistic approach to sustainable development

[20] European Commission (2020). COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS A new Circular Economy Action Plan For a cleaner and more competitive Europe

forward as part of the EU Green Deal is the **Zero Pollution Action Plan**[21], which targets to reduce air, water, and soil pollution to levels that are no longer considered harmful to health and ecosystems. Aviation is a key element within the Green Deal policies, since one of the main actions is to accelerate the shift to sustainable and smart mobility.

The European Commission established a new **circular economy action plan** in March 2020, constituting one of the main elements of the European Green Deal, and being crucial to achieve the EU's 2050 climate neutrality targets and to halt biodiversity loss. This action plan includes initiatives throughout the entire life cycle of products. It introduces both legislative and non-legislative measures targeting areas where action at the EU level provides significant added value. This action plan is focused on the sectors that use most resources and where the potential for circularity is high such as: electronics and ICT, batteries and vehicles, packaging, plastics, textiles, construction and buildings, food, water, and nutrients. Several actions have been listed as part of the Circular Economy Action Plan. Even though this action plan is not directly targeted towards aviation, the steps made can be adapted to it. In addition, one of the main elements of the Circular Economy Action Plan is the expansion of the eco-design practices. Examples of actions that can be linked to aviation are shown in the table below.

Table 1. Examples of actions from the Circular Economy Action Plan

Key actions	Date
Proposal for a new regulatory framework for batteries	2020
Review of the Directive on the restriction of the use of certain hazardous substances in electrical and electronic equipment and guidance to clarify its links with REACH and Eco-design requirements	2021
Review of the rules on proper treatment of waste oils	2022
Waste reduction targets for specific streams and other measures on waste prevention	2022

Sustainable aviation is one of EASA's priorities. The **EASA Sustainability Aviation Programme** streamlines the certification and standardisation activities to reach the same level of success in sustainability as for safety and provides industry and stakeholders with guidance and instruments needed to meet the challenges. The key priorities of the EASA's SAP area are to support innovative greener technologies through environmental certification and standards, to facilitate decarbonisation of the aviation system and to promote operational efficiency in areas such as maintenance, training, and air traffic management.

In addition, **EASA** put int place the **Environmental Strategy 2020-2024**. In order to implement the objectives of the Environmental Strategy, EASA prepared the Environmental Strategy Action Plan, which defines work packages, key deliverables, delivery dates and responsibilities. The four main objectives of the Environmental strategy are:

A) Facilitate the decarbonisation of the aviation system through Agency initiatives
B) Act towards sustainable aviation through environmental certification and standards
C) Act towards sustainable aviation through a Flight Standards Environmental Action Package
D) Act towards sustainable aviation through effective transversal actions

Within Objective C, an action was agreed to work on the sustainability in Maintenance and Production, leading to the need of this project.

[21] European Commission (2022). Zero Pollution Action Plan

1.4 How to measure sustainability?

As it has been presented already in this document, sustainability has an extensive scope, which makes measuring it a complex task. To measure sustainability, we need to be able to evaluate each of its components, either individually or by grouping them. **There are several methods to measure sustainability aspects**. In this subchapter, examples of different methods to measure sustainability are presented.

One of the most relevant methods to estimate the sustainability of a product or process is the **Life Cycle Assessment**. As indicated by Mascle et al (2015)[22], Life-cycle Assessment (LCA) is a systematic scientific approach to assess the environmental impacts of a product, service, or process throughout its entire life cycle for a given functional unit. Its methodology is defined by ISO standards 14040[23] and 14044[24], involving a goal and scope definition, an inventory analysis, an impact assessment, and a final interpretation. The outputs of the process are a set of scores for several impact categories. Its main strength is that it can consider several impacts (for instance, acidification, eutrophication, global warming potential, etc.) and that it has a comprehensive "cradle-to-grave" approach. However, LCAs require considerable time and data input and the interpretation of the results might prove to be complex.

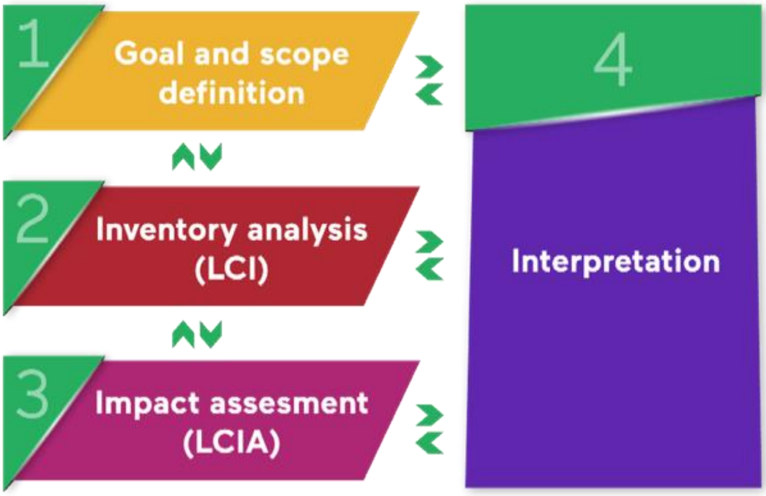

Figure 12. The LCA Process (ISO 14040)

In addition to LCA, **Cost Benefit Analysis** (CBA) is another tool that can be considered to assess sustainability, in particular its economic pillar. CBA has been a core tool of public policies and consists of the systematic calculation of the different benefits and costs of policies and projects. It is well established that the environmental impacts of a project are crucial to determine its economic implications. Environmental costs and benefits of projects can therefore be included into the calculations, thus obtaining economic results that incorporate the environmental matters behind. CBAs are then a useful tool that can help to complement and enrich the results obtained with other methods such as LCA.

The general concept of LCAs and CBAs can be applied and expanded to specific sectors. This is the case for aviation as well. For instance, Pohya et al. (2021)[25], presented an environment for economic and operational assessment of aircraft and related products named LYFE. This tool can employ discrete events simulation which models the product lifecycle through decades of operation and maintenance until disposal. Therefore, it can model the influence on engine health, fuel efficiency and overall economic viability, thus contributing the overall sustainability assessment of the aircraft.

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[22] Mascle et al. (2015). Process for Advanced Management and Technologies of Aircraft EoL

[23] ISO 14040. Environmental Management. Life Cycle Assessment. Principles and Framework

[24] ISO 14044. Environmental Management. Life Cycle Assessment. Requirements and guidelines

[25]. Pohya et al. (2021). A Modular Framework for the Life Cycle Based Evaluation of Aircraft Technologies, Maintenance Strategies, and Operational Decision Making Using Discrete Event Simulation

Another option to measure sustainability is the employment of **Multi Criteria Analysis** (MCA). This method has the goal of evaluating the overall environmental consequences of an alternative, considering multiple criteria and their weights. Its process consists of establishing the context, criteria, scoring, weighting, examining the results and conducting a sensitivity analysis. The final output of the process is an environmental score based on an aggregation of criteria[26].

Other processes to assess sustainability and which are linked to options evaluation are the **Analytic Hierarchy Process** (AHP)[27] and the **Multi Criteria Decision Making** (MCDM)[28] techniques. The AHP is a method that combines mathematics and psychology to organise and analyse complex decisions and which has been applied to environmental matters, therefore contributing to the assessment of sustainability. MCDM explicitly evaluates various confronting criteria that are part of decision making. Criteria employed in this analysis are cost or price, quality (usually increasing with price), safety, etc. Therefore, the way to employ MCDM to assess sustainability is to include the main criteria driving the sustainability of the decision to be made. As indicated, these two decision-making methodologies can be helpful to determine the sustainability of the considered project or actions.

It is also important to mention the application of **Environmental Impact Assessments** (EIAs) and **Strategic Environmental Assessments** (SEAs). These two assessment types focus on the environmental impacts of projects and policy plans, respectively. They originated during the second half of the 20th century, acquiring more importance. This raising importance translated into the inclusion of the processes in European Directives which have led to the transposition into national laws. These processes aim to analyse the various environmental impacts, first identifying them, and then providing an estimation of their magnitude. The overall impacts estimated by the assessment are considered to determine if the action or policy is compatible or needs modifications in order to be carried out without significant impacts to the environment. Thus, these methodologies are helpful to anticipate potential impacts, avoid them, and mitigate or compensate when the avoidance is not possible.

To present the results of the sustainability analysis, it is crucial to use metrics that reflect the results in a meaningful way. As indicated in Sikdar (2003)[29], there are two classes of metrics to indicate the state and performance of a system. These metrics are more popularly known as **indicators**. The ones that indicate the state of a system are known as content indicators and those that measure the behaviour of a system are denominated performance indicators. Usually, research is done to measure improvements in each of the sustainability areas, therefore studying ecological metrics, economic metrics, and sociological metrics. These metrics measure only one aspect of the system, and, therefore, are one-dimensional (1-D). Another approach would be combining two aspects at the same time, to obtain 2-dimensional sustainability metrics. Finally, 3-dimensional metrics can be obtained from the intersection of all three aspects, which could be called true sustainability metrics. It was also suggested that the number of chosen sustainability metrics should be small, and as independent of each other as possible.

Two of the most common metrics used in the field of end-of-life are **recoverability** and **recyclability**. In this regard, the main reference calculation methods are both the ISO 22628[30] standard, which addresses the automotive industry, and the IEC/TR 62635 report, which refers to the electrical and electronic equipment industry. As indicated in the ISO 22628 standard, recoverability is the ability of component parts, materials, or both that can be diverted from an end-of-life stream to be recovered. A similar definition is given by the IEC technical report (IEC/TR 62635[31]), which considers it as the ability of a waste product to be recovered, based on actual practices. In this latter report, recyclability and recoverability rates are shown to be calculated by

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[26] IPBES (2022). Policy support tool. Multi-Criteria Analysis
[27] Vaidya and Kumar (2006). Analytic Hierarchy Process: An overview of applications
[28] Velasquez and Hester (2013). An analysis of multi-criteria decision-making methods
[29] Sikdar (2003). Sustainable Development and Sustainability Metrics
[30] ISO 22628:2002. Road vehicles. Recyclability and Recoverability. Calculation method
[31] IECT TR 62635:2012

dividing the recyclable/recoverable masses of each part of the product (part mass weighted by the recycling/recovery rate of a defined EoL scenario) by its total mass.

In addition, **sustainability labels (Ecolabels)** are often employed to mark products or processes that fulfil a series of sustainability requirements. The International Organisation for Standardisation (ISO) has created standards for labelling practices within the ISO14000 schema. Three categories of labels have been proposed:

- Type I (ISO 14024[32]), which correspond to voluntary multi-criteria ecolabels assessed by independent third parties that consider the life cycle impacts of the product or process.
- Type II (ISO 14021[33]), that are self-declared claims made by manufacturers or retailers without third-party auditing.
- Type III (ISO/TR 14025[34]), which are constituted by environmental product declarations that consist of quantified product information on the life cycle impacts. In this type, instead of assessing or weighting the environmental performance, the objective data obtained during the sustainability assessment is presented, which facilitates the comparison among products.

Among the different sustainability labels, it is relevant to mention the **EU Ecolabel**[35], established in 1992 and recognised across Europe and worldwide. The EU Ecolabel is a label that is awarded to products and services meeting high environmental standards throughout their life cycle. It analyses: the extraction of raw materials, the production, distribution, and disposal of the product or service. This label promotes the circular economy by encouraging producers to generate less waste and CO_2 emissions during the manufacturing process. The EU Ecolabel criteria also encourages companies to develop products that are durable, easy to repair and recycle.

1.5 Aviation sustainability challenges

Aviation is a complex sector which causes different sustainability impacts. The main direct **impacts coming from the operational phase** of the aircraft are noise, pollutant emissions, and greenhouse gas emissions. In addition, all the related activities, such as airport operation or aircraft manufacturing pose additional impacts, like waste generation, or land-use change. The three pillars of sustainability are involved in the aviation impacts. As an example, greenhouse gas emissions do directly contribute to climate change, therefore posing an environmental threat, that also leads to negative economic and social effects. Another example is aircraft noise, which constitutes a negative environmental effect since it has an evident and important negative social effect by producing sleep-disturbance and annoyance to affected people in the airport surroundings. Moreover, noise control has economic effects, for instance since airports may impose noise-related charges to airlines, or with the implementation of more stringent noise certification standards which affect the aircraft design and manufacturing.

[32] ISO 14024:2018. Environmental labels and declarations. Type I environmental labelling. Principles and procedures

[33] ISO 14021:2016. Environmental labels and declarations. Self-declared environmental claims (Type II environmental labelling)

[34] ISO 14025:2000. Environmental labels and declarations. Type III environmental declarations

[35] European Parliament and Council (2009). Regulation (EC) No 66/2010 of the European Parliament and of the Council of 25 November 2009 on the EU Ecolabel

Figure 13. Parked aircraft at Tarmac Aerosave (Teruel, Spain)[36]

The **generation of waste** is one of the main sustainability impacts of the aviation sector. As we are seeking to achieve climate neutrality by 2050, there should be a focus as well on the implementation of circular economy principles in the sector. There are currently no official requirements for the aviation industry to design new products considering the recovery of materials when aircraft are scrapped. Another challenge in this area is that it is not mandatory for aircraft and engine manufacturers to publish manuals that identify the materials of each component, the type of treatment that can be used in their recovery, or the hazard that the unproper management of the linked waste can produce to the environment.

A crucial element among the aviation sustainability challenges is the **aircraft EoL**. More than 15,000 commercial aircraft had been retired worldwide in the period from 1980 to 2017. During the years before the beginning of the Covid pandemic, around 700 aircraft were being retired annually, having an average age of 27 years. In addition, it was estimated that 12,000 aircraft would be retired in the next two decades (IATA, 2018)[37]. Due to the pandemic, this trend has been altered. In fact, as it can be consulted in the next figure, only around 420 aircraft were officially retired in 2021, which represents the lowest level since 2007. The aircraft types leading these retirements were the A320ceo and the 737NG families (Naveo Consultancy, 2022). The reason for this modification is that parking and long-term storage have been relatively cheap, therefore airlines and lessors favoured waiting and seeing how traffic recovers. It is more interesting to keep aircraft stored if there is the chance that it could come back to service or to be sold for part-out later, when the demand for MRO is higher. Various airlines have taken the opportunity of the low demand period to retire their entire fleets of old aircraft models (e.g., 747, A340). Despite the high public attention given to these retirements, their overall numbers are relatively limited.

[36] Aeropuerto de Teruel (2022). Tarmac Aerosave

[37] IATA (2018). Best Industry Practices for Aircraft Decommissioning (BIPAD)

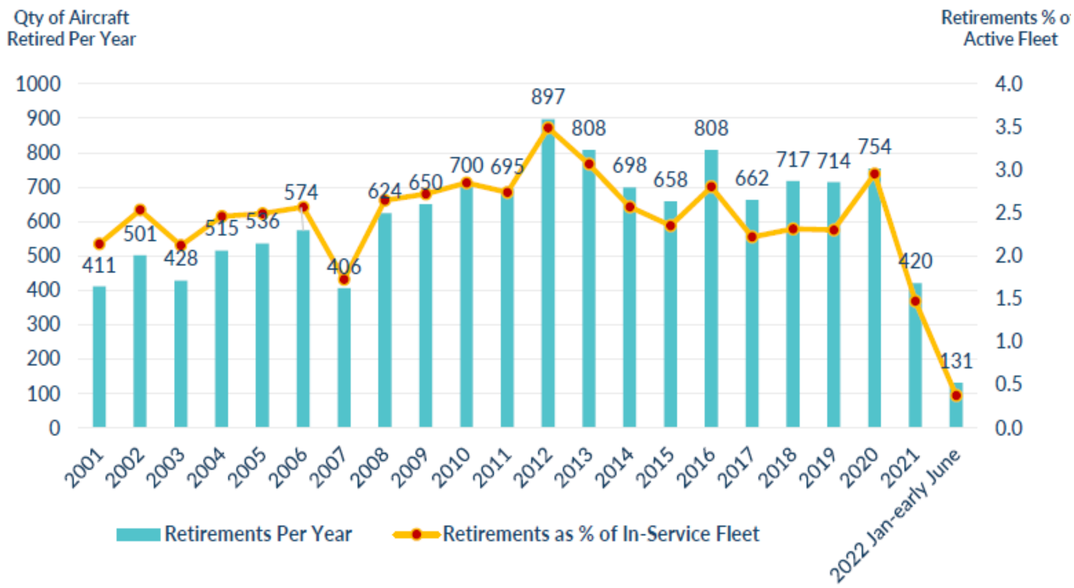

Figure 14. Air Transport Retirements 2001 to early June 2022. (Naveo Consultancy, 2022)

Aircraft retirements are expected to increase in the coming years to 20-25% compared to previous decades, since many older aircraft are due for retirement and newer generations will substitute them, although this depends on the pace of the recovery, fuel prices, etc. Most major in-service aircraft types have seen less than 25% of their total production enter retirement.

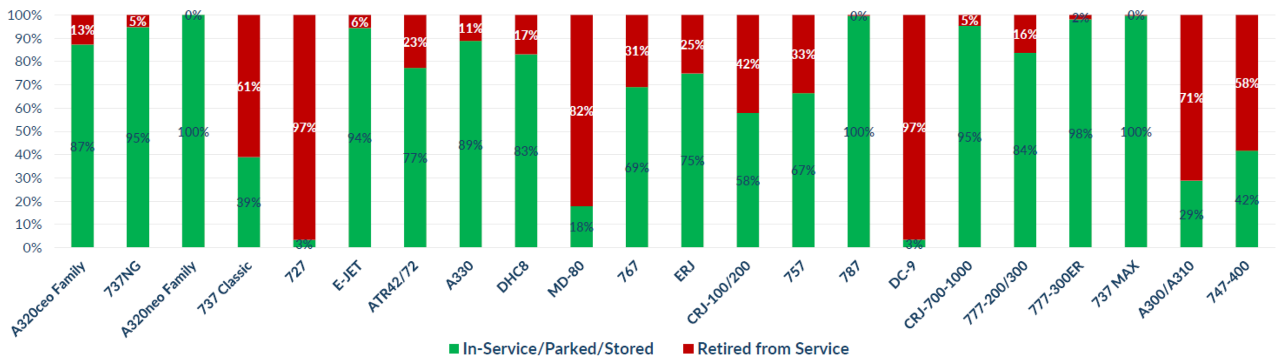

Figure 15. In service/stored/parked versus already retired share by aircraft type, ranked by total quantity of aircraft manufactured (Naveo consultancy, 2022)

In the case of **Part 145 activities**, as it can be observed in the next figure, less work was available during the Covid crisis since there was little motivation to disassemble parts from retired aircraft as demand for spare parts was low, also influencing their price, which decreased. After years of aftermarket growth, the 2020 MRO market went down around 35% due to the grounding of most of the airlines' fleets. However, the scrapping services were busier during this period due to the final retirement of entire fleets of old aircraft models by various airlines. The market is expected to recover by 2023, exceeding pre-pandemic levels (Naveo Consultancy, 2022). During the period from 2021 to 2031, the MRO market is forecasted to grow slower, due to the retirement of maintenance-intensive aircraft and their replacement by newer ones. When a new generation of aircraft starts replacing larger numbers of older model aircraft in service, this leads to lower requirements of spare parts of the older aircraft generation. This suggests that the current trend towards lower aircraft retirement age trend might experience a reverse to older ages when new generation aircraft enter the market, lowering the value of the previous generation spare parts. Covid increased the problematic of finding parts for aircraft maintenance when needed due to the lower MRO activities and aircraft retirements.

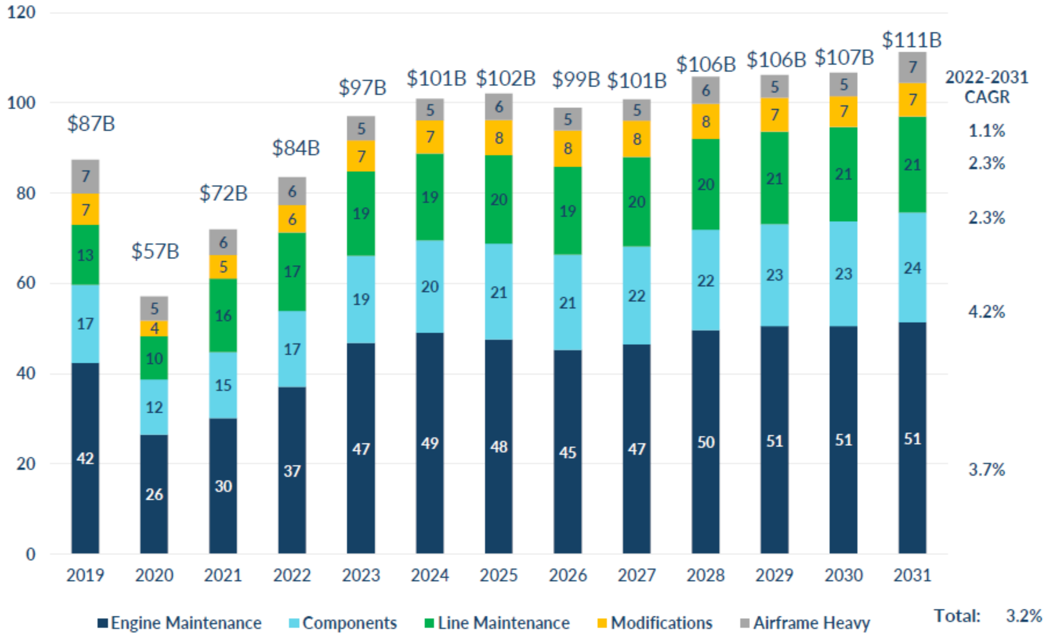

Figure 16. Air Transport MRO Market Forecast, 2019-2031 by MRO Category (Naveo Consultancy, 2022)

Thus, **aircraft EoL** is a phase that constitutes an important element of the cycle and that is expected to increase in the following years. Therefore, there is an important need to optimise the aircraft EoL phase as much as possible, to reduce environmental impacts, reduce costs while optimising the residual value of aircraft parts, and produce a positive net social impact.

2. Overview of the status quo

2.1 Key areas, units, and processes in the M&P Domain

To structure the whole aircraft lifecycle, areas, units, and processes have been identified:

- **Areas** refer to the business areas subject to different legislation.
- **Units** indicate individual steps or subareas. These are differenced by the nature of the processes that take part in them and the stakeholders involved.
- **Processes** are actions or activities that take place within the identified units.

The **aircraft life cycle** can be divided into 3 main areas: the aerospace business per se, the waste business and the non-aerospace use.

The **aerospace business** is constituted by all units in which the aircraft and their parts keep being utilised with their original purpose, serving air traffic operations. In this area, aircraft components are still certified for airworthiness. This area begins with the design phase, which leads to the manufacturing of the aircraft and its parts. When the parts are completed, they enter the use and maintenance phase. These two phases belong to **M&P**. At some point in their lifecycle, aircraft are decommissioned, therefore entering their **EoL** phase. After decommissioning, aircraft are disassembled, reusing the still serviceable aircraft components as spare parts, and requiring keeping a valid certification or recertifying the component. After disassembling, aircraft are dismantled and the materials are either recycled, used for energy recovery, or go to landfill. The phases covering the time from the decommissioning decision to the **waste business**, belong to the End-of-life. In addition, as a result of the disassembling process, aircraft parts can be employed for alternative reuse and enter the **non-aerospace business**. Another important flow from this area is the production of waste during the operational phase of the aircraft, which will enter the waste business.

As it can be observed in the diagram below, although **M&P** is included in the Aerospace business, it is directly connected and therefore influences EoL, as well as the alternative reuse in non-aerospace markets.

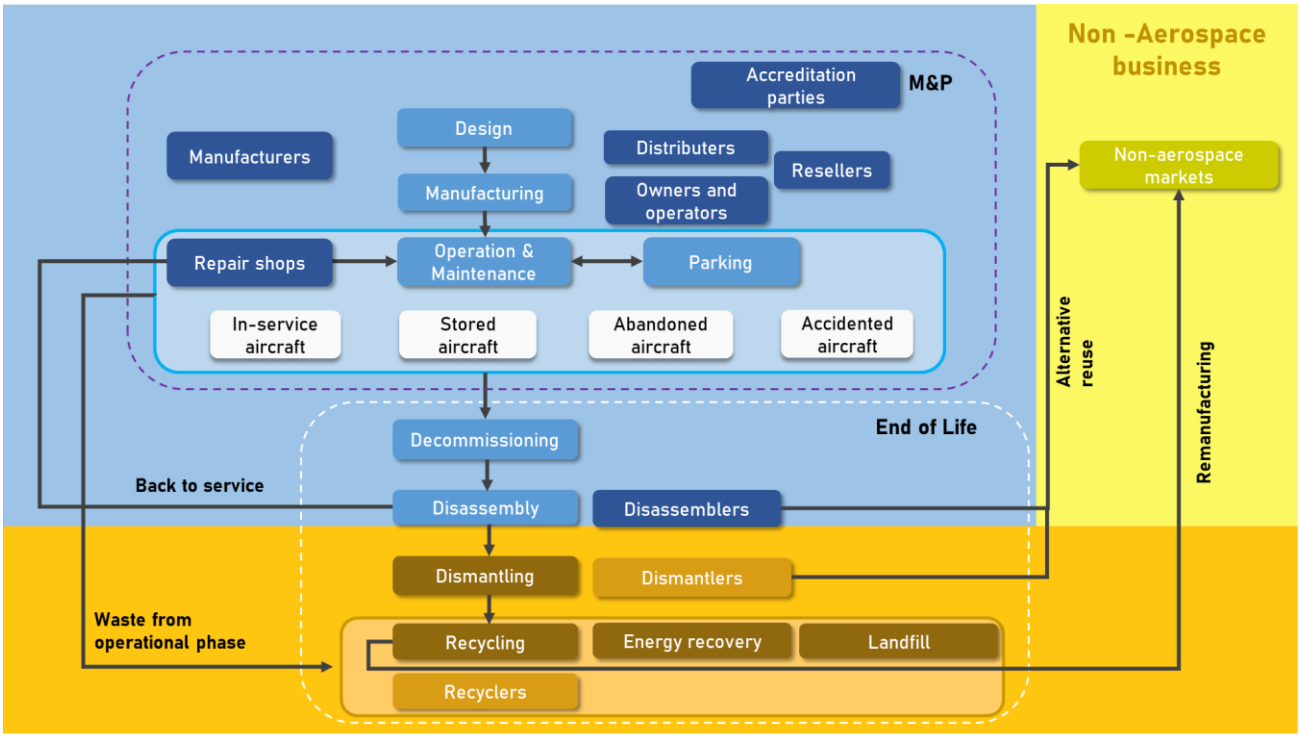

Figure 17. Main areas and units in the aircraft lifecycle (Envisa, 2022)

At some point of the aircraft lives, when the continuation in their use is not economically viable or due to safety issues, aircraft owners take the **decision to decommission** them and prepare them for disassembling. After **disassembling**, parts can be reused and employed as spare parts for other aircraft (still in the aerospace business) or taken to **alternative reuse** in the non-aerospace business, for instance with educational or decoration purposes. The use as spare parts is mainly the case for pieces of equipment (electronic, hydraulic, etc.), whereas the non-aerospace reuse is mostly done for structural parts or cabin furnishing. The decommissioning decision depends significantly on the current value of the engine and landing gear, which are the most valuable parts of an aircraft. The decision to decommission an aircraft depends on the aircraft owner, since they want to get value out of them. In some cases, aircraft are being parted out by their owners to keep their own fleet flying.

Generally speaking, the **EoL stage** has been neglected within the aviation sector. However, due to the increasing number of retired aircraft, there is a need to improve the dismantling process of current aircraft types and the design of new aircraft types to optimise aircraft end-of-life sustainability. A widespread practice at the EoL of aircraft has been the storage in airplane graveyards. This storage often takes place in desert areas where there is enough space and where the climate conditions are favourable for aircraft conservation in view of taking them back into service at a later stage. On average, aircraft not going back into service remain parked for two years after their last flight before dismantling pre-pandemic. The COVID-19 pandemic led to an increase of the number of jets in storage. In the diagram above, the end-of-life phase of aircraft has been identified, which involves the units: decommissioning, disassembly, dismantling, recycling, energy recovery and landfill.

After disassembling, aircraft enter the **waste business**, starting with the dismantling, where they are shredded and their materials are prepared to be either recycled, used for energy recovery, or sent to landfill if none of the previous options are available any longer. From recycling, there is a process of re-entry of materials into manufacturing in other non-aerospace businesses, as it can be the case of recycled metals, for instance. In the waste business we also consider the waste produced during the aircraft operational phase (cleaning and catering cabin waste, and maintenance waste).

The following areas, units and processes can be identified in the aircraft life cycle:

Table 2. Key areas, units, processes, and key stakeholders in the aircraft M&P domain

Areas	Units	Processes	Key stakeholders
Aerospace business	Design	Planification of materials Design for Decommissioning	Manufacturers Certification authorities
	Manufacturing	Aircraft construction Transfer to aircraft owners	Manufacturers Accreditation parties
	Operation and Maintenance	Operational phase Repairs Distribution Reselling	Distributors Resellers Owners and operators Repair shops
	Parking[38]	Ferry flight Storage	Owners and operators Storage facilities
	Decommissioning	Inspection Cleaning Decontamination	Disassemblers
	Disassembly	Parts and materials handling Return of parts to operational use	Disassemblers

[38] The parking phase is not mandatory since the decommissioning decision can also be taken while the aircraft is still in service.

Areas	Units	Processes	Key stakeholders
Waste business	Dismantling	Final draining of the systems Categorisation of materials to waste treatment routes Removal of hazardous materials Removal of parts for non-aerospace use Removal of non-recyclable materials Shredding Transportation of dismantled materials	Dismantlers
	Recycling	Sorting Material recovery	Recyclers
		Remanufacturing	Non-aerospace business manufacturers
	Energy recovery	Conversion of non-recyclable waste materials into usable heat, electricity, or fuel.	Waste management companies
	Landfill	Inclusion of waste into landfills	Waste management companies
Non-aerospace business	Non-aerospace uses	Use of parts for outside of the aviation sector (alternative reuse)	Non-aerospace companies

More information regarding the different areas, units and processes indicated in the table below is given in Subchapters 2.5 and 2.6.

Note: The scope of this report includes worldwide organisations, not being restricted to those covering EU countries. Organisations from Europe (EU, UK, and Switzerland), the US and Canada have been contacted in order to obtain information about their practices and involvement in sustainability practices in their sector.

2.2 New technologies

During the last years, the implementation of renewable energies together with electrification have shown the potential of how emissions can be significantly reduced by the introduction of **new technologies**. Currently, air mobility implies a large use of fossil fuels. Therefore, the integration of sustainable energy sources in the aviation sector represents a challenging and necessary objective to meet the various sustainability goals. The energy transition started with the use of Sustainable Aviation Fuels (SAF), with 52 airports that offer this energy source, continuously or in batches (June 2022)[39]. The importance of this technology was recognised by the second ICAO Conference on Aviation Alternative Fuels[40], indicating that alternative aviation fuels are crucial to the efforts of international civil aviation to reduce CO_2 emissions. The main obstacle to widely implement SAF is economic, since it is not yet available at competitive cost compared to conventional jet fuel[41]. However, the increasing use of SAF, together with the improvement of energy efficiency in aircraft and operations, will not be enough to reach the EU CO_2 emissions reduction targets. Therefore, the introduction to the fleet of aircraft that employ new alternative energy sources e.g., hydrogen, is of great importance. Hydrogen can be used as propulsion fuel for combustion in conventional engines replacing jet fuel, and in fuel

[39] ICAO (2022). Sustainable Aviation Fuels
[40] ICAO (2017). Second ICAO Conference on Aviation Alternative Fuels (CAAF/2)
[41] IATA (2019). Aircraft Technology Roadmap Report

cells for electrical power. Hydrogen is lighter than jet fuel and for the same energy content, its volume, even in liquefied form, is four times larger. Due to its different characteristics, the storage facilities as well as the entire aircraft fuel system must be adapted[42]. In addition, the use of hydrogen in aviation is constrained by its production, which needs to be sustainable as well to consider the whole use as such, and by the requirement of appropriate supply infrastructures. The European Destination 2050 report states that in 2050 net zero CO_2 emissions can be achieved, facilitated by a large contribution from hydrogen-powered aircraft introduced in 2035, followed by SAF usage[43]. Hydrogen is expected to be a fitting solution for reaching sustainable flights, starting with smaller regional aircraft. While hydrogen aircraft do not produce CO_2 emissions during flight, they still cause an impact on climate change, mainly through the energy needed for liquefaction, as well as potentially with the emissions of water vapour that is higher than for kerosene-powered aircraft. The current main challenges for this technology are the storage of the liquid hydrogen and its production from renewable energy sources.

As indicated, an innovative trend that is foreseen to be implemented in the air transport system of the near future are **battery-electric aircraft**. This technology is currently restricted to small aircraft, being in an experimental stage for commercial air transport applications[44]. An example of the application of electric propulsion are the electric vertical take-off and landing (eVTOL) aircraft, such as by Volocopter and Lilium projects. The substitution of jet fuel with electricity can lead to an important reduction of the greenhouse gas emissions from aviation since operations will not produce CO_2 emissions from fuel combustion. It is important however to keep in mind that this reduction will only be achieved from a life cycle perspective if the electricity is obtained from low-carbon sources. An important aspect regarding the sustainability of the use of electric aircraft are the lifecycle impacts of their batteries, which are currently made of lithium mostly. The production of these batteries can lead to several environmental impacts, starting from the mining activities that can produce toxic leakages and air pollution. In addition, toxic chemicals are required as well to process Lithium. In order to be able to meet the global demand, considering the limited availability of Lithium worldwide, the recycling of these batteries is crucial[45].

2.3 Composite materials and structural health monitoring

In comparison with more conventional materials, **aeronautical composite materials** can be typically characterised by excellent mechanical characteristics, lighter weight than comparable metal structures, and high performance[46]. The use of composite materials has allowed designers to overcome barriers present with the use of metals. These materials are essentially constituted of two or more phases, which for aircraft airframe structures are predominantly carbon-fibre reinforced plastics (CFRP). The cockpit and cabin interior contain numerous components that are made of polymers or glass-fibre reinforced plastics. It is also important to note here that cabin interiors are replaced several times during the aircraft lifecycle, therefore producing materials to be treated during their EoL at a much higher rate and giving more importance to the development of techniques to increase the recoverability and recyclability of composites.

Carbon-fibre reinforced polymer composites cannot be recycled by conventional processes designed for metallic alloys. Although **recycling technologies** for these materials have been developed recently, these are not yet readily available at a global scale. Thus, polymers and composite materials are currently generally sent to landfill or incineration. Therefore, organised recycling networks and procedures will be required in the future to include composite wastes.

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[42] ACI (2021). Integration of Hydrogen Aircraft into the Air Transport System

[43] NLR – Royal Netherlands Aerospace Centre (2021), European Destination 2050 report, NLR

[44] ICAO (2021), Aerodrome Design and Operations Panel Working Group Fifth Meeting, Discussion Paper

[45] Doose et al (2021). Challenges in Ecofriendly Battery Recycling and Closed Material Cycles: A Perspective on Future Lithium Battery Generations

[46] Soutis, C., Yi, X., & Bachmann, J. (2019). How green composite materials could benefit aircraft construction. Science China. Technological Sciences

Composite scrap from aviation business can be divided into: wastes originated during the manufacturing process and parts from aircraft EoL. Carbon fibre and epoxy resin are the main elements constituting the composite materials. Unlike the manufacturing scrap, the EoL scrap is quite heterogenous, as it can contain other materials, and can be contaminated with chemicals like paints, solvents, and oil residuals, making the recycling process much more challenging[47].

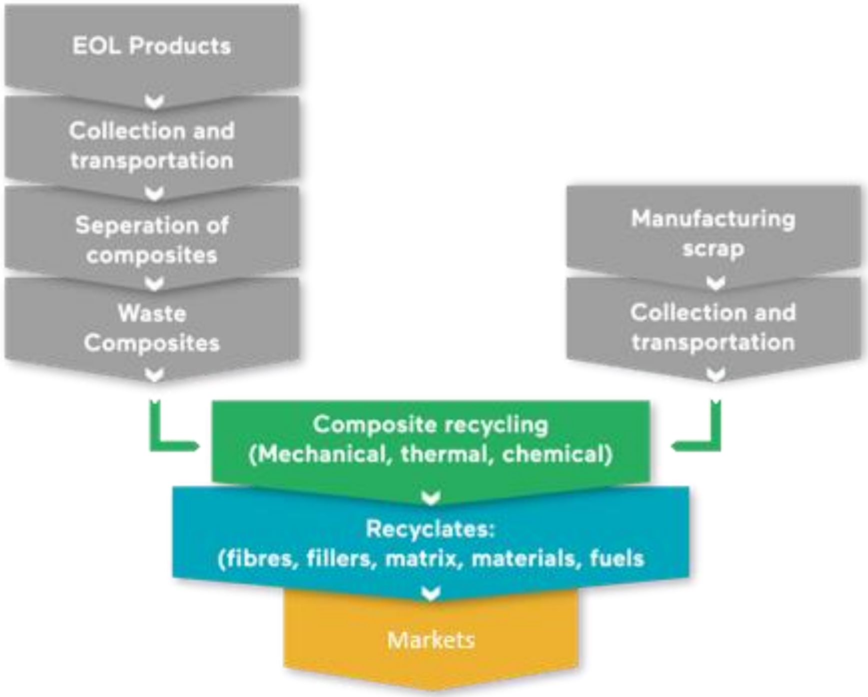

Figure 18. Structure of recycling system for composite materials. Yang et al (2012)[48]

In the following table, a summary of the **types of composites and the recycling methods** is provided (Yang et al, 2012).

Table 3. Composite types and recycling methods

Type of composites	Recycling methods
Thermoplastic-matrix composites	Remelting and remoulding Chemical recycling Thermal processing
Thermoset-matrix composites	Mechanical recycling Thermal recycling Chemical recycling
Metal-matrix composites	Re-melting -casting

Due to the lack of suitable recycling methods for composites until recently, they have not been recycled as much as other materials (as the metals, for instance). Even though recycling methods exist nowadays for these materials, the lack of adequate markets, the high recycling costs, and the lower quality of the recycled material constitute barriers to the application of these processes. To improve this situation, extensive **R&D activities are needed to develop and design better recyclable composites and to improve separation techniques**.

[47] Wong et al. (2017). Composites recycling solutions for the aviation industry
[48] Yang et al. (2012). Recycling of composite materials

As indicated by Schmücker et al. (2021)[49], **digitalisation and data management in aircraft maintenance** is a process that would be beneficial to increase efficiency and reduce obstacles for interoperability. In this paper, the individual process steps for fibre-reinforced composite structures repair are presented, together with the suitable technologies that could be employed to allow the complete digitalisation of the process. The processes considered in this study are event detection, inspection, assessment, and definition of acts, planning and preparation, execution of the repair, and documentation preparation. This digitalisation concept can be used as reference to guide efforts for other maintenance operations, also leading to more sustainable practices, reducing economic and environmental impacts.

Damage to engineering infrastructures is a consequence of loads applied to them, which have to be tolerated from a design point of view. Maintenance is the action that is required to deal with the damage that is caused, and the need for it increases with the age of the structure. Structural health monitoring (**SHM)** has already been identified as a promising maintenance strategy to replace the schedule-based maintenance with traditional non-destructive techniques that require access to the structure and long grounding time. For SHM to make a real impact in the damage tolerant design of composite structures, it needs to be integrated from the design phase of the structure all the way to its EoL.

The current acceptable damage detection method is visual inspection. The application of SHM can enhance the Damage Tolerant Design (DTD) of advanced structures in two ways:

1. Increased reliability of damage detection resulting in condition-based maintenance, optimising the life cycle analysis of the structure and its EoL (sustainability and lower environmental impact),

2. Adjusting the design resulting in lighter structures.

Moreover, by optimising the SHM system (sensor location and number), it can contribute to the integrated vehicle health management (IVHM) concept, which transforms the system data into operational support information, optimising the maintenance and repair strategy for the full life cycle of the structure based on individual aircraft mission profile. SHM can contribute to the digitalisation and data management in aircraft maintenance, also leading to an increase of the sustainability during this phase of the aircraft lifecycle, since the repairs can be targeted to those components and moments when they are required.

Health management techniques enable the determination of the condition as well as predictions about the remaining component lifetime and can contribute to decision-making in surrounding process fields. It is important to note here that the logistic of the spare parts and the inventory management are processes that can greatly benefit from this technology. By introducing SHM techniques, the overall lifecycle impacts of the structures they are included in is lowered, since they optimise the maintenance operations required (which are taken forward when informed as needed by the SHM systems and which can target more efficiently those areas or parts where the repair is necessary) and reduce the exchange of parts required. This results in a lower amount of waste from aircraft structural material, both aluminium and composite.

[49].Schmücker et al. (2021). Digitalization and data management in aircraft maintenance based on the example of the composite repair process

2.4 Sustainability initiatives affecting aviation

2.4.1 Standards and regulations

2.4.1.1 Aviation-specific

2.4.1.1.1 EU-Specific

Rules for Continuing Airworthiness[50]

Part M concerns specifically the continuing airworthiness of aircraft and aeronautical products, parts, and appliances together with the approval of organisations and staff involved in these tasks. Part M is presented as two sections, Section A (called the "Technical Requirements") is applicable to industry, and Section B ("Procedure for Competent Authorities") is applicable to the Regulator – Competent Authority. Each Part M organisation nominates a Continuing Airworthiness Manager (CAM) who is responsible for the Continuing Airworthiness Management Organization (CAMO) following the Regulatory requirements described in Part-M.

EASA Part 145 approval is a company level certification to the European Commission Regulation standards of design, production, maintenance, and operation of aircraft components. An aircraft component is described as any product, part, or appliance installed in European Aircraft. This approval allows organisations authorise certain competent individuals to certify aircraft maintenance tasks and checks within the scope of the approval granted to the organisation. This approval also allows the organisation to disassemble the parts.

EASA Part 21 Subpart G describes the requirements and procedure for approval of organisations which manufacture aircraft parts and appliances in conformity with approved data. The production organisation certifies and releases the product on either Form 52 for a complete aircraft or EASA Form 1 for components. Part 21 Subpart G Organisations are required to hold a Product Organisation Exposition (POE) which includes the structure of the organisation, identify the capability, and reference the procedures within the POE.

Part-147 delivers the regulations governing a Maintenance Training Organisation responsible for either Basic or Type Training for Part 66 Engineers. Part-66 is the regulation governing a common European aircraft maintenance license recognised in all EASA member states.

Part-T is applicable to aircraft registered in a third country (non-EU) and whose oversight has not been delegated to a Member State. It concerns the airworthiness management of aircraft which are leased for a short term (less than 7 months)

Part -ML simplifies existing maintenance rules and offers a less prescriptive approach to maintenance programmes, airworthiness reviews, defects deferments and Time Between Overhauls (TBO) extensions.

Part-CAMO contains the requirements to be met by an organisation to manage the continuing airworthiness of an aircraft and its components for installation.

EASA Part -CAO (Combined Airworthiness Organisation Regulatory Obligations) applies to independent entities that specialise in the airworthiness management (and/or aircraft maintenance) of non-complex aircraft.

[50] EASA (2022). Easy Access Rules for Continuing Airworthiness (Regulation (EU) No 1321/2014)

Regulation (EU) 2018/1139 [51]

The **Regulation (EU) 2018/1139** of the European Parliament and of the Council of 4 July 2018 on common rules in the field of civil aviation and establishing a European Union Aviation Safety Agency indicates in its Article 87, dedicated to environmental protection, that in order to inform interested parties and the general public, the Agency shall, at least every three years, publish an environmental review, which has to provide an objective account of the environmental protection status relating to civil aviation in Europe.

2.4.1.1.2 Non-EU

ASA-100 quality system and FAA AC00-56

In 1996, the FAA published Advisory Circular (AC) 00-56, titled, "Voluntary Industry Distributor Accreditation Program". The purpose of this Advisory Circular was to describe an accreditation system for civil aircraft parts distributors based on voluntary industry oversight and provide information useful for developing an accreditation program. The Aviation Suppliers Association assisted the FAA in writing AC 00-56, and later developed its own quality system standard, **ASA-100**[52]. The ASA-100 Quality System Standard has since become the main quality system standard under the scope of FAA AC-0056. The ASA-100 quality system standard includes best management practices for the auditing, facilities, training, procurement, inspections, material equipment, certification, shipping, records etc. This standard shows a similar approach to the one contained in the AFRA BMP, but in this case focused on the aviation suppliers. Thus, its contribution is relevant to cover aviation suppliers.

UK Environment Agency Regulatory Position statement 164.

The UK Environment Agency released a Position Statement[53] regarding the removal of airworthy parts from waste aircraft. This position statement included a series of requirements that, if followed, would allow the removal of parts from an aircraft that is waste without an environmental permit.

Aircraft are considered waste when the decommissioning decision is taken (when it is decided that they will not fly again and after the last ferry flight to the dismantling facility). When this happens, the removal of its parts requires a special permit for waste recovery. However, in practice, the process they have to go through to recover the parts that are still serviceable is not different from the one that parked aircraft will experience. For this reason, the UK Environment Agency released a Position Statement that eliminates the requirement to have the special permit for waste recovery under the conditions indicated below:

- The aircraft remains under a care and maintenance programme by a Part 145 organisation
- The only parts/materials removed are:
    - Parts specifically requested by the aircraft or part owner
    - Parts or materials that must be removed to enable the aircraft to be stored safely or for a specified part to be recovered. Parts and materials that are not for re-use will be waste and must be stored, recycled, or disposed of appropriately
    - Parts from military aircraft required to be removed for security reasons.
- Advice is followed on legal responsibility and good environmental practice set out in the UK Environment Agency pollution prevention guidelines.
- The relevant objectives of the Waste Framework Directive are met:

[51] European Parliament and Council (2018). Regulation (EU) 2018/1139 of the European Parliament and of the Council of 4 July 2018 on common rules in the field of civil aviation and establishing a European Union Aviation Safety Agency, and amending Regulations (EC) No 2111/2005, (EC) No 1008/2008, (EU) No 996/2010, (EU) No 376/2014 and Directives 2014/30/EU and 2014/53/EU of the European Parliament and of the Council, and repealing Regulations (EC) No 552/2004 and (EC) No 216/2008 of the European Parliament and of the Council and Council Regulation (EEC) No 3922/91

[52] ASA Accreditation Program

[53] Environment Agency (2014). Regulatory Position Statement 164. The removal of airworthy parts from waste aircraft

"…Ensuring that waste management is carried out without endangering human health, without harming the environment and in particular:

- *(i) without risk to water, air, soil, plants, or animals*
- *(ii) without causing a nuisance through noise or odours; and*
- *(iii) without adversely affecting the countryside or places of special interest."*

2.4.1.1.3 ICAO

ICAO Annex 16

ICAO has developed nineteen Technical Annexes to the Convention on International Civil Aviation (also called Chicago Convention) which are applied universally to produce a high degree of technical uniformity within international civil aviation.

Annex 16[54]: Environmental Protection is constituted by four volumes:

- Volume I – Aircraft Noise
- Volume II – Aircraft Engine Emissions
- Volume III – Aeroplane CO_2
- Volume IV – CORSIA

Volume I describe the noise certification standard, indicating the aircraft noise certification procedures, the noise measurement for monitoring purposes, the assessment of airport noise and the balanced approach to noise management. Volume II, on the other hand provides the description of the emissions certification and the non-volatile particulate matter assessment for inventory and modelling purposes. Aeroplane CO_2emissions standard is explained in Volume III, based on the fuel consumption. Finally, volume IV includes the description of the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA).

Therefore, **ICAO Annex 16** and its volumes contribute to the achievement of sustainability in aviation, since they help to mitigate noise, emissions, and CO_2 from a certification point of view. Annex 16 does not contain indications on aircraft EoL; however, CAEP WG2 (Airports and Operations) carried out a study on the state-of-play in aircraft end-of-life during the CAEP/11 cycle (2016-19).

2.4.1.2 Non-aviation specific

2.4.1.2.1 EU-specific

EMAS[55]

EMAS is an EU voluntary environmental management tool for companies and organisations that has the aim to evaluate, report and improve their environmental performance. The central element of the EMAS is the establishment of an Environmental Management System (EMS). This system allows organisations to structure procedures to assess and improve their environmental performance. If organisations follow appropriately the EMAS requirements, they can be EMAS-registered. EMAS requirements include:

- Compliance with all environmental legislation, which has to be reviewed by a verifier and a public authority.
- Continuous improvement of the environmental performance.
- Verification of the performance by a specifically trained verifier.
- Publication of key environmental data in an annual report.

EMAS contributes to the sustainable development together with other additional tools, such as the EU Ecolabel and Green Public Procurement (GPP). EMAS-registered organisations commit to reduce their

[54] ICAO (2022). Annex 16 - Environmental Protection
[55] European Commission (2022). EMAS

environmental impacts, from energy and water consumption to waste generation. Thus, EMAS is linked to several types of environmental policies:

- Biodiversity
- Energy efficiency
- Hazardous substances
- Climate change mitigation
- Air and water pollution
- Waste management

In addition, EMAS is linked to wider policy areas that directly contribute towards sustainability, such as:

- Corporate Social Responsibility (CSR)
- Circular economy
- Eco-design and eco-labelling
- Green Public Procurement
- Sustainable supply chains
- Green Finance

As we can see, EMAS holds similarities with ISO 14001. However, **EMAS includes added value in comparison with ISO 14001**. EMAS is seen by verifiers as more reliable than ISO 14001 when it comes to ensure legal compliance. In addition, it includes higher transparency, since organisations are required to publish an annual report on their performance (RAVE Study, 2017[56]). Moreover, EMAs shows other higher standards, such as:

- Stricter requirements for the measurement and evaluation of environmental performance against objectives and targets, and the continuous improvement of that environmental performance.
- A strong involvement of the personnel.
- Registration by a public authority after the verification by an accredited environmental verifier specially trained to use or promote EMAS.

Table 4. Main differences between EMAS and ISO 14001 (EC, 2011)[57]

Elements	EMAS	ISO 14001
Legal status	Regulation (EC) No 1221/2009 ("EMAS III")	International, commercial standard under private law
Participation	Voluntary	Voluntary
Geographical outreach	Global	Global
Focus and objective	Continual improvement of environmental performance of an organisation	Continual improvement of environmental performance of an organisation
Environmental aspects	Comprehensive initial environmental review on the status of activities, products, and services	Requires only a procedure to identify environmental aspects Initial review is recommended, but not required.
Legal compliance	Proof of full legal compliance is required	Only commitment to comply with applicable legal requirements No compliance audit

[56] EU (2018). Reinforcing Added Value for EMAS (RAVE)
[57] European Commission (2011). EMAS - Factsheet. EMAS and ISO 14001: complementarities and differences

Elements	EMAS	ISO 14001
Employees involvement	Active involvement of employees and their representatives	Not required (ISO 14001 and EMAS booth foresee training for employees).
Suppliers and contractors	Influence over suppliers and contractors is required	Relevant procedures are communicated to suppliers and contractors
External communication	Open dialogue with external stakeholders is required External reporting is required on the basis of a regularly published environmental statement.	Dialogue with external stakeholders not required External reporting is not required
Internal environmental auditing	EMS audit Performance audit to evaluate environmental performance Environmental compliance audit	Includes only the Environmental Management System audit of the requirements of the standard
Verifier/Auditor	Environmental verifiers are accredited/licensed and supervised by governmental bodies Independence of the environmental verifier is required	Certification bodies are accredited through a National Accreditation body Independence of the auditors is recommended
Audits	Inspection of documents and site visits to be carried out according to Regulation Check for improvement of environmental performance Data from environmental statement needs to be validated	No certification rules in standard (other standards for auditing and certification) Check of Environmental Management System performance, but no frequency specified or required.
Derogations for SMEs	Extension of verification intervals from three to four years Updated environmental statement needs to be validated only every two years (instead of every year) Environmental verifier considers special characteristics of SMEs	No derogations foreseen
Official registration by authorities	Publicly accessible register records each organisation Each registered organisation receives a registration number	No official register
Logo	Yes	No

EMAS is compatible with other management systems, whether Environmental such as ISO 14001, quality, like ISO 9001, or Workplace Health and Safety (ISO 45001).

EU taxonomy for sustainable activities

To be able to meet the EU climate and energy targets for 2030 and reach the aims of the EU Green Deal, direct investments are required towards sustainable projects and activities. To be able to allocate these fundings in an efficient and effective manner, a common language and a clear definition of sustainability is needed. This is the reason why the Action plan on financing sustainable growth called for the elaboration of a common classification system for sustainable activities – the "**EU Taxonomy**"[58]. The EU taxonomy is a classification system that establishes a list of environmentally sustainable economic activities. In this way, the list can create security for investors, since they can reliably know which activities are sustainable and shift their investments to the areas that are most needed.

The taxonomy regulation entered into force on 12 July 2020 and creates 4 overarching conditions that an economic activity needs to meet to qualify as environmentally sustainable. To be classified as a sustainable economic activity according to the EU taxonomy regulation, a company needs to not only contribute to at least one of the environmental objectives, but also to not violate any of the remaining ones. The classification of an economic activity in terms of sustainability is based on the following four **criteria**:

1) The economic activity contributes to one of the six environmental objectives
2) The economic activity does "no significant harm" to any of the six environmental objectives
3) The economic activity has no negative social impact
4) The economic activity complies with the technical screening criteria developed by the EU Technical Expert Group

The taxonomy regulation establishes six **environmental objectives**:

1) Climate change mitigation
2) Climate change adaptation
3) Sustainable use and protection of water and marine resources
4) The transition to a circular economy
5) Pollution prevention and control
6) The protection and restoration of biodiversity and ecosystems

The EU taxonomy is therefore designed primarily to be used as a tool for sustainable investment, helping investors understand more clearly where companies stand in relation to the others. It also plays an important role helping to guide business decision-making.

EU Waste Framework Directive and European List of Waste

The **EU Waste Framework Directive**[59] sets the basic concepts and definitions related to waste management, including the definitions of waste, recycling, and recovery. In addition, it sets the basic waste management principles, indicating that waste has to be managed without endangering human health nor endangering the environment, without any risks to water, air, soil, plants, or animals, without causing nuisances through noise or odour, and without adversely affecting the countryside or places of special interest. It includes the concepts of the "extended producer responsibility," reinforces the "polluter pays principle" and distinguishes between waste and by-products. It is based on the "Waste hierarchy" concept, which establishes the order of preference for managing and disposing of waste.

[58] European Commission (2022). EU taxonomy for sustainable activities

[59] European Parliament and Council (2008). Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives

Figure 19. Waste hierarchy (Envisa, 2022)

Moreover, **targets are included as part of this Directive**, for instance, preparing for re-use and recycling of municipal waste shall be increased to a minimum of 55%, 60% and 65% by weight by 2025, 2030 and 2035, respectively. The Directive provides additional labelling, record keeping, monitoring and control obligations "from cradle to grave" and bans the mixing of hazardous waste with other categories of hazardous waste, and with non-hazardous ones. More information on the classification of all types of waste can be found in the European List of Waste. This Directive includes the End-of-waste criteria as well, which determine when certain waste ceases to be waste and becomes a product or a secondary raw material. Criteria have been laid down for:

- Iron, steel, and aluminium scrap
- Glass cullet
- Copper scrap

Therefore, the European Waste Framework Directive provides the main regulatory reference within the EU to be considered in the waste business side of aircraft life cycle. The European **List of Waste** provides a common ground to classify waste across the EU. Codes are given to various activities, including the transportation of waste, installation permits or as a basis for waste statistics, therefore helping the waste management (including hazardous waste as well). This List is revised regularly, and a guidance document is available to help organisations to implement it correctly.

***Directive 2000/53/EC*[60]**

The **Directive on end-of-life vehicles** (ELV Directive) sets targets for End-of-Life vehicles and their components. Furthermore, it forbids the use of hazardous substances when manufacturing new vehicles, except in situations in which there are no adequate alternatives. The main objectives of this Directive are:

- To prevent and limit waste from EoL Vehicles and their components
- To improve the environmental performance of all economic operators involved in the life cycle of vehicles.

[60] EC (2000), Directive 2000/53/EC of the European Parliament and of the Council of 18 September 2000 on end-of life vehicles

The ELV Directive follows a circular economy approach that encourages eco-design, aims to eliminate the use of hazardous substances in the vehicles, and establishes high reuse/recycling and recovery targets. It also includes reporting obligations for Member States.

Another important aspect of this Directive is that manufacturers, importers, and distributors must provide systems to collect the End-of-Life Vehicles and, where technically feasible, the used parts from repaired passenger cars. Producers are required to meet a significant part of the costs involved in the delivery of the vehicles to the waste treatment centres. This relies on the value of the scrap metal and components removed for reuse to cover the costs.

The Commission is currently reviewing the ELV Directive and expects to present a legislative proposal for the review of the Directive in 2022.

This Directive, however, does not cover aircraft, only road vehicles.

REACH

REACH[61] is a regulation of the European Union, with the aim to improve the protection of human health and the environment from the risks that can be posed by chemicals, at the same time it fosters the competitiveness of the EU chemicals industry. Another important objective it has is to promote alternative methods for the hazard assessment of substances to reduce the number of tests on animals.

REACH applies to all chemical substances, therefore it has an impact on most companies in the EU, and of course a direct impact on aviation, since there are many chemical substances involved in the whole life cycle of the aircraft.

REACH creates procedures for the collection and assessment of the information on the properties and hazards of substances. Companies need to register the substances they produce, working together with the other companies that register the same substance. Registrations are checked by the National Authorities and the ECHA scientific committee.

REACH has an impact on a wide range of organisations among various sectors. In general, two main roles can be differentiated:

- For chemicals manufacturers, who must register their products and inform about their characteristics.
- Downstream users. Most companies do use chemicals; therefore, they need to check their obligations if they handle any chemicals during industrial or professional activities.

Since the use of chemical substances happen at all phases of the aircraft lifecycle, this regulation is of very high importance in the aviation sector, affecting its sustainability, since it has environmental, economic and safety implications. In particular, it is relevant for the selection of materials and chemicals used in aircraft manufacturing, as well as for the rules of disposal of hazardous substances occurring in decommissioned aircraft.

[61] European Parliament and Council (2006). Regulation (EC) No 1907/2006 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 18 December 2006 concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH), establishing a European Chemicals Agency, amending Directive 1999/45/EC and repealing Council Regulation (EEC) No 793/93 and Commission Regulation (EC) No 1488/94 as well as Council Directive 76/769/EEC and Commission Directives 91/155/EEC, 93/67/EEC, 93/105/EC and 2000/21/EC

2.4.1.2.2 Non-EU

ISO 14001

Environmental management systems help organisations identify, manage, monitor, and control their environmental issues in a holistic manner. Other ISO standards use a high-level structure as well, thus allowing the integration of all of them for the same organisation.

ISO 14001 sets the criteria for environmental management systems and can be certified to. It creates the framework that a company or organisation can follow to achieve a reliable environmental management system. The main goal of these criteria is to assure that the company management and employees of the company or organisation are measuring the environmental impact and work towards the improvement (reduction of negative impacts with the aim to avoid them when possible). ISO 14001 can be employed for organisations of all types and sizes and requires them to consider all environmental issues relevant to its operations, such as air pollution, water and sewage issues, waste management, soil contamination, climate change mitigation and adaptation, and resource use and efficiency.

As it is the case for all the ISO management standards, ISO 14001 aims to achieve continual improvement. Moreover, it helps to demonstrate compliance with current and future statutory and regulatory requirements, increase the confidence of the involved stakeholders, and helps to obtain competitive and financial advantages from the reduction of costs and the efficiency improvements driven by the reduction of environmental impacts. Due to its flexible nature, ISO 14001 can be applied equally to the aviation business, targeting any organisation within it. It is also important to mention that ISO 14001 highlights the relevance of the use of a life cycle approach (therefore being linked to LCA) and to the communication with stakeholders.

There are as well other standards in the **ISO14000 family**[62] that complement ISO 14001. Those are:

- ISO 14004[63], which provides guidance on the establishment, implementation, maintenance, and improvement of an environmental management system and its coordination with other management systems.
- ISO 14006[64], that helps to integrate eco-design into other management systems.
- ISO 14064-1[65], that includes the principles and requirements that are needed at an organisational level for the quantification and reporting of GHG emissions and their removal.

ISO 9001, AS9100, AS9110 and AS9120

The **ISO 9000 family**[66] is a set of standards that helps organisations to meet customers and other stakeholders needs in terms of statutory and regulatory requirements related to products or services, dealing with the fundamentals of the quality management systems. The seven quality management principles are: customer focus, leadership, engagement of people, process approach, improvement, evidence-based decision making and relationship management.

ISO 9001[67] is the international standard that specifies requirements for a quality management system. Organisations use this standard to demonstrate their capabilities to consistently provide products and services that meet customer and regulatory requirements. Any organisation can adhere to ISO 9001 standards to organise their processes, improve their efficiency and to continually improve their methodologies. Therefore, they are applicable to any of the stakeholders involved in the entire aircraft life cycle. Even though ISO 9001

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[62] ISO (2022). ISO 14000 Family
[63] ISO 14004:2016. Environmental Management Systems. General guidelines on implementation
[64] ISO 14006:2020. Environmental Management Systems. Guidelines for incorporating ecodesign
[65] ISO 14064-1:2018. Greenhouse gases. Part 1: Specification with guidance at the organization level for quantification and reporting of greenhouse gas emissions and removals
[66] ISO (2022). ISO 9000 Family. Quality Management
[67] ISO 9001:2015. Quality Management Systems. Requirements

is not linked with environmental impacts, it does have principles that influence the sustainability of the organisation where it applies, as the engagement of people (linked with the social pillar of sustainability), or the improvement, which can be used to guide the evolution to circular economy.

There are three **ASD standards**, which are typically mutually exclusive: AS9100 for Design, Develop or Manufacture, AS9110 for aircraft maintenance and organisations, and AS9120 for ASD distributors of components like electronics and hardware. **AS9100**[68] is a standardised quality management system developed for the aerospace industry. It was created by the International Aerospace Quality Group. It fully incorporates the current version of ISO 9001 and adds requirements related to quality and safety. Major aerospace manufacturers and suppliers request compliance or registration to AS9100 as a requisite to do business with them.

ISO 19011

ISO 19011[69] is an international standard that provides guidelines to management systems auditing. The standard contains guidance on managing an audit program, the principles of auditing, and the evaluation of individuals responsible to manage and audit the programs. While both ISO 9001 and ISO 19011 aim at building effective management systems, ISO 19011 focuses on management systems in general, while ISO 9001 focuses on quality management systems.

ISO 50001

The **ISO 50001**[70] standard focuses on energy management, with the aim to save energy and to reduce greenhouse gas emissions worldwide. It establishes and implements standardised, process-based energy management structures to create sensible and systematic approaches to improve the energy performance of organisations in a sustainable way. Organisations following the ISO 50001 standard can help to establish viable methods to create policies, programs, and culture of energy management in an accurate, repeatable, timely and cost-effective manner. A proper energy management allows organisations to work towards sustainability, since this will directly lead towards less GHGs emissions and therefore mitigating climate change.

Table 5. Comparison of ISO management systems

Content	ISO 50001	ISO 14001	ISO 9001	ISO 19011
Reference for guidelines	Energy consumption of the organisation	Environmental aspects	Clients' quality requirements	Client's management systems requirements
Policy	Energy policy indicating the strategy of the organisation on energy management. The policy provides the framework to set up associated objectives and targets to improve energy performance	Environmental policy indicating how the organisation deals with environmental matters. The policy is expected to include the commitments regarding prevention of pollution, regulatory compliance, and continuous improvement	To meet the clients' requirements	To meet the clients' requirements

[68] AS9100 (2022). What is AS9100?
[69] ISO 19011:2018. Guidelines for auditing management systems
[70] ISO 50001. Energy Management

Content	ISO 50001	ISO 14001	ISO 9001	ISO 19011
Strategy	Conduction of energy reviews to identify relevant energy use activities, set up the energy baseline and decide the energy KPIs. In addition, compliance to relevant regulatory requirements and set up of objectives, targets and implementation plans are required.	Achievement of the environmental regulatory requirements. Need to establish environmental objectives, targets, and implementation plans.	Need to set up quality objectives, targets, and quality management plans	Need to set up management objectives, targets, and quality management plans
Baseline	The energy baseline is the reference to establish the system	No baseline required	No baseline required	No baseline required

Risk management standards

Risk management standards aim to establish a set of strategic processes that begin with the main aspirations and goals of an organisation and try to help to identify the involved risks and promote their mitigation using best practices.

ISO 31000[71], Risk assessment – Guidelines, provides principles, a framework, and a process to manage risk. This standard can help organisations to increase the chances to achieve their objectives, improving the identification of opportunities and threats and helping the effective allocation of resources to treat the risks. This ISO cannot be used for certification processes but provides guidance for internal or external audit programmes.

ASTM Waste Management Standards[72]

Once the aircraft materials reach the dismantling phase, they leave the aviation business, thus being treated as other similar wastes. Therefore, general waste management standards, such as the ASTM ones are applicable to materials that are obtained from the aircraft dismantling process. These standards include tests, practices, and guides addressing medical waste, municipal solid waste, sampling and monitoring, physical and chemical characterisation, site remediation, treatment, recovery and reuse, and processing equipment.

2.4.2 Best Practices Handbooks

2.4.2.1 AFRA BMP

The Aircraft Fleet Recycling Association (AFRA) is a membership-based not-for-profit association promoting global collaboration on aircraft retirement. Companies can be accredited to AFRA's disassembling and recycling standards that ensure the employment of environmental and safety best practices. These are described in **AFRA's Best Management Practice** for Management of Used Aircraft Parts and Assemblies and for Recycling of Aircraft Materials (BMP)[73], which includes recommendations concerning best practices for the management of parts removed from aircraft, engine, or any other asset during the disassembly of the asset at the end of its service life, and for the recycling of aircraft parts and materials.

[71] ISO 31000. Risk Management
[72] ASTM (2022). ASTM Volume 11.04: Waste Management
[73] AFRA (2022). The AFRA BMP

The AFRA BMP includes sections that indicate recommendations for the facility infrastructure, management process, training, documentation and records, tooling, parts and materials management, environmental protection, accountability to the customer, scrapping and aircraft EoL KPIs.

The AFRA BMP Guide is a global voluntary auditable standard that organisations applying for AFRA accreditation need to meet. Aircraft owners can require decommissioning service providers to be AFRA accredited as an option to ensure that their aircraft are retired following strict environment and safety protocols.

2.4.2.2 IATA BIPAD

IATA has developed its **Best Industry Practices for Aircraft Decommissioning** (BIPAD) manual[74], which has the goal of providing guidelines for aircraft owners and operators (being complementary to the AFRA BMP, which focuses on aircraft dismantling and recycling companies) to manage aircraft decommissioning in a sustainable way, while meeting all relevant regulations. The BIPAD manual covers all phases of the aircraft end-of-life process and considers the importance of its multi-disciplinary character. It includes a multi-stakeholder coordination (airlines, AFRA, dismantling and recycling companies, aircraft, and engine manufacturers) and multi-disciplinary process (safety/airworthiness, environment, and economics).

After its first chapter with the background and introduction, it tackles the various aircraft EoL phases: decision to Decommission, selection of facilities, disassembling, dismantling and parts distribution and recertification. In addition, each chapter is subdivided to consider the respective economic, operational, legal, safety-related, and environmental aspects, as it can be observed in the diagram below.

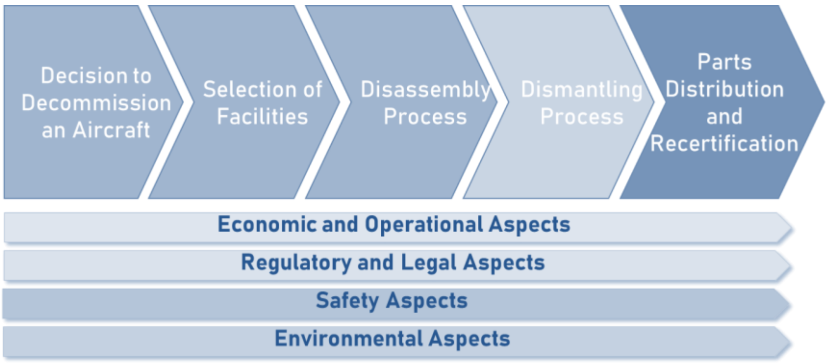

Figure 20. IATA BIPAD Structure

2.4.2.3 IATA Guidance material for the implementation of Paperless Aircraft Operations in Technical Operations (PAO:TO)

This guidance document was published by IATA in 2017[75]. The main benefits of this implementation would be saving long-term costs, the efficient transfer of assets, facilitating airworthiness compliance, and to build and optimise knowledge management.

The Guidance Material and its accompanying "Electronic Signature and Record Keeping Regulatory Checklist" were developed to benefit the industry and to help organisations to achieve paperless operations. It provides ideas regarding new technologies and techniques that can be employed to facilitate more efficient aircraft activities involving technical operations. These operations are constituted by aircraft maintenance activities, parts supply chain and logistics, and the transfer of aircraft assets (aircraft and engine and components).

The vision IATA proposed was that new aircraft and components would directly follow the paperless operations. In-service aircraft would transition to paperless after 2020 and when going through heavy maintenance, shop visit, or Poll event. In this Guidance, Near, medium, and long-term advancements in

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[74] IATA (2018). Best Industry Practices for Aircraft Decommissioning (BIPAD)

[75] IATA (2017). Guidance Material for the implementation of Paperless Aircraft Operations in Technical Operations (PAO:TO)

paperless technical operations were suggested by focus area, covering the whole aircraft lifecycle. These advancements include forms and documents that can be employed to achieve the paperless operations, as well as descriptions of technologies that can support the implementation. The objective of the Guidelines was to provide relevant material to allow organisations to conduct their individual analyses and to then develop their own business cases.

2.4.2.4 IATA Cabin Waste Handbook[76]

This handbook describes the current cabin waste management practices and finds examples of cases in which best practices are already carried out to produce less waste and provide recycling solutions and regulatory compliant disposal. The solutions are brought together as series of actions that airlines and their service partners can take to deliver improvements in this area. The action list per area provided in this handbook can be consulted in the next figure.

Strategy and corporate (S&C)

1. Undertake a cabin waste compliance and characteristics assessment
2. Generate a shared understanding of cabin waste between airlines and regulators
3. Waste resource efficiency strategy guidance
4. Develop a waste resource efficiency strategy
5. Knowing and owning the cost of cabin waste
6. Work with catering companies to reduce over-ordering and food waste
7. Developing cabin waste objectives, targets and pledges

Monitoring and measuring (M&M)

1. Establish a baseline of cabin waste arisings and composition
2. Periodic reporting of cabin waste KPI's
3. Standard cabin waste composition analysis methodology

Reduction

1. Pre-flight food ordering
2. Reduce on-board paper use
3. Improving the passenger experience to minimise cabin waste

Re-use and reinjection (R&R)

1. Food reinjection
2. Food donation

Recycling

1. Develop standard operating procedures for segregation of cabin waste
2. Recycling trolley carts
3. Promote the development of airport material reclamation facilities for cleaning waste
4. Cabin design includes cabin waste handling and management
5. Passenger participation in cabin waste solutions
6. Recyclable material colour coding to enable waste segregation

Disposal

1. Alternative cabin waste treatment and disposal options
2. Safe disposal of sharps

Figure 21. Actions per area in the IATA Cabin Waste Handbook

[76] IATA (2019). IATA Cabin Waste Handbook

2.4.3 Sustainability projects

2.4.3.1 PAMELA-LIFE project

An important project regarding aircraft EoL was the Process for Advanced Management of End-of-Life of Aircraft (**PAMELA**). This project was funded by EU (LIFE05 ENV/F/000059), and it was initiated by Airbus (with partners: SITA (Groupe SUEZ, France), EADS SOGERMA (France), EADS CCR (France and Germany), Préfecture des Hautes-Pyrénées (France) and, in the frame of its ISO 14001 certification and according to its long-term vision, is voluntary setting up references and solutions for its aircraft End-of-Life phase. This project started in 2005 and lasted until 2007.

Due to the already commented expected growth in the number of retired aircraft, the management of their End-of-Life must be addressed in a responsible manner. Airbus joined forces with key partners to draw up and disseminate a process capable of decommissioning and dismantling aircraft in safe and environmentally responsible conditions.

The **objectives of PAMELA- LIFE**[77] were:

- To demonstrate, by full-scale experimentation on aircraft, that 85% of the weight of an aircraft can be recycled, reused, or recovered
- To set up a new appropriate standard for safe and environmentally responsible management of the End-of-Life of Aircraft (ELA). This process will cover all aspects, from storage (d1) (at pre-decommissioning phase) to disassembling (d2), smart and selective dismantling (d3) and recycling or elimination of materials or parts through controlled dedicated processes
- To install, through an efficient, competent, and complementary partnership, international network capable of further disseminating the so-called 3D process (d1, d2, d3[78])

This project involved smart and selective dismantling and valorisation, in which the data collected about the kind of activity, the tools and the means used, as well as the amount of material removed from the aircraft.

The **monitoring** system in place was supplied with data such as time, cutting tools and devices, materials by type and by weight resulting from smart and selective dismantling, consumables. Data were taken from each operation by engineers. This way, the production costs of every secondary raw material from the aircraft could be estimated with accuracy. Every smart and selective dismantling practice performed for the PAMELA–LIFE project on one or more sections was extrapolated to the overall size of the aircraft.

The **data collected** during the project was used to:

- set up dismantling procedures used
- populate a dedicated database and analysed considering manual/mechanical ratio activities
- adapt/choose the dismantling process techniques according to the economic conditions of the market thanks to an interactive software (based on the LME–London Market Exchange)

The project provided the following **benefits**:

- Energy saving for aluminium casting (down by 90% compared to initial)
- Re-use of materials (e.g., aluminium) for aerospace purpose as secondary raw materials
- Saving of material resources by using secondary raw material
- Significant reduction of land filled wastes (down by 66%)
- Environmental Care

[77] European Commission (2022). LIFE Public Database. Process for Advanced Management of EoL of Aircraft

[78] This nomenclature is not to be mistaken with the use of D1, D2 and D3 (with capital letter), which refer to the three main deliverables of this project.

- Ensuring the safety and security of people
- Certifying the required reliability and safety relating to aerospace parts and equipment

2.4.3.2 AiMeRe

The **AiMeRe**[79] (Aircraft Metal Recycling) project was awarded as a result of the Call ID "SP1-JTI-CS-2012- 01-ECO-01-050" ("Metal recycling: Recycling routes screening and design for environment") of the Clean Sky Joint Undertaking (JU), to the consortium formed by ENVISA and Bartin Recycling Group.

The objective of the AiMeRe project is an improved method for recycling aircraft material based on the following:

- Reutilisation of high-grade alloys for suitable industry outcomes
- Profitability of recycling practices
- Enhanced compliance to environmental constraints
- Identification of new recycling routes and opportunities

the main scientific results of the AiMeRe project were:

- Information on the current state of the aircraft recycling industry, current recycling practices and legislative aspects
- Detailed information on aircraft composition both for valuable metals and hazardous waste
- Economically and environmentally improved dismantling and cutting methods
- Economically and environmentally improved sorting and processing methods
- New information on potential fields of application for metal alloys in aircraft industry
- New information on potential fields of application for metal alloys in other industries
- Constitution of an Advisory Group and dissemination activities
- Feedback for Design for Environment activities

The main technical results included:

- State of the art study on the aircraft recycling industry (including aircraft recycling main stakeholders, status of current recycling practices and of guidelines, standards, and regulations)
- Aircraft cartographies for valuable metals and other materials
- Aircraft cartographies for waste
- Assessment of enhanced dismantling and cutting methods
- Assessment of enhanced sorting and processing methods
- Analysis of plugs and connectors (containing gold)
- Study of potential fields of application for metal alloys in aircraft industry
- Study of potential fields of application for metal alloys in other industries
- Recommendations for design for environment and preliminary life cycle assessment of aircraft metals recycling

2.4.3.3 SUSTAINair

SUSTAINair[80] is a project funded by the H2020 programme, which applies circular economy principles to the design, manufacturing, operations, and end-of-life phases of aircraft. This includes:

- Circular design of individual components and joining technologies for airframe construction
- Real-time structural health monitoring of materials and joints during operations

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[79] European Commission (2022). EU Research results. Aircraft Metal Recycling
[80] SUSTAINair (2022). Project website

- Improved maintenance and repair technologies to extend aircraft lifetime
- Automated dismantling robotics for improved recovery of high-quality recycling materials

This project aims:

- To reduce mass, improve fuel consumption and reduce emissions, thanks to the use of multi-material design philosophy with novel metal alloys and composite materials.
- To increase aerodynamic efficiency and maintain aircraft safety, SUSTAINair´s integrated sensor technology is aimed to allow real-time, onboard damage diagnostics for SHM.
- To introduce industrially viable flexible wings with morphing capabilities.
- To lower the production of waste incurred during the manufacturing and EoL processes, with the use of novel up- and recycling methods for both metal and composite aviation materials. Upcycling solutions will also be developed for carbon- and glass fibre thermoset materials, as well as high-performance thermoplastic composites.

2.4.3.4 Alternative reuse projects

Alternative reuse involves the transformation of aircraft EoL parts into added-value products outside the aerospace sector. This process increases the aircraft recoverability and fosters circular economy, by encouraging the reuse of parts that are more difficult to recycle. A good example of alternative reuse projects is the one carried out by Bombardier, the University of Montreal and the Consortium for Research and Innovation in Aerospace in Québec, which was named "Eco-design of products." This project proposes conceptual designs with an integrated life cycle approach while using EoL aircraft parts. The key criteria to be considered in the proposed concepts were the complexity to use EoL aircraft parts in new industrial products, establishing a bank of ideas, recognising the environmental benefit derived from the alternative reuse, and the communication of the sustainability benefits to the public. This project provided insights on how the alternative reuse leads to lower environmental impacts than recycling. Examples of the alternative reuse items considered were a bicycle, a leather jacket, and a wall clock[81]. Some projects have been launched to increase the recyclability of carbon waste. For instance, Airbus has created an alternative reuse project to employ recycled carbon waste from aircraft EoL to produce bicycles[82]. Another example is a project launched by Boeing to recycle composites left over from production to be employed in cars and consumer goods[83].

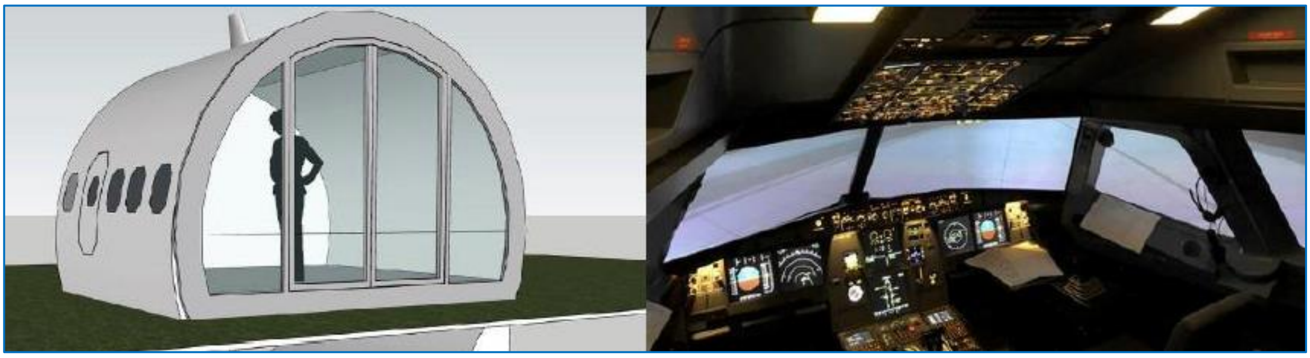

Figure 22. Alternative reuse of cabin sections and cockpit (courtesy of Aerocircular)

When using aircraft components and sections for alternative reuse, the priority is to preserve the form and function, therefore preserving the value to the highest. **Examples of re-purposing** of components and sections are the use of cockpits for simulators and floor panels for staging, for instance.

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[81] IATA (2018). Best Industry Practices for Aircraft Decommissioning (BIPAD).
[82] Airbus (2021). From aircraft to bikes, Airbus is breaking away to upcycle carbon waste.
[83] Boeing (2018). Boeing, ELG Carbon Fibre find new life for airplane structure material in ground-breaking partnership.

Figure 23. Use of panels for staging (courtesy of AeroCircular)

On the other hand, when form and function cannot be kept, the focus is to preserve the material properties. **Examples of keeping the material properties** are:

- Upcycling of aircraft Aluminium and Titanium. In this case, it is important to keep the metals in aero grade. This is only possible when creating volume and scale with several recyclers therefore making worth for them the process of segregating parts of different alloys., Otherwise, the aluminium loses its aero grade, and it is instead used in other sector's streams.
- Upcycling of tire rubbers.
- Upcycling of valuable critical raw materials in jet engines (Co, Ni, Re, Pt).

2.4.3.5 AFRA Aircraft EoL KPIs

AFRA included in the Revision 5.0 of their Recycling Practice Guide and Minimum Standards KPIs that can voluntarily be employed by facilities. **KPIs targeting the different aircraft EoL areas** are included. The project to develop these KPIs was carried out by **Envisa**, and followed the steps indicated in the figure below.

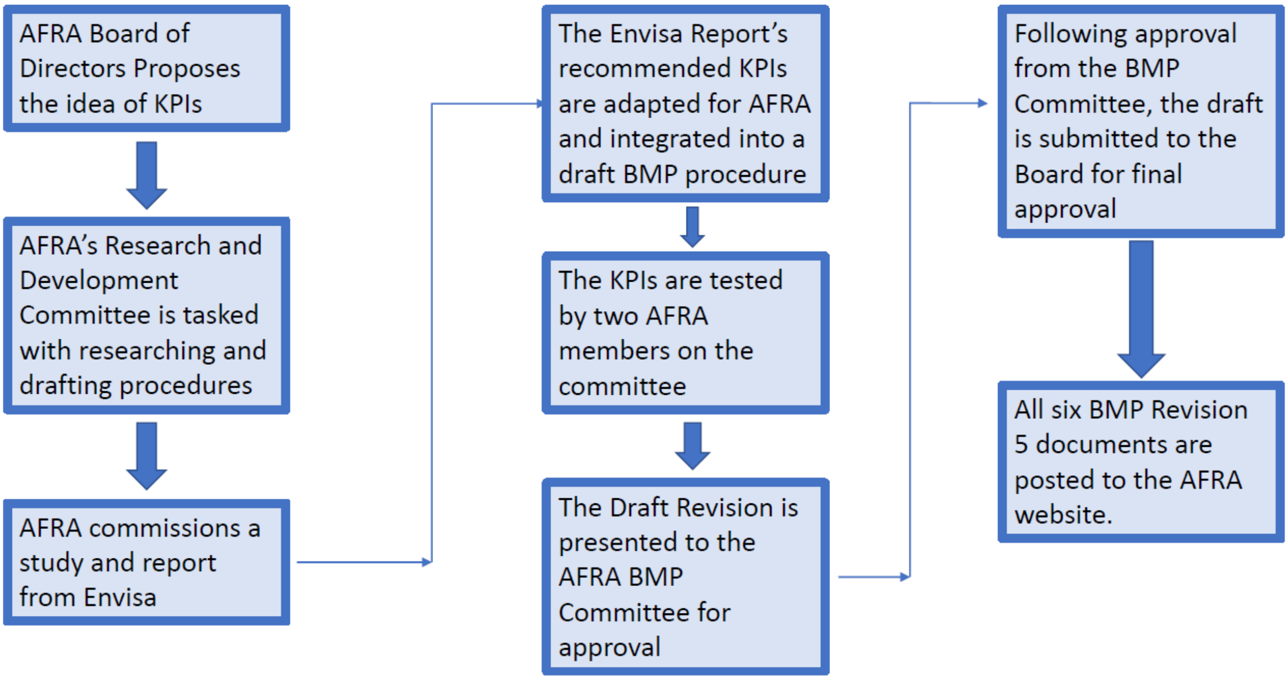

Figure 24. AFRA EoL KPIs revision process. (AFRA,2022)

A step-by-step approach starting from a simple data collection system to more advanced is presented, portraying different levels of data requirements. This approach has the aim to allow facilities to start contributing to the data acquisition from the most basic approach and then be able to refine the data acquisition progressively. In the next Table, the four levels and their KPIs are indicated.

Table 6. AFRA EoL KPIs per level

Bronze	Silver	Gold	Diamond
Number of parts reused Recyclability rate	Number of parts reused Recyclability rate Total waste Total hazardous waste Core disposal rate	Number of parts reused Recyclability rate Total waste Total hazardous waste Core disposal rate Reusability rate	Number of parts reused Recyclability rate Total waste Total hazardous waste Core disposal rate Reusability rate Energy recoverability rate

To achieve the Diamond level, individual KPI data must be clearly derived from and attributable to a serialized asset, such as an aircraft MSN, Engine Serial Number or APU Serial Number.

All KPIs are indicated to be measured every two years, or more frequently if desired. For the Diamond level, rather than every two years, the KPI data must be attributable to the asset by aircraft MSN or asset serial number.

2.4.3.6 Design for decommissioning and Eco-design Transverse Activity

More than 80% of environmental impacts of products are determined during the design phase[84]. Due to this, the use of eco-design principles is crucial to diminish the impact of the products during their lifecycle. **Eco-design** involves the integration of environmental considerations at all phases of the product innovation life cycle, using energy efficiently, getting rid of hazardous substances, and ensuring the recyclability and recoverability of the products. An example of the use of eco-design principles, involving Environmental Product Declarations as well is being taken forward by Bombardier[85].

The **Eco-design Transverse Activity** is the part of the Clean Sky programme that focuses on the “cradle to cradle” approach to design, manufacturing, maintenance, and disposal. Eco-design considers the full cycle from idea to EoL disposal of the aeronautical industry’s products and services and revisits every step to maximise environmental performance and reduce the impacts of the air transportation system. One of the core principles of eco-design is to create aircraft that have easy-to-separate fractions, therefore making the dismantling process easier to carry out. Also, in line with the ease to separate the fractions is the use materials mapping in aircraft. This way, dismantlers can obtain detailed information regarding the locations of the different materials in the aircraft, facilitating the dismantling and further recycling process as well.

Applications are being developed which apply eco-design approaches for the airframe, engine, and system components. In the core of these approaches is the **use of LCA**, which allows to estimate the environmental impacts during each of the steps of the aircraft lifecycle. In addition, as part of this activity, Life Cycle Inventory Data about varied materials and processes is being gathered to be able to employ it in future applications.

2.4.3.7 Catering waste study (Iberia group)[86]

The Life + Zero Cabin Waste project, headed by Iberia and with the participation of Gate Gourmet, Ferrovial, Ecoembes and ESCI-UPF, created a **sustainable management model for catering waste**. As a result of this project, more than 2,250 tonnes of packaging from Iberia flights were recycled thanks to this project. The zero-cabin waste project started in 2016 with the classification of the waste that is generated inside the aircraft and included the design of an improved trolley to carry out on-board waste separation and was implemented by 2019 in all flights operated by Iberia. An increase of 42% of the cabin waste weight to be recycled was obtained compared to the data from the time before the project started.

[84] EU Commission (2022). Sustainable Product Policy
[85] Bombardier (2022). Ecodesign
[86] IBERIA (2019). 2019 Sustainability report.

The compartmentalised trolleys make possible to separate the different types of waste. Furthermore, trainings have been carried out within Iberia to increase the awareness of the importance of recycling.

In addition, through this initiative, the airline implemented other initiatives to reduce the waste that is generated on flights, like not using board press and reducing the plastic wrapping on blankets or headphones. All these measures contributed to reduce flight weights and the amount of waste originated per flight.

2.4.4 Other studies

2.4.4.1 Aircraft decommissioning study. SGI Aviation

SGI Aviation published in 2018 a study focused on aircraft decommissioning[87], appointed by IATA. The main objective of this study was to analyse the status of aircraft decommissioning, the mechanisms and operations employed by stakeholders, and to identify the key issues to find best-practice solutions for the sector.

This analysis found three **main drivers of aircraft retirement**:

- Changes in oil prices
- Development of new aircraft models
- Demand for high value components

In addition, it was indicated that aircraft operators focus on internal factors when deciding to decommission an aircraft, such as fleet planning and organisational and technical changes. On the other hand, aircraft owners and part out companies take this decision based on in the market and value of the aircraft, usually when maintenance costs are high. Another factor to be considered in these decisions is that industry believes that aircraft types that have a large number still in service and which have a follow-up model (such as the A320 family) will have a higher demand for disassembly.

Moreover, the **main drivers to select a disassembling facility** were indicated:

- Costs, such as the import tax and ferry cost
- The location of the facility and the climate (in case of storage)
- Capability and credibility of the facility
- The saleability of parts in the market
- Legal protection
- Environmental aspects

The following recommendations and best practices were suggested as beneficial for the industry:

- To establish workshops and guidance materials for aircraft operators and other relevant stakeholders to improve the procedures of aircraft decommissioning.
- To improve the retirement process by creating guidance on how to handle hazardous materials (for instance fuels and oils), new materials (such as carbon fibres) and parts used on aircraft.

Furthermore, **recommendations** were given regarding the interaction between governmental bodies and industry:

- To further explore the usage and requirements of the Incident Clearance Statement (ICS)
- To improve the acceptance level of parts removed from disassembled aircraft
- Increasing uniformity in the major aviation regulatory regimes to allow acceptance of foreign release certificates for new and used parts
- To develop an accurate and comprehensive database that tracks the aircraft status and parts movements.

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[87] SGI Aviation (2018). Aircraft Decommissioning Study. Final report

- To research the feasibility of a Certificate of Retirement (or equivalent) to be employed when an aircraft is retired or disassembled.
- Suggestion to get advice on the governmental restrictions on aircraft age and the environmental issues related to aircraft operations.
- To make a comparison of import tax and sales tax regulations on aircraft and components in different countries to provide insights in these practices and aircraft movements.

2.4.4.2 Circular economy indicators for the aviation industry

Circular economy is a concept that inherently enhances sustainability since it directly reduces the environmental impacts during the lifecycle of a product and reduces economic costs. Therefore, the use of circular economy indicators is useful for the determination of the performance of a system from a sustainability point of view. **Circular economy indicators for the aviation industry** can be set covering the various phases of the aircraft lifecycle. In the following table, a preliminary list of indicators to evaluate the circularity of the aviation industry are shown (Ecorys, 2019)[88]. These indicators cover the lifecycle of the aircraft and are relevant to monitor the sustainability of the aviation system.

Table 7. Aviation industry circular economy indicators

Phase of the lifecycle	Topic	Indicator	Data source
Design	Standardisation	Number of aircraft with EPD	EPD Database
Design	Standardisation	Number of drones with CE Marking	
Design	Concept trade-off	Carbon footprint during production/unit of production	Aircraft/drone manufacturers
Design	Concept trade-off	Carbon footprint during operation/RTK	
Production	Component reuse	Percentage of reusable components from total	Component manufacturers
Production	Energy consumption	Percentage of renewable energy used in aircraft production	Aircraft/drone/component manufacturers
Production	Waste	Percentage of waste collected for recycling per unit of production	Aircraft/drone/component manufacturers/recycling companies
Production	Waste	Percentage waste sent to landfill per unit of production	Aircraft/drone/component manufacturers
Production	Drones' material	Percentage of non-recyclable plastic/material	
Operation	Airline	CO2 per RTK	Airlines
Operation	Airline	Net CO2 saving from European Trading Scheme	EASA
Operation	Airline	Achieved CO2 offset (%)	CORSIA data ICAO
Operation	Airline	Percentage of sustainable aviation fuel (SAF) used	Airlines, IEA

[88] Ecorys, 2019. Methodological Impact Assessment Support on Social Impacts and Circular Economy Indicators. Client: EASA.

Phase of the lifecycle	Topic	Indicator	Data source
Operation	Airport	Airport Carbon Accreditation Level 3+ (pax served, % airports)	ACI
Operation	Airport	Number of carbon accredited airports	ACI
Operation	Airport	Percentage of waste collected for recycling	Airport operators
Operation	Airport	Percentage of waste sent to landfill	Airport operators
Operation	Drones	CO2 per payload/km	
MRO	SHM	% Of aircraft equipped with SHM systems	MRO companies
MRO	SHM	Life cycle extension (%) achieved through operation maintenance strategy	MRO companies
MRO	SHM	Average ratio of maintenance hours and service hours	MRO companies
MRO	Waste	Waste collected for recycling	MRO companies
MRO	Waste	Waste sent to landfill	MRO companies
Phase out	Recycling	Recyclability rate	Recycling companies/AFRA
Phase out	Recycling	Percentage to landfill	Recycling companies/AFRA
Phase out	Recycling	Number of AFRA accredited companies	AFRA
Phase out	Recycling	Metric-tons delivered to recycling facilities	AFRA
Phase out	Recovery	Recoverability rate	Recycling companies/AFRA
Phase out	Disassembly	Average service hours at time of disassembly	NSA, ICAO
Phase out	Disassembly	Average age of aircraft being disassembled	IATA, ICAO, AFRA
Phase out	Reuse	No. of aircraft moving from A-tie to B-tier airline	NSA records
Phase out	Reuse	% Of freighters that are converted aircraft	www.freighter data
Phase out	Service life drones	Average service life of drones	

2.4.4.3 SENASA white paper on aviation sustainability[89]

SENASA's white paper on aviation sustainability has the objective of identifying the research challenges to foster a sustainable transportation system in Spain and contribute to the environmental objectives of the

[89] SENASA (2020). Libro blanco del I+D+i para la sostenibilidad de la aviación en España

sector in Europe and in the worldwide system. In this document, the state of the art regarding the identified areas is indicated, strategic objectives are defined, and action areas are identified.

Three challenges are identified in this white paper, subdivided as well into seven work areas:

Figure 25. Challenges and work areas in the SENASA white paper on aviation sustainability

From these challenges, the second one (Circular economy) is linked to the scope of this project, targeting lifecycle issues and recycling, as well as waste management. The main ambition in this second challenge is to promote the recycling of the aerospace components and set Research and Development as a priority in aviation, based on the circular economy model.

Nine strategic objectives are set as part of the Lifecycle and recycling within the circular economy challenge:

1. To consolidate the growth and competitiveness of the aerospace industry, enhancing its production processes.
2. To reduce the lifecycle costs.
3. To anticipate to future requirements to avoid environmental obsolescence.
4. To increase the participation of Spain into European Research and Development programmes.
5. Reach an 85% of recycled and reused materials and components.
6. To develop recycling methods for composite materials.
7. To foster and make visible the recycling industry in Spain
8. To engage the industry providers in their contribution to circular economy.
9. To include the maintenance operations in the recycling processes.

Moreover, four strategic objectives are set as part of the waste management within the circular economy challenge:

1. To minimise the use of natural resources, especially those that are non-renewable.
2. To limit and control the use of products that require a post-treatment (hazardous and dangerous).
3. To promote the reuse of purified water for uses that are compatible.
4. In the area of Waste Management, to promote the application of the waste hierarchy.

2.5 Analysis of the aircraft lifecycle outside of the waste business

2.5.1 Processes concerned

In this subchapter, the **focus is set on the areas of the aircraft lifecycle that belong still to the aerospace business**. That means that the aircraft and their parts are still employed with their original objectives and applications in the aviation sector. The target of this subchapter is to provide an overview of the status quo, while more information regarding the day-to-day practices and technical culture elements are provided in Chapter 3.

The **areas, units, processes, activities, and stakeholders** corresponding to this part of the aircraft lifecycle are those indicated in the next table. In addition, the uses in the non-aerospace business are also included in, therefore all aspects of the aircraft lifecycle except for the units and processes belonging to the waste sector are part of this subchapter.

Table 8. Areas, units, processes, and stakeholders (focus outside of the waste business)

Areas	Units	Processes	Key stakeholders
Aerospace business	Design	Planification of materials Design for Decommissioning	Manufacturers Accreditation parties
	Manufacturing	Aircraft construction Transfer to aircraft owners	Manufacturers Accreditation parties
	Operation and Maintenance	Operational phase Repairs Distribution Reselling	Distributors Resellers Owners and operators Repair shops
	Parking	Ferry flight Storage	Owners and operators Storage facilities
Aerospace business	Decommissioning	Inspection Cleaning Decontamination	Disassemblers
	Disassembly	Parts and materials handling Return of parts to operational use	Disassemblers
Waste business	Recycling	Remanufacturing	Non-aerospace business manufacturers
Non-aerospace business	Non-aerospace uses	Use of parts for outside of the aviation sector (alternative reuse)	Non-aerospace companies

Therefore, these units constitute the entirety of the M&P domain, as well as the initial phases of the end-of-life and the uses in the non-aerospace business.

In this subchapter we focus on the list of the subprocesses that take place outside of the waste business for each of the areas, units, and processes identified. The definition of areas, units, and processes can be consulted in Subchapter 2.1.

Moreover, **subprocesses** are activities and steps that occur as part of the main processes and that affect the sustainability of the whole aircraft lifecycle. The subprocesses for the identified units can be found in the table below.

Table 9. Subprocesses (focus outside of the waste business)

Areas	Units	Processes	Subprocesses
Aerospace business	Design	Planification of materials Design for Decommissioning	Electricity energy due to office work Wind tunnel testing Flight test campaigns
	Manufacturing	Aircraft construction	Materials extraction Material production Manufacturing Use of production facilities

Areas	Units	Processes	Subprocesses
Aerospace business	Manufacturing	Transfer to aircraft owners	Transportation to the new owner's facilities
	Operation and Maintenance	Operational phase	Cruise flight and LTO emissions LTO and cruise emissions LTO noise Production of cabin waste
		Repairs	Maintenance, repair, and overhaul Production of maintenance waste (e.g., oils)
		Distribution	Transportation of parts and items required for the operation and maintenance phases
		Reselling	Sell of parts that are treated during the maintenance phase
	Parking	Ferry flight	Same as the operational phase subprocesses
		Storage	Minimum maintenance activities Production of maintenance waste
	Decommissioning	Inspection, cleaning, and decontamination	Cleaning, decontamination of hazardous substances, draining of tanks and piping, and implementation of safety procedures
	Disassembly	Parts and materials handling	Physical disassembling process Material diagnosis Removal of parts
		Return of parts to operational use	Recertification
Waste business	Recycling	Remanufacturing	Use of recycled materials as manufacturing input in other sectors
Non-aerospace business	Non-aerospace uses	Use of parts and materials outside of the aviation sector (alternative reuse)	Parts and materials can be used without further processing in other sectors

2.5.2 Maintenance and production

Sustainability aspects (environmental, economic, and social) need to be considered in each of the areas, units, and processes in the aircraft lifecycle, to be able to reach a fully sustainable system. This is a challenging and crucial task that needs to be achieved with the cooperation of all stakeholders involved in the aircraft lifecycle.

It is key to consider **sustainable practices during the operation phase**, for instance, with the development of sustainable alternative fuels and air traffic management solutions that help to increase fuel savings during the aircraft's entire service life. In addition, since the operation phase is the longest considering the whole aircraft lifecycle, it produces large sustainability impacts and thus requires special attention. Several actions help to increase the sustainability of the operational phase, such as:

- Optimising flight routes.
- Using sustainable fuels.
- Compensating net carbon emissions.

- Using modern aircraft technologies (latest aircraft types and contributing to the development of electrical, hydrogen-powered or hybrid aircraft).
- Reducing cabin waste.

The operational impact is by far the largest because of its carbon dioxide emissions. However, in this report we focus on the rest of the areas of the aircraft lifecycle, targeting M&P, aircraft EoL and alternative reuse.

Sustainability practices need to be considered from the very beginning in the **design phase**, selecting the right materials and using them as efficiently as possible during production. Design aspects are crucial, since they affect the environmental performance of the aircraft during its operations, the maintenance, and the recoverability and recyclability of the parts and materials that constitute the aircraft. The concept of designing aircraft with their EoL aspects in mind is named “Design for decommissioning,” which was first realised by Bombardier. It is important then to give priority to the inclusion of circularity and sustainability already in the design phase. It is also significant to note that sustainability practices should be fostered as well in the regular activities and office work of the manufacturing companies, since they also have sustainability implications that, even if they are tangent to the aircraft lifecycle, are still important to control. This can be extrapolated of course to all other stakeholders within the aircraft lifecycle. As it was presented already in this report, the use of Environmental Management Schemes or KPIs can be helpful to achieve these goals.

An important share of the **manufacturing** footprint is produced as part of the energy and resources required for industrial practices. An option to manage the footprint of the industrial operations is to apply environmental management systems, such as ISO 14001. These systems focus on the different areas that lead to the generation of environmental impacts, like the use of energy, production of CO_2, water use, air pollutant emissions and waste production.

Another important action to be taken from design and manufacturing is to establish a **sustainable supply chain**, meaning that the materials selection targets ethical and environmentally friendly options. The supply chain includes all the organisations which the main company interacts directly or indirectly, from the place of origin to the final product user.

During the maintenance phase, waste is generated, and sustainability aspects apply. The airworthiness of commercial aircraft is subject to stringent EC regulation and is regulated by the European Aviation Safety Agency. Particularly, the **maintenance of aircraft and parts including the re-use of parts recovered from decommissioned aircraft** is subject to the requirements of EASA Part M (the management of aircraft maintenance) and Part 145 (the undertaking of aircraft maintenance). All airworthy parts are subject to certification by a Part 145 organisation. Records of maintenance, repair and overhaul are a necessity to maintain the airworthiness of an aircraft. In addition, avionics need continuous upgrades to remain compliant with safety regulations.

More details about the disassembling of aircraft parts and their status that apply to both maintenance and post-decommissioning steps are given below.

2.5.3 Decommissioning and disassembling

Decommissioning and disassembling constitute the **entry into the EoL phase**, being this decision made mainly by economic and safety factors. The main reasons for the retirement of aircraft are:

- increasing operational costs,
- high fuel consumption,
- steady or sudden rises in fuel prices,
- new regulatory requirements such as expensive technology upgrades,
- and difficulties in obtaining spare parts.

When the costs are expected to become excessive, the airline operator or the leasing company owning the aircraft decides to retire the aircraft from its fleet. The average ages when this occurs were reported to be 25–30 years for passenger aircraft and 30–40 years for freighters. It has been reported as well that around 700 aircraft are retired per year in the world. This rate is expected to increase, reaching 11,000 **aircraft retirements** over the next 10 years[90]. However, there is a small but increasing trend of younger aircraft being retired, since dismantling companies indicated that they have recently received several aircraft aged around 15 years or younger for disassembly. This decommissioning decision, as indicated, depends on the moment in which the value of the individual parts of the aircraft is higher than the aircraft itself.

Aircraft that are withdrawn from service do not become waste immediately. Often, **decommissioned aircraft** are **put into storage** under a maintenance programme while it is decided whether they are put back into service or definitively retired. Several months (or years) can pass by before the decision is taken. During this interim period, they may have parts removed from them to support the rest of the fleet of the aircraft owner or for resale. Aircraft are only considered waste when a final **decommissioning decision** is taken and the first cut is applied to the structure, meaning that they will not fly again.

Depending on the circumstances, the intention might be to scrap a decommissioned aircraft, but only after all the valuable airworthy parts have been recovered. This process is known as "**parting out**" the aircraft. On some occasions, an aircraft in a fleet might be retired from service to provide spare parts for the rest, or due to failing a major maintenance check.

The disassembling key points are the physical disassembling process with the equipment and parts removal, the sorting and storage of parts and materials, and the material diagnosis.

Figure 26. Aircraft section after disassembling of valuable parts. (Envisa, 2022)

Although disassembling companies may buy aircraft and then proceed to carry out the dismantling, **disassembling is usually done for the aircraft owners**, who will receive the disassembled parts that have still value and will either reuse them or sell them.

As a **result of the disassembling process**, the following parts and materials categories can be differentiated:

- **Main parts to be reused (Engines, APU, Landing Gears and Components).** These equipment and parts that need (re-) certification for use as spare parts. This reuse is influenced by the availability of the parts records, which determines the value of the part and the possibility to be reincorporated to the aerospace sector.
- **Parts and materials not to be reused** (alternative reuse, recycling, and landfill):
  - **Consumables/expendables (with limited life expired)**, such as fluids, nuts, and bolts (lubricants, hydraulic fluids, chemicals, etc..).
  - **Components for alternative (non-aerospace) use**. For instance, the composite parts of the aircraft, including the fuselage and interior parts, could potentially be employed in other

[90] IATA (2022). Helping Aircraft Decommissioning

industries. Even the whole aircraft or large sections could be used for demonstrators and exhibitions in shows and museums.

- **Materials for recycling**.
- **Unrecyclable materials**, which either destinated to energy recovery or sent to landfill.

Three main types of aircraft components can be identified, depending on their life expectancy[91]:

- Life-limited parts
- Time-controlled components
- Other components

Life-limited parts are components that have a determined period of use that is indicated by the maximum number of operating hours or cycles before the component must be replaced. After the removal, the component shall not re-enter the aerospace business. To protect the value of the life-limited parts, a back to birth history should be kept with its linked supporting documents.

Time-controlled components are those that require periodic removals for restoration, replacement, or quantitative inspection of their performance. These components are usually safety-critical and hold a high value and demand.

On the other hand, there are **other components** which, even though not requiring detailed maintenance records or schedules, are valuable. The tracking of these components will vary among aircraft owners.

The **value of the parts** that are disassembled is determined as well by the supply and demand in the market. This value can be consulted using various online portals. It is estimated that about 80% of the value from retired aircraft is generated from the salvaged engines, provided that their maintenance records are well documented. Other valuable components include landing gears, APUs, electricity generators and avionics equipment. These components are identified, tested, recertified, or overhauled and resold for reuse in second-hand market or returned to the airline company as parts for the remaining fleet. Regarding the interior components, like seats and galley trolleys, these are generally reused in other aircraft. Moreover, in the recent years, increasing trends in the alternative reuse of these interiors (for instance for home or office furniture) have been observed (Wong et al, 2017).

When aircraft components are removed from a decommissioned aircraft with the aim to be returned to the active aviation fleet, they need to follow the **applicable airworthiness standards**. The country of registration of the aircraft to which the part will be installed determines the applicable airworthiness standards. To be able to maximise the remarketing opportunities for components, it is important to know which states recognise each other's airworthiness standards. The four aviation authorities in the major Western commercial aircraft manufacturing countries (FAA, EASA, Transport Canada and ANAC Brazil) have developed together an **airworthiness form** that is recognised by each other under certain conditions. This form is denominated as Authorized Release Certificate (ARC 71), and is alternatively known as:

- Form 1 (EASA)
- Form 8130-3 (FAA)
- Canadian Form 1 (Canada), formerly known as TCCA 24-0078
- SEGVOO 003 (Brazil)

The **level of recognition of these forms** between these four aviation authorities is laid down in the various bilateral agreements between them. If a component needs to be installed in an aircraft registered in a country that does not recognise the current airworthiness certificate of the component, this needs to be recertified according to the airworthiness standards of the respective country in an approved maintenance organisation

[91] IATA (2018). Best Industry Practices for Aircraft Decommissioning (BIPAD).

(according to EASA Part 145, 14 CFR 15, or equivalent) that is authorised to inspect and certify the part or component as airworthy.

Even despite the rigorous system for inspections, there are still parts that re-enter the aviation business while not fulfilling the applicable requirements. These parts are known as **"unapproved parts,"** in contrast with those that do actually fulfil the requirements, which are named "approved parts."

Occasionally, **counterfeit parts** are found, i.e., those unapproved parts that are created deliberately to mislead, pretending to have been produced under approved systems and methods. Counterfeit parts can be as well those that initially had been properly produced, but that have reached a design life limit or have been damaged beyond possible reparations, but that are deliberately manipulated to look as acceptable, with the intend to defraud.

Aircraft parts conditions are indicated with different codes, which can be consulted in the table below.

Table 10. Aircraft part conditions

Code	Condition
AI	As Is, meaning that the part is being sold in any condition or state it is in. In the aviation industry this usually means that there are tracing and/or documentation issues.
AR	As Removed, meaning that the part is sold in the condition it was when removed from the aircraft. Sometimes this part will come with a reason for removal or with a removal tag. It could be repairable or beyond economical repair (BER). These items must go to a certified MRO for functional test or repair.
FN	Factory New, directly from the Original Equipment Manufacturer
NE	New Equipment, produced on conformity with approved data that is accompanied by a manufacturer's material certification at the time of sale, and has no operating time or cycles
NS	New Surplus. The part is new and has no operating time or cycles and the owner had the potential to use the part and to install it.
OH	Overhauled. "Overhaul" means a process that ensures the aeronautical article is in complete conformity with the applicable service tolerances specified in the type certificate holder's, or equipment manufacturer's instructions for continued airworthiness, or in the data which is approved or accepted by the Authority. No person may describe an article as being overhauled unless it has been at least disassembled, cleaned, inspected, repaired as necessary, reassembled, and tested in accordance with the above-specified data.
SV	Serviceable. A serviceable unit is one that is fulfilling its function adequately and that is useable. These units go through bench tests to determine if they work. These units have been functional tested in accordance with OEM specifications and will possess an airworthiness certification.
RP	Repaired. The repaired condition is a serviceable unit that requires additional treatment, like the addition of minor pieces to meet the functional test requirements. Gaskets, bolts, and small expendables are the normal piece parts used in repairs. This condition will come with an airworthiness certification and teardown detailing what was done and what piece parts were used in the repair.

2.5.4 Alternative reuse

Alternative reuse refers to:

"*Any operation by which products or components that are not waste are used for a different purpose from the one they were conceived for.*"

This EoL pathway is especially useful, since it provides significantly higher added values to materials and parts the dismantling phase and that would otherwise be used for recycling or, in the worst case, sent to landfill.

Any **parts and components that are recovered for alternative reuse** are first put through a process which ensures they cannot go back into service. After this process is done, they can be supplied to several non-aviation related companies. Examples of these companies are furniture manufacturers and the film industry, R&D activities, decoration, creation of training material, etc.

Figure 27. Aircraft cabin section undergoing a process to be reused as an office. (Envisa, 2022)

Alternative reuse solutions can be taken forward for some of the outputs of the aircraft dismantling. These alternative reuses can have for example decoration purposes. Although the alternative reuse allows to have a remarkably high added value to the dismantled materials, it might be difficult to find a market for all of them. It is important then to have access to alternative reuse and recycling fates for each of the components and materials that are outputs of the dismantling phase, thus allowing for the reduction of the waste fraction to the minimum.

For the moment, **alternative reuse pathways are applied to relatively small fractions** of the materials that go through the dismantling process. However, these types of procedures are preferred from a circular economy point of view, since they help to make the life of the materials and parts last longer, being a closer loop from the circular economy systems diagram (See relevant figure from Subchapter 1.2). Therefore, fostering the alternative reuse is a key step to be considered in order to increase the sustainability and circularity of the aircraft lifecycle.

2.6 Analysis of the aircraft lifecycle within the waste sector

In this subchapter the **focus is established on the areas of the aircraft lifecycle that belong to the waste business**, meaning that the aircraft parts and materials are not employed anymore with their original objectives and applications, in contrast with the previous subchapter of this report.

The **areas, units, processes, activities, and stakeholders involved in the waste business** are those indicated in the table below. More information regarding the day-to-day practices, and technical culture elements are included in Chapter 3 of this document.

Table 11. Key areas, units, processes, and key stakeholders in the waste business

Areas	Units	Processes	Key stakeholders
Waste business	Dismantling	Final draining of the systems Categorisation of materials to waste treatment routes Removal of hazardous materials Removal of non-recyclable materials Shredding Transportation of dismantled materials	Dismantlers
	Recycling	Sorting Aggregation Material recovery	Recyclers
	Energy recovery	Conversion of non-recyclable waste materials into usable heat, electricity, or fuel	Waste management companies
	Landfill	Inclusion of waste into landfills	Waste management companies

The units indicated constitute the entirety of the **waste business domain**. It is important to note that, while in the previous subchapter, regulation and processes belong specifically to the aviation industry, in the waste business no aviation-specific rules are applicable. During the dismantling process, a clear link to the aviation industry can be made since the dismantling of an aircraft has its own particularities. However, for the cases of recycling, energy recovery and landfill, there are no significant differences within the flows of materials produced from the aircraft lifecycle in comparison to others arising from other industries.

2.6.1 Processes concerned

In this subchapter the focus is on the description of the subprocesses that take place within the waste business for each of the areas, units, and processes identified. Areas, units, and processes had been defined previously in this report in Subchapter 2.1. The **subprocesses corresponding to the waste business area** of the aircraft lifecycle can be consulted in the table below.

Table 12. Subprocesses within the waste business

Areas	Units	Processes	Subprocesses
Waste business Waste business	Dismantling	Final draining of the systems	Draining of fuel Draining of hydraulic systems
		Categorisation of materials to waste treatment routes	Localisation of materials and parts left Planning of recycling and landfill fractions
		Removal of hazardous materials	Removal of any radioactive, batteries, etc. left
		Removal of parts and materials for non-aerospace use	Obtention of parts and materials that will be used outside of the aerospace business, such as in decoration, training, film industry, etc

Areas	Units	Processes	Subprocesses
Waste business		Removal of non-recyclable materials	Removal of the "unwanted fraction," i.e., the fraction that is non-recyclable or not worth to recycle. This fraction will either be used for energy recover or sent to landfill
		Shredding	Cut of the materials in order to prepare them for recycling
		Transportation of dismantled materials	Send the cut materials to the recycling facilities
	Recycling	Sorting	Separation of the cut materials by metal type in order to allow the recycling
		Material recovery	Melt of the metals to obtain new input materials for manufacturing in other sectors
	Energy recovery	Conversion of non-recyclable waste materials into usable heat, electricity, or fuel	Combustion, gasification, pyrolysis, anaerobic digestion, and landfill gas recovery
	Landfill	Inclusion of waste into landfills	Isolation of waste and monitoring of by-products, leaks, and any other process that may damage the environment

2.6.2 Dismantling

Aircraft **dismantling** constitutes the entry of the aircraft parts and materials to the waste business, meaning that they cannot re-enter the aerospace business, are considered as waste, and are under the general regulations covering waste treatment. Aircraft dismantling consists of the following steps: the final draining of the systems, the categorisation of the materials that are left and the end-of-life fates that they will follow, the removal of hazardous materials, removal of non-recyclable materials, shredding, and transportation to recycling and recovery facilities.

As indicated previously, a useful way to increase the value of materials and components that go through the aircraft dismantling process is to promote their **alternative reuse**, this means to employ them in different contexts from those that they were conceived. For instance, a section of a cabin that would have a value of some hundreds of euros due to its materials can rise this value very significantly if marketed to be employed in the decoration industry. The alternative reuse was covered in the previous subchapter of the report and more details about the current practices are provided as part of Chapter 3 of this document.

Figure 28. Aircraft section under dismantling. (Envisa, 2022)

In the following table, a **list of materials and components that are found in an aircraft, as well as their possible fates** is provided. These fates include possibilities for recycling and reuse independently from the derived costs. In order to achieve a fully circular aircraft lifecycle, initiatives will be required to reduce these costs, otherwise, there will still be an “unwanted” fraction that will end up being used as input for energy recovery activities or sent to landfill. More details regarding initiatives and solutions to increase the circularity of the sector are included in Chapter 4 of this report.

Table 13. List of materials and components and their possible fates

Material or component	Fate (non-exhaustive)
Cabin interiors	Obtention of new products and materials
Fuel	Conditioning and reuse
Cockpit	Use in flight simulators
Avionics	Part 145 reuse and materials recycling
Wiring	Stripping and remelt
Engines	Part 145 reuse and materials recycling
Landing gear tires	Part 145 reuse and creation of new products
Metal structural components	Remelt of Ti, Ni, and reuse of Corrosion-resistant steel.
Steel, Hydraulic pumps, batteries	Recycle
APU	Part 145 reuse
CFRP Structures	Use in new products and materials
Thermal insulation and seats	Part 145 reuse and use in new products
Serviceable parts	Part 145 reuse
Fuselage barrels	New products for alternative reuse
Fuselage	Remelt

End-of-life aircraft contain plenty of materials and parts that can be recycled, which makes the dismantling and recycling key units in the aircraft lifecycle. As we can see from the previous table, most of the materials and parts that entre the dismantling phase of an aircraft do have the potential to be either reused or recycled, although this is not taken to the maximum in practice due to the economic side of the material separation and recycling activities. Production of new aircraft parts requires raw materials, capital, energy, and labour. Through recycling or reuse, a great amount of material and parts can be recovered, and consequently primary and natural resources can be saved. Moreover, the production of secondary raw material requires significantly less energy than the production of primary raw materials. Because of this, recycling leads to a reduction of emissions to air, water, and soil. Finally, recycling leads to a reduction of waste, and because of this to a reduction of land use in landfill sites.

An important flow to be considered when analysing the dismantling phase is the **percentage of material that ends up disposed as landfill**. The objective of the entire system is to reduce this amount to a value as close to zero as possible.

2.6.3 Recycling, energy recovery and landfill

After the dismantling, the **recycling, energy recovery, and landfill** steps take place. After having removed all valuable components, the remaining fuselage is broken up into small pieces and processed by a metal recovery company. Those materials that allow for energy recovery are taken to incineration facilities to extract energy from the combustion of the materials. Finally, materials that cannot be either recycled or used for energy recovery, are sent to landfill.

The study carried out by Asmatulu et al (2013)[92], gave insights about the state of the art of **aircraft recycling**. In this regard, they indicated that, in addition to economic returns, recycling has environmental benefits, as well. For example, aluminium manufacturing is an energy-intensive process due to the electrolysis step (or Bayer process). However, when aluminium is directly recovered and reused, it reduces the initial energy by 90%, and reduces raw material consumption. By reducing the amount of energy used by the aircraft industry, recycling reduces greenhouse gas (GHG) emissions and minimises climate change. Additional benefits of recycling are the reduction in emissions from incinerators, and lesser materials to fill the landfills.

Recycling of end-of-life aircraft is a voluntary action, which is not regulated by legislation, as it is the case for land vehicles (EoL Vehicle Directive 2000/53/EC, EU) and ships (The Hong Kong Convention, International Maritime Organisation). Once an aircraft is retired from operational service, it used to be generally stored in an aircraft boneyard, which are commonly located in desertic areas or in remote sections of an airfield. However, aircraft today are usually kept in the storage areas only if a chance Is seen to put them back into service (e.g., during the COVID crisis); if it is certain that the aircraft will be permanently retired, more and more airlines send them directly to a dismantling facility.

After the disassembling has been completed, the airframe is usually cut into pieces with sizes that are suitable for transportation into recycling facilities that can be sorted depending on the materials. Metals are mostly recycled to aerospace smelter.

Materials employed in aircraft manufacturing, which have a significant impact on their EoL phase, have gone through great changes over the last years, as shown in the figure below. As we can observe, the share of composite materials has very significantly increased in the last decades. On the contrary, the use of metals has been greatly reduced. Given the average lifespan of aircraft, which is around 25 to 30 years, the recently retired aircraft are mostly from the nineties, which contain a much higher percentage of metals than modern aircraft. These materials have been successfully recycled with recycling rates higher than 80% by weight. This fact has a substantial impact on the recycling activities and therefore on the recyclability of recent and upcoming aircraft. This is due to the differences in the recycling options between metals and composite materials. While for metals recycling is a mature and consolidated pathway, that is not the same case for composites, which still have difficulties and for which recycling processes are still under research phase.

[92] Asmatulu et al., (2013). Recycling of aircraft: State of the Art in 2011

Technologies required to recycle composites have been developed only recently and are still in many cases non-viable from an economic perspective (Wong et al., 2017). Thus, it is expected that the recyclability rates of current and future aircraft types will diminish, unless recycling solutions are given to the materials that are used to build them.

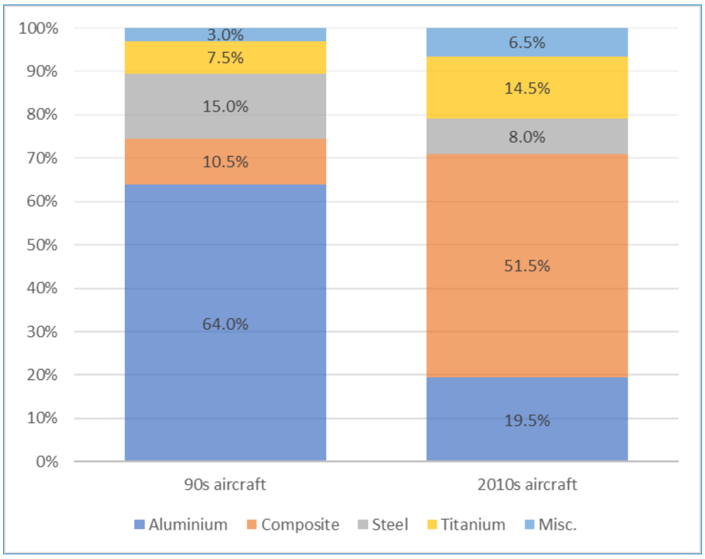

Figure 29. Representative aircraft material compositions in the 90s and 2010s (Wong et al. 2017)

In the case of the **car industry**, for which a dedicated directive exists (ELV Directive), relatively high reuse/recovery and recycling rates are being obtained by the different EU countries. Since 2015, EU Member States are required to meet rates for reuse and recycling of ≥ 85 % and for reuse and recovery of ≥ 95 %, by an average weight per vehicle. In 2019, the reuse and recycling rate for end-of-life vehicles in the EU stood at 89.6 %, 2.3 percentage points higher than in 2018 and 1.7 percentage points higher than in 2017. On average in the EU, 95.1 % of the parts and materials were either reused or recovered (including energy recovery), while 89.6 % were reused or recycled. The rate of 118.8 % reported in 2019 by Poland stems from the treatment of stocks of parts of end-of-life vehicles at dismantling and shredding sites that had not been treated in the previous years. Therefore, comparable **recycling and reuse rates** are achieved in the car industry in comparison with those that have been obtained for aircraft. For example, for the case of the most common aircraft types that become dismantled currently (A320s, B737s, etc.), approximately one third of their weight is reused, 60% is recycled, 8% goes to energy recovery, and 2% to landfill.

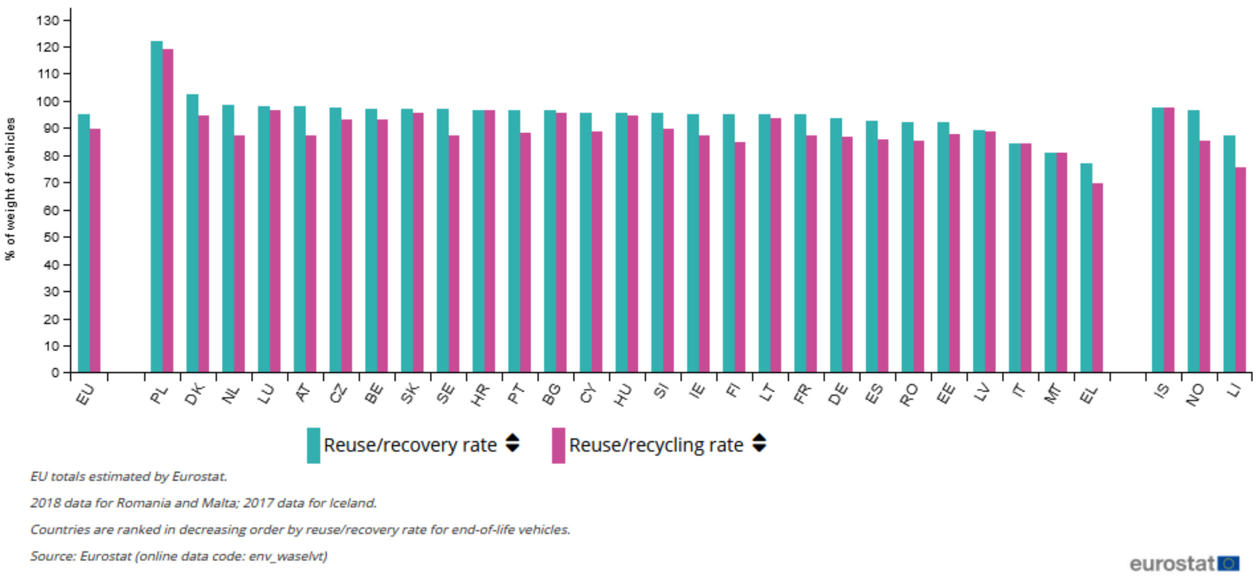

Figure 30. Reuse/recovery rate and reuse/recycling rate for end-of-life vehicles, 2019 (EUROSTAT)

Energy recovery is defined as a form of resource recovery in which the organic fraction of waste is converted to some form of usable energy. Recovery may be achieved through the combustion of processed or raw refuse to produce steam through the pyrolysis of refuse to produce oil or gas; and through the anaerobic digestion of organic wastes to produce methane gas.

Having established the goal to be carbon neutral by 2050, the EU puts efforts on processes above energy recovery in the waste hierarchy, namely, waste prevention, reuse and recycle. Therefore, even though energy recovery is still a better path than landfilling, it still has related issues and should not be the focus to increase circularity and sustainability.

A **landfill** area is a site for disposal of waste materials. According to the EU's waste hierarchy, landfilling is the least preferable option and should be limited to the necessary minimum, therefore, the EU rules aim to limit the amount of waste sent to landfill to the necessary minimum.

As it is the case for energy recovery, the process of sending aviation waste to landfill is not aviation-specific, since at this point of the aircraft lifecycle, this waste has no specific legislation and follows the same steps as waste from other industries and sectors.

The EU Landfill Directive indicates the operational requirements for landfill sites with the objectives of protecting human health and environment. To support the EU's transition to the circular economy, the Landfill Directive also introduces restrictions on landfilling of all waste that is suitable for recycling or other material or energy recovery from 2030, therefore aiming to limit the use of waste as well for energy recovery, as indicated previously.

Landfills are divided into three distinct categories, depending on the type of waste they are prepared to keep:

- landfills for hazardous waste
- landfills for non-hazardous waste
- landfills for inert waste

Landfill facilities may not accept used tyres or waste which is liquid, flammable, explosive or corrosive, or from hospitals and medical and veterinary practices. In addition, only waste that has been treated may be landfilled. Moreover, following the principle of "who pollutes pays," National authorities must ensure that the price operators charge for disposing of waste covers all the costs involved from opening to final closure of the site.

Aviation waste will therefore be subject to the indicated legislation and will be treated and if required sent to landfill following similar processes as in other sectors and industries.

3. Elements of the aviation system and technical culture which could support the implementation of sustainability

The **different areas, units, processes and their related daily practices and culture elements are described** in this chapter of the report. The analysis follows the scope defined in Chapter 2. This Chapter commences with a description of some general elements that apply to all areas: planning, management, and cooperation; followed by a description of the activities carried out within the aerospace industry, in alternative reuse and in the waste sector.

3.1 General elements

3.1.1 Management and planning

Management and planning are fundamental to any organisation. As it was indicated in the introduction, sustainability involves different pillars: environment, economy, and society. All these pillars are influenced by the planning and management of the organisations involved. Therefore, sustainability should be included in the planning and management to achieve its practical implementation and improvement.

Sustainable management considers the fact that taking non-environmentally responsible economic actions make it difficult to preserve good environmental and social conditions in the future. It aims to run organisations in a way that allows to meet the needs of the company without harming future generations' natural and social resources. Sustainable management includes aiming for long-term profit, circularity, reduction of carbon footprint, ensuring sustainable supply chains, and societal sustainability.

The **sustainability of the aviation industry** has to be considered at all stages of the aircraft lifecycle in order to achieve global improvements. Therefore, initiatives targeting the design phase, supply chain, manufacturing, the operational phase, and the EoL phase need to be carried out. Bigger aviation organisations, such as Airbus and Boeing, perform important efforts to develop and implement sustainability reporting and monitoring initiatives covering the whole aircraft lifecycle. They include sections in their teams that are devoted to sustainability-related initiatives, which cover various areas, such as reduction of GHG emissions, development, use of SAF, increase equity and diversity in the organisations, and eco-design initiatives.

A tool that aviation organisations use in the area of sustainable management is the publication of **Environmental statements and reports**. Environmental policies are intended to establish a framework of reference for the integration of the protection of nature and the environment within the strategy of the organisation, as well as its investments and operations. These policies show the main principles of conduct and the priority lines of action that aim to achieve sustainability. Usually, the sustainability/environmental reports include:

- A description of the organisation
- The definition of its sustainability goals
- A description of the different areas in which sustainability implications apply, such as: biodiversity, water, soil, air quality, etc.
- Description of KPIs for the areas indicated
- An analysis of the trend in KPIs and how the future goals will be achieved

The use of these reports and the involved monitoring of KPIs and advancements is a useful tool, although it is still not widely applied, and its implementation requires to be improved in some cases. Therefore, it would be beneficial to stimulate the inclusion of these activities.

Figure 31. Examples of aviation sustainability reports. Boeing 2022 sustainability report on the left and EASA, EUROCONTROL, and EEA 2019 EAER on the right

Planning and management meetings are routinary day-to-day practices in which sustainability aspects can also be tackled. However, **these aspects are traditionally considered from the perspective of the economic performance** of the activities, not giving much priority to the other two sides of it: environmental and social aspects. Sustainability topics are still not broadly discussed as part of the planning meetings unless the organisations preparing them have an environmental management system. Therefore, it would be beneficial to include these aspects as well in the scheduled planning meetings of the organisations that participate as stakeholders during the aircraft lifecycle.

The **use of electronic platforms** to manage the activities carried out by the different organisations is widespread. These platforms however do not include in many cases sustainability monitoring, meaning for instance the tracking of environmental and social KPIs. This is an area for improvement in order to enhance sustainability since they allow the monitoring of the processes, sustainability reporting, and improving the efficiency of the activities that the organisations carry out.

Even though several sustainability projects and initiatives are available regarding planning and management, there is still room for improvement. In fact, many of the currently existing initiatives are not broadly included by the stakeholders, especially those that constitute smaller organisations. One of the reasons of this gap is the higher attention given to the economic aspects of the aviation industry, in comparison with the two other sustainability pillars: environment and society. Thus, planning and management activities do include in some cases sustainability considerations, although this is practice is not followed by all organisations, and the degree of involvement and ambitions can be increased.

3.1.2 Cooperation among organisations

Cooperation between the different organisations that participate in the whole aircraft lifecycle is crucial to ensure the proper and successful performance of the business in general and to implement the various sustainability initiatives.

When analysing the general cooperation between the identified organisations, **two main groups can be established: those belonging to Maintenance and Production and those belonging to aircraft EoL and non-aerospace business**. Within these two main groups, the cooperation actions are widespread. For example, within the aircraft EoL area, intense cooperation happens between disassemblers, dismantlers, and recyclers to work with the different aircraft parts and materials and allow their reuse or recycling. However, there are less interactions between the M&P and the EoL actors, although MRO organisations also perform part-out and EoL activities. In particular, more information coming from the design and manufacturing phase would be greatly beneficial to improve the EoL activities carried out by dismantlers and recyclers, such as the contents of the different materials in the aircraft structure and their locations within the aircraft types. This lack of information is seen as an issue by the industry since it does not allow for a proper material separation and therefore leads to increased difficulties to recover the materials and lower recyclability rates.

Table 14. M&P and EoL stakeholders

M&P	EoL
Certification authorities	**Disassemblers**
Manufacturers	**Dismantlers**
Distributors	**Recyclers**
Resellers	**Alternative reuse organisations**
Owners and Operators	**Waste management companies**
Repair shops	

The cooperation among the different organisations can happen through different pathways, including specialised centres for aircraft EoL treatment such as TARMAC and associations such as AFRA.

One of the cases in which the cooperation among organisations is crucial is **the implementation of environmental management systems**, such as EMAS and ISO 14001.

Regarding the **EMAS implementation**, there are different key stakeholders that contribute to the quality, public credibility, and reliability of the system. In the side of the development of the system, there are three main actors: the European Commission, the EMAS Committee (representatives at Member State Level) and the EMAS Helpdesk (which handles complex enquiries about the EMAS framework for all interested parties). On the verification side, there are the accreditation and licensing bodies (responsible for the accreditation and issuing of licences) and the environmental verifiers (which ensures that organisations seeking EMAS registration fulfil the requirements). Finally, the competent bodies provide guidance and advisory support on the entire process. The competent bodies are designated by the Member States and constitute the first point of contact for any organisation interested in registering with EMAS. With the revision of EMAS in 2010, the scheme is also open to non-European organisations and European organisations operating in third countries.

ISO 14001 includes a clause regarding the understanding of the needs and expectations of interested parties. ISO 14001 defines interested parties as "those persons or organisations that can affect, be affected, or perceive themselves to be affected by a decision or activity". ISO 14001 requires the organisation that implements it to determine:

- The interested parties relevant to the environmental management system
- The relevant needs and expectations or requirements of interested parties
- Which of those needs and expectations are or could become compliance requirements?

Other ISOs, such as ISO 9001 and 50001, include as well similar indications about how to identify and consider the needs of the different interested parties. These clauses and considerations are of much interest to the organisations implementing the environmental standards, since they help to increase the performance and effectivity, as well as the reach to society.

Cooperation with research centres and universities occurs between the different stakeholders. This cooperation allows for the development of innovative techniques. Examples of these interactions include:

- Projects to improve current practices
- Development of new technologies
- Development of new materials
- Training and educational projects.

Companies in these phases of the aircraft lifecycle may participate as well in **Sustainability R&D projects** investigating recycling methods, disassembling techniques, etc. This participation in research projects is a practice carried out by some companies in the sector in order to improve the current techniques and methodologies and synergise the knowledge from researchers together with the practical experience of the companies.

Case study: GJD Sustainability R&D projects

There are two companies that constitute GJD: **GJD Aerotech Ltd.**, which is involved in MRO activities, and **GJD Services Ltd.**, which does the dismantling, both based in Wales. Essentially, GJD Aerotech performs activities in the Aerospace business and is a certified aviation maintenance organisation (EASA PART 145 Approval No CAA.UK.145.0125), while GJD Services performs activities outside of the aerospace business.

GJD Services and GJD AeroTech has carried out several projects over the previous years and has been awarded by BAE Systems for the Logistics Life-long for fleet Fortitude. They pioneered what is non-standard practice keeping an aircraft in storage to use as a “robbery” ship so parts can be removed, sent to shop, and reused in flying aircraft or by an MRO under Part 145, issued with a Form 1 and sent directly to an operating aircraft. This was developed during the Iraq conflict when they decommissioned the VC10 fleet for BAE and the MoD. It saved £10m in the first two aircraft and reduced lead time scales.

GJD were as well finalists in the Chartered Institute of Waste Management annual Sustainability Awards in 2017. They disposed of a B747 for British Airways recovering and recycling 99% of the entire aircraft by weight. This was a special project to test the viability and to carry out a cost benefit analysis from British Airways’ point of view. It was not repeated as the financial cost outweighed the environmental gains at the time.

3.1.3 Legal elements

There is **currently no regulation worldwide about EoL specifically targeting aircraft**. There is, however, regulation which indirectly impacts aircraft recycling, such as the waste regulation. The processes are indirectly affected by different existing regulations because of the characteristics of materials that are used in aircraft. For example, EU regulations affecting Waste Electrical and Electronic Equipment, Packaging and Packaging Waste, Chemicals, etc. affect aircraft parts as well. In addition, the EU Waste Framework Directive includes general elements of the Waste Management, such as the “polluter pays” principle and the waste hierarchy, which affect the waste management in aviation. There is as well a Regulatory Position Statement from the UK Environment Agency regarding the removal of airworthy parts from waste aircraft.

When **comparing the legal status of end-of-life aircraft with other transportation means**, different situations are found:

- In the case of the railway industry, there is also no special regulation within the EU that defines the treatment of those trains that are decommissioned. Wagons are usually simply classified as waste.
- In the shipping industry, there is on the other hand regulation that applies and governs the EoL – “The Hong Kong International Convention for the Safe and Environmentally Sound Recycling of ships.” This convention includes the requirement to perform an inventory of hazardous materials at the moment in which ships are sent for recycling. There are still problems going on in this industry since ships are often dismantled in ship boneyards in countries where the environmental requirements are lower.
- The case of the car industry is the most researched and expanded, due to the considerable number of cars that reach their EoL every year, together with the link with the private citizens, which does not apply to the cases of the railway, nor the shipping industry sectors. The automotive industry is controlled in Europe by the Directive 2000/53/EC on “End-of-Life Vehicles”, which incorporates the obligation for car manufacturers to accept end-of-life vehicles back, target recycling rates, as well as some procedure limitations.

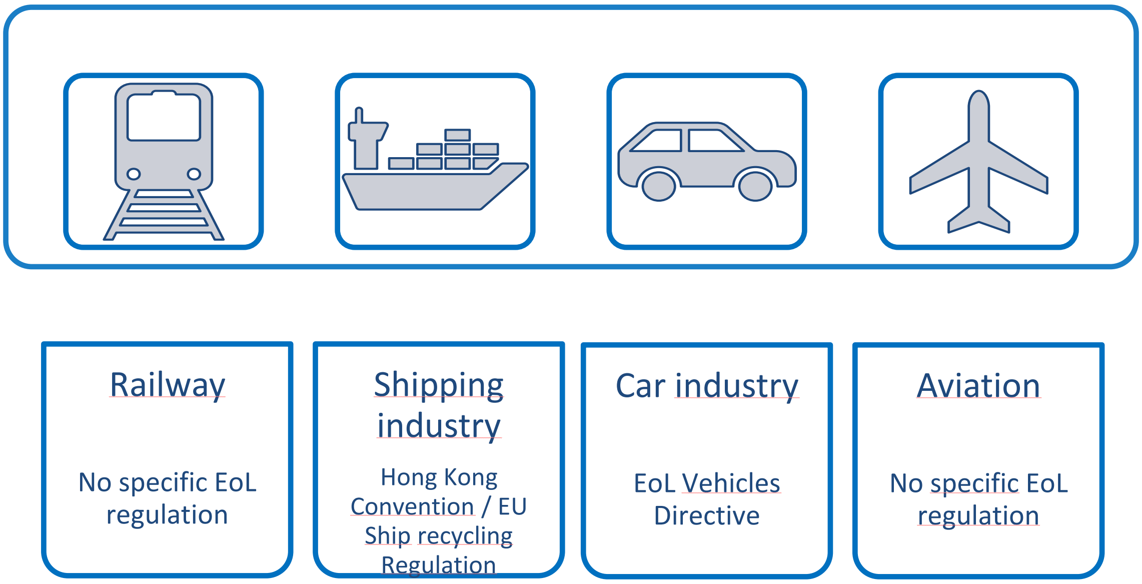

Figure 32. EoL Regulation in different modes of transportation

The aviation industry has to face social pressure and the request to include recycled materials into the business which need to fulfil very high-quality requirements while staying economically feasible. An essential element of the aviation industry that increases the difficulty of the management of the aircraft EoL is the much higher amounts of **safety and documentation efforts** in comparison to the other transportation modes.

In summary, in the case of aviation, there is currently no regulation worldwide about EoL specifically targeting aircraft although, since the moment in which the aircraft is categorised as waste, the respective waste treatment legislation of the country in which the aircraft is located applies.

3.2 Elements within the aerospace industry and in the alternative reuse

In this subchapter, day-to-day practices and technical culture elements are indicated for those **units and processes that are within the aerospace industry and in the alternative reuse areas.** More information regarding these units and processes can be found in Chapter 2.

3.2.1 Maintenance and production

3.2.1.1 Design and production

Starting from the beginning of the aircraft lifecycle, **eco-design activities** are crucial as a first step to lower the total environmental impacts produced during the aircraft lifecycle. Among the eco-design activities, we can find the use of innovative materials and structures. Manufacturers invest in these activities that involve environmental and economic benefits. They also invest in the evolution of their designs, so they achieve improved environmental performance. In the following Figure, the evolution of the environmental performance in Airbus aircraft is shown, resulting in lower carbon emissions per passenger, optimised aerodynamics, and reduction in weight.

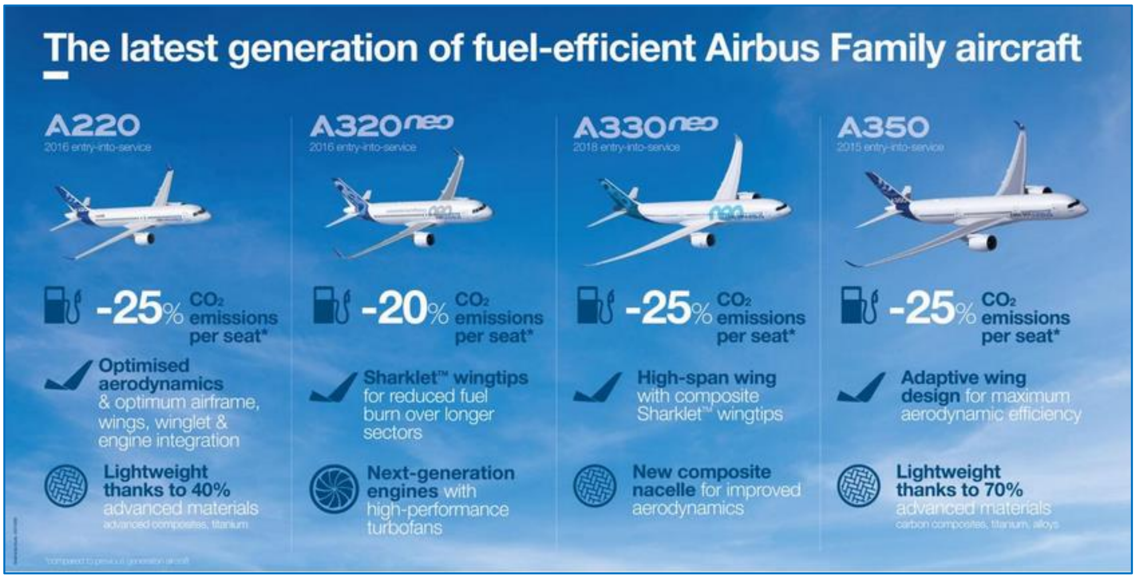

Figure 33. Fuel efficiency evolution in new generation Airbus aircraft. (Airbus, 2022)

Aircraft manufacturers have also made efforts to improve aircraft EoL, both Airbus and Boeing have worked on this topic.

In the case of Airbus, it launched the "Process for Advanced Management of EoL of Aircraft" called **PAMELA**. This project aimed to prove that 85-95% of an aircraft can easily be reused, recycled, or recovered. It also aimed to establish a new standard for safe and environmentally friendly management of "EoL Aircraft." Moreover, it also targeted the creation of a European network to enable further dissemination of the resulting dismantling process (EC, 2022)[93].

Following the PAMELA project and applying its results, Airbus created the Tarbes Advanced Recycling and Maintenance Aircraft Company (**Tarmac Aerosave**), which was done in collaboration with other companies. Tarmac Aerosave provides solutions for aircraft maintenance, storage and recycling and is approved according to several standards, such as: EASA Part 145, FAA Part 145, EASA Part 147and ISOs 14001 and 9001.

Boeing, on the other hand, followed a different approach when tackling sustainability of the aircraft EoL, and in partnership with European and American companies founded the Aircraft Fleet Recycling Association (**AFRA**) in April 2006. The organisations who joined AFRA came from different industries such as waste management, manufacturers, research, aircraft maintenance, etc. and put together their expertise to perform aircraft scrapping with the best technical standards. Based on these experiences, AFRA has published its best management practices that cover Aircraft disassembling, dismantling, and recycling. AFRA members agree to ensure that aircraft and parts recovered from them are safe for future use in aerospace applications, unserviceable parts are removed in a responsible manner, best practices are spread, at disassembly the airframe and its components are disposed in accordance with current legislation and best environmental practices.

In addition to Airbus and Boeing, other aircraft manufacturers joined the movement to increase sustainability practices in aircraft EoL in one way or another. For example, in the case of Bombardier, they started working on a metal recycling project with the Consortium Research and Innovation in Aerospace in Quebec (CRIAQ), other industry players and academic institutes. The Bombardier C-series, renamed to Airbus A220 in 2018, was even awarded an Environmental Product Declaration, which is a standardized way of quantifying a product's life cycle environmental impact, as the aircraft model was designed for end-of-life (Bombardier, 2020)[94].

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[93] EC (2022). Process for Advanced Management of EoL of Aircraft

[94] Bombardier (2020). Bombardier C Series CS300 Aircraft Environmental Product Declaration

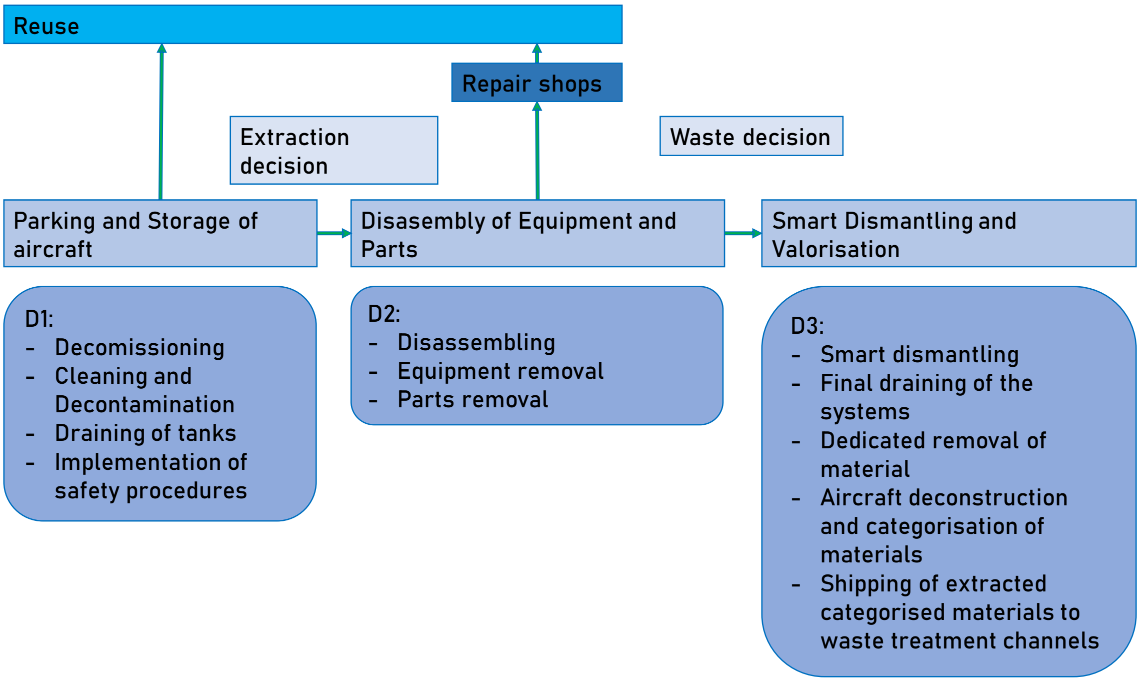

Figure 34. PAMELA's 3D Approach (adapted from Ribeiro 2015[95])

The **environmental impacts from the aircraft manufacturing phase** originate from different steps, such as the extraction of raw materials, their transportation, production and casting, and their use to produce the different components until the final assembly. During each of these steps, energy and water is consumed, as well as waste is produced. From the whole aircraft manufacturing step, the largest contributions to energy and water consumption were produced by the airframe manufacturers and the aluminium alloy production. The carbon emissions occur mostly in the manufacturing stage, with the production of electronics, systems, engines and airframe, their subassembly and final assembling and testing. Water withdrawals mainly originate from the material extraction, production, and casting (Pierrat et al, 2021)[96].

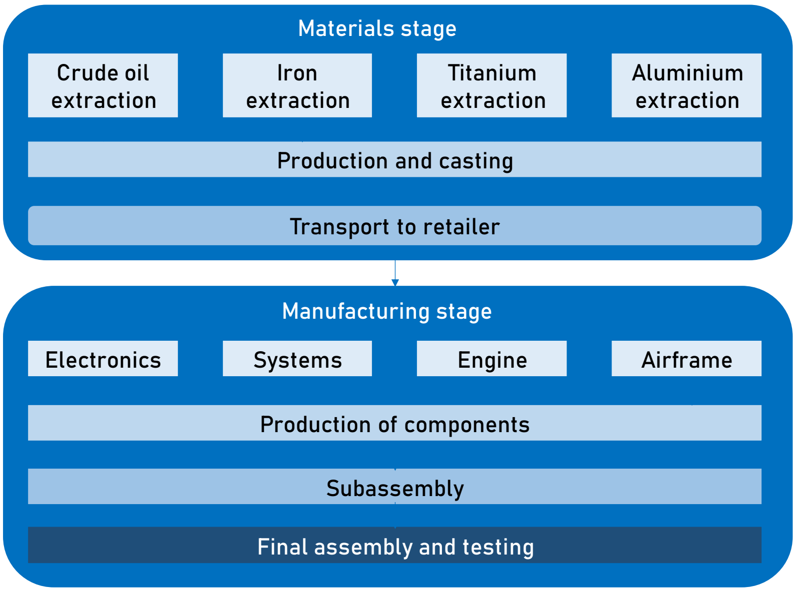

Figure 35. Diagram of the materials and manufacturing stages of the aircraft lifecycle (Adapted from Pierrat et al. 2021)

[95] Ribeiro (2015). Proposed Framework for End-of-Life Aircraft Recycling
[96] Pierrat et al. (2021). Global environmental mapping of the aeronautics manufacturing sector

From the different aircraft components, **the engine is the structure containing resources with the highest scarcity**. Engine, wings, and fuselage production produce the highest environmental impacts due to the use of aluminium, titanium, tantalum, molybdenum, and tin. The hotspots for sustainability impacts have been found to occur in alloying resources with a low mass share. These elements have strong impacts even considering the relatively small masses used in aircraft manufacturing. When it comes to the manufacturing phase, the use of lightweight composite materials does not lead to significant advantages to reduce demand for scarce materials and the environmental impacts. In particular, higher lightweight composite material shares in the aircraft increases impacts in the categories climate change and fossil resource depletion by 12% and 20%, respectively, whereas the impact of the category acidification, political stability, and demand growth decreases by 16%, 35%, and 60%, respectively (Dolganova et al, 2022)[97].

Case study: Pratt and Whitney Environment, Health, and Safety initiatives[98]

The engine manufacturer Pratt and Whitney has launched several goals in order to further enhance the sustainability of its factories. They work on cutting emissions, energy and water use, and increased recycling and generation of solar power in their facilities and supply chain.

An example of the energy savings in their facilities is the inclusion of twelve of their buildings into the LEED system, which is a framework to evaluate the environmental performance of buildings and to encourage the market transformation towards sustainable design.

In addition, they include social initiatives into their sustainability program, such as grants to improve the communities where their employees work and the designation of sustainability focal points within the company.

Pratt and Whitney have the following environmental goals for 2025:

- 10% reduction in GHG
- 10% reduction in water consumption
- 10% reduction in waste to landfill and incineration
- 100% implementation of water, waste, and energy/greenhouse gas best management practices.

Moreover, forums are organised in order to allow the different manufacturing facilities to share their own best practices to achieve the environmental goals.

Aircraft manufacturers **work on reducing the environmental impacts of their manufacturing processes**. These strategies involve better waste management, as well as the reduction in the energy consumption at their facilities and health and safety aspects. In addition, materials savings during the production phase lead to reduced environmental footprints. For the latter, there is potential in 3-D printing, which can bring reductions in raw material waste.

3.2.1.2 Operations

The **operational phase** is the source of the largest proportion of impacts, such as noise, air pollution and climate change, as well as the production of waste. In order to avoid and mitigate these impacts, actions are taken in many ways, such as: the development of technology to reduce noise and emissions at source, the use of operational changes to reduce exposure of population to noise and to reduce the emissions, development of biofuels, schemes to compensate carbon emissions, etc. As indicated, the operational impact is by far the largest due to the GHG emissions that are produced because of the fuel combustion. However, in this report we focus on the rest of the areas of the aircraft lifecycle, targeting M&P, aircraft EoL and alternative reuse, which have traditionally been targeted less than the operational phase of the aircraft lifecycle.

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[97] Dolganova et al. (2022). Assessment of Critical Resource Use in Aircraft Manufacturing

[98] Raytheon Technologies Corporation (2020). 2025 EH&S Sustainability goals

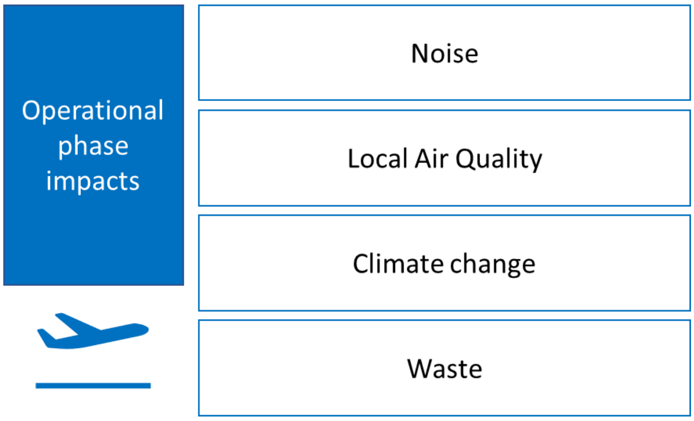

Figure 36. Operational phase impacts (Envisa, 2022)

Case study: The view from the lessors

The business of leasing companies is largely driven by financial considerations, much less by operational or technical aspects including sustainability. In the case that it is difficult to find a new lessee for an aircraft and part-out is profitable, relatively young aircraft (for instance with less than 15 years), are sometimes decommissioned although being perfectly flyable. Therefore, the focus on this sector is almost purely economic, not giving priority to extending the lifetime of the aircraft.

Regarding the sustainability initiatives put in place, lessors in some cases publish sustainability reports that meet just the minimum requirements of the finance sector. It could be a suitable time to try to obtain more recognition of sustainable practices, as sustainable behaviour is becoming a competitive advantage also in the finance sector. For instance, lessors could set a requirement for disassembly companies buying their decommissioned aircraft to be AFRA-certified and publish this as a sustainability measure. The currently observed trend in the finance sector towards giving more weight to sustainability aspects is expected to make such requirements more likely than in the past when decisions were dominated by pure profitability aspects.

From the point of view of the lessors, it is particularly important to have traceability of all aircraft parts; that is a crucial prerequisite to obtain a high value out of the parts (due to being able to know their condition and therefore increasing their value). All part status documents need to be available and verified to ensure back-to-birth traceability.

3.2.1.3 Maintenance

According to the DIN-Norm 31051, **maintenance** is described as: "a measure to preserve and restore the target condition and to determine and assess the actual condition." This includes the servicing, inspection, and repair of the aircraft. The scope of the maintenance programs is defined for each aircraft type divided into scheduled maintenance works and unscheduled maintenance events. These include national requirements, specific airline and manufacturers specifications and reliability issues (IATA, 2014)[99].

Aircraft maintenance is divided into:

- **Base maintenance**, which is performed at the airline's home base station
- **Line maintenance**, such as cleaning, refuelling, or light inspections.

In addition, when there is an unexpected issue with the aircraft or because of pilot's complaints, **non-routine maintenance tasks** also occur. These tasks are to be performed immediately to ensure safety and airworthiness. The different **inspection groups** can be found in the table below.

[99] IATA. (2014). Airline Operational Cost Management Guidelines

Table 15. Aircraft inspection groups. (Rahn, 2021)[100]

Inspection group	Description
Pre-flight	The pre-flight test is a visual inspection at the beginning of each operation, performed by maintenance mechanics and the pilot. Thereby, fluid levels, tires, brakes, emergency equipment etc. are inspected
A-Check	The A-check consists of general inspections of the interior and exterior as well as the aircraft's power supply. In addition, a more detailed engine inspection is included. The A-check is performed approximately every 400 to 600 flight hours or every 200 to 300 flight cycles
B-Check	The B-check includes mainly preventive maintenance tasks, such as oil change or inspection of the oil filters. The interval between these checks is about 750 flight hours. Nowadays the B-check is usually integrated in the A-check and not performed separately
C-Check	This check contains detailed inspection of airframe, engines, and systems. Additionally, the flight controls are recalibrated and tested. This is performed approximately every 3,000 flight hours
D-Check	This heavy check is the most intensive maintenance package which restores the aircraft to its original condition. For a more detailed inspection, the cabin interior, such as seats, galleys, furnishing, etc., is removed from the aircraft. This check takes about one month and is required every 6-8 years

In the EU legal framework, the airworthiness of commercial aircraft is subject to stringent EC regulation and is regulated by the European Aviation Safety Agency. Particularly, the **maintenance of aircraft and parts including the re-use of parts recovered from decommissioned aircraft** is subject to the requirements of EASA Part M (the management of aircraft maintenance) and Part 145 (the undertaking of aircraft maintenance). All airworthy parts are subject to certification by a Part 145 organisation. Records of maintenance, repair and overhaul are a necessity to maintain the airworthiness of an aircraft. In addition, avionics need continuous upgrades to remain compliant with safety regulations.

During **aircraft maintenance, environmental impacts** are produced due to the energy use, the production of maintenance products (e.g., cleaning products) and spare parts, as well as the waste produced. The production of spare parts and maintenance products have impacts that are comparable to those that happen during the aircraft production phase. On the other hand, the waste production is similar in the case of aircraft decommissioning and disassembling, including for instance the disposal and recycling of parts that are no longer usable and the draining of fluids. According to existing literature, there is not a unique approach to considering the impact of maintenance phase in life cycle assessment since different scopes can be considered. For example, in the maintenance operations, the manufacturing of spare parts might be included or alternatively removed from the analysis.

In order to counter these environmental impacts, **MRO organisations carry out different sustainability actions**, such as: reducing their direct input needs (for example the raw materials, energy, and water), performing a proper waste separation to prepare for recycling, measuring their carbon footprint output, and the implementation of offset measures. In addition, MRO organisations are required to ensure compliance with the applicable environmental laws and standards.

In the MRO business, which is driven by time pressure, safety and reliability concerns, and pressure to save costs, **sustainability is usually not yet a main topic being addressed, therefore being usually handled with lower priority**. The MRO organisations comply with the regulations for waste management but additional

[100] Rahn (2021). Life Cycle Assessment Methodologies for Aircraft Maintenance

measures to increase sustainability are still not broadly extended. They partner with specialised dismantling companies when dealing with aircraft reaching their EoL phase, although sustainability considerations are not necessarily a main part of the decision to choose these partners. Sustainability actions could however lead to some environmental and social benefits, e.g., reusing parts to save costs contributes directly to increased sustainability and promoting circular economy.

Figure 37. Engine maintenance activities (Envisa, 2022)

In contrast with the land vehicles sector, aviation OEMs do not pay for the environmental impacts and costs associated with EoL. As a good emerging initiative, aircraft designers are starting to be aware of the concepts of sustainability and circular economy to facilitate EoL treatment of their products. It can be seen that such eco-design is being increasingly implemented by manufacturers, although more effort would be required to widely implement “design for decommissioning” principles, i.e., design **modifications to ease the final treatment of aircraft parts and materials during the aircraft EoL**.

3.2.2 Decommissioning and disassembling

3.2.2.1 Decommissioning

Decommissioning and disassembling constitute the **entry into the EoL phase**, this decision being made mainly by economic and safety factors. When the costs are expected to become excessive or due to safety issues, the airline operator or the leasing company owning the aircraft normally decides to retire it from the fleet. In this case, the **decommissioning decision** therefore depends on the moment in which the value of the individual parts of the aircraft is higher than keeping the aircraft itself. Aircraft only enter the waste treatment route once this final decommissioning decision is taken and the first cut is applied to the structure, meaning that they will not fly again.

In some cases, young aircraft (less than 15 years old) are decommissioned in order to obtain a higher economic value than continuing to operate the aircraft. For example, in the case of the A380, the average retirement age during the last three years has been 11.3 years old (Naveo consultancy, 2022). These cases are becoming more frequent but are still not the norm. Typical situations of early retirement are e.g., the end of a lease contract with no new lessee in view, or the risk of failing a major maintenance check (D-check). There is a slight trend in general towards lower age of retiring aircraft.

Aircraft that are withdrawn from service are often not dismantled immediately. Instead, **they** are **put into storage** under a maintenance programme while it is decided whether they are put back into service or definitively retired. It is more interesting to keep aircraft stored if there is the chance that it could come back to service or to be sold for part-out later, when the demand for MRO is higher. This period can last for several months or years before the decision is taken. Parts may be removed from aircraft during this interim period to support the rest of the fleet of the owner or for resale. Parking and long-term storage are relatively cheap, therefore airlines and lessors favour parking aircraft during low-demand times, such as during the periods with most important COVID-19 restrictions, to be able to wait and see how traffic recovers. On average, aircraft not going back into service remain parked for around two years after their last flight before dismantling pre-pandemic, although aircraft parked for already over 6 months become likely not to return into service. However, the COVID-19 pandemic led to an increase of the number of jets in storage, also increasing the parking time, making aircraft be parked for longer periods than usual before getting back into service.

Case study: Traceability of parts during maintenance

The identification of components must match with those that are indicated in the part history. When this is not the case, the mismatching component(s) do need to be removed and go through a test to prove that they are still serviceable. If the origin of that component is unknown, it gets a tag indicating that, although it can still get the serviceable tag if it passes the tests. Larger items use individual series numbers to track their origin. When delivered by the manufacturer as part of a new aircraft, they are accompanied by the manufacturer's certificate of conformity. When used as spare parts, they require a Form 1, stating that a product, a part, or a component was manufactured in accordance with approved/not approved design data.

Parts and components are stored with tags indicating their status as well as their part and batch numbers.

Figure 38. Parts identification and storage (Envisa, 2022)

For the moment, the parts history is a manual process, which can lead to a higher frequency of mismatches or failures to update the records. IATA developed an "electronic parts lifecycle record," which has been tested, but is not yet implemented at larger scale.

Therefore, this essential element of the maintenance activities has a big potential to be improved with the inclusion of electronic databases to keep track of all the documentation. This evolution would also have sustainability implications, since it would contribute to material and energy savings, as well as to lead to a lower likelihood of mismatches and increased safety.

Prior to receiving an aircraft in a storage facility, a **risk assessment** and a method statement which outlines where the potential hazards are and what/how it is planned to mitigate those risks might be performed. An example of the tables that are used to help with this process can be found below. This example shows the Dust/Litter/Odour/Pests risks, but similar ones would apply to other types of risks, such as noise, for instance.

Figure 39. Aircraft put in storage with engines covered to protect them from degradation (Envisa, 2022)

When the decommissioning decision is taken and the aircraft is decided to be sent to a disassembling facility, a special flight permit must be established if the aircraft is no longer operated by an airline, i.e., has lost its Certificate of Airworthiness. During **decommissioning**, aircraft cleaning and decontamination of hazardous substances, draining of tanks and piping, and the implementation of safety procedures take place. In addition, the list of aircraft parts which could be disassembled and re-used is prepared.

Table 16. Sample hazard management table

What do you do that can harm and what could be harmed?			Managing the risk	Assessing the risk		
Hazard	**Receptor**	**Pathway**	**Risk Management**	**Likelihood**	**Harm**	**Risk**
Dust/Litter/Odour/Pests						
Dust/Litter remaining following decommissioning of aircraft interior/exterior	People/other areas of airport	Wind blown	Fencing to be in situ. Litter to be collected on an ongoing basis. Materials to be boxed	Litter likely to be produced, but unlikely that is generate beyond the exterior fencing	Impact on amenity or operations at site	Very low
Odour from waste	People/other areas of airport	Wind blown	Materials handled are unlikely to emit odours.	Very unlikely	Impact on amenity or operations at site	Very low
Scavenging animals and scavenging birds	Local human population	Air and over land	Waste types not attractive to birds. All crew food waste placed in lidded bins and emptied weekly	Very infrequently	Nuisance and harm to human health from waste carried off site	Not significant

In order to treat the various **hazardous liquids** contained in the aircraft, drainage and ventilation processes need to be carried out. The following table contains some examples of these hazardous liquids and their corresponding European Codes for disposal. These European Codes were put in place from the implementation of the European Waste Directive.

Table 17. Hazardous fluids contained in an aircraft and European Waste codes (Jeanvré and Duwe, 2013[101])

Hazardous fluid	European Waste Code
Fuel oil and diesel	130701*
Brake fluids	160113*
Antifreeze fluids	160114*/15
Oil filters	160107*
Synthetic hydraulic oils	130111*
Mineral-based non-chlorinated engine oils	130205*
Petrol	130702*
Aqueous liquid wastes	161002*

To **empty the tanks**, a defueling station is required. After this procedure, tanks must be force-ventilated with compressed air. Another important process is the handling of the pressured hydraulic oil systems, which involves the whole depressurization of the systems and the storage of the liquids in special containers. After

[101] Jeanvré and Duwe (2013). Technologies and practical experiences on AC EoL operations from a dismantler's point of view. Conference: First European Aircraft Recycling Symposium. Volume 1

having removed the fluids, any **other hazardous materials** need to be taken out manually. Specialised companies do the emptying of the tanks. Emptying the tanks is performed under safety conditions, so the spill risk is controlled. In addition, in some cases radioactive materials can be found, such as smoke detectors, fluorescent signs, and ballas weights out of depleted uranium (only in old aircraft, manufactured in the 1980s or before). These are treated by specialised companies for radioactive waste as handling regulations for nuclear material have to be observed. Special attention is to be given to radioactive parts, which are not itemised as waste in the EU Waste Framework Directive, and that need to be then treated separately as part of the Atomic Agency Act. The list of hazardous non-liquids in an aircraft and their European waste codes is shown in the following table.

Table 18. Hazardous non-liquids in an aircraft and their European waste codes[91]

Hazardous material	European Waste Code[102]
Explosive components	160110*
Components containing PCB	160109*
Brake pads containing asbestos	160111*/12
Components containing mercury	160108*
Insulation Materials (KMF)	170603*
Chlorofluorocarbons, HCFC, HFC	140601
Oxygen generators	160507
Lead batteries	160601
Ni-Cd batteries	160602
Gases in pressure containers (Halon)	160504
Absorbents, filter materials	150202
Smoke detectors	Atomic Energy Act (AEA)
Fluorescent signs	Atomic Energy Act (AEA)
Ballast weights out of depleted uranium (only in old aircraft, manufactured in the 1980s or before)	Atomic Energy Act (AEA)

Figure 40. Decommissioned aircraft with containers to store the recovered fluids (Envisa, 2022)

3.2.2.2 Disassembling

The steps of the disassembling before dismantling can be summarised as follows:

- Removal and disposal of Hazardous materials and components
- Removal of interior and insulation and disposal if customer demands it
- Removal of parts list, identifying with tags showing part number, etc.
- Individual packaging for each component
- Shipping of hazardous materials to a place where it is recycled or disposed

[102] Hazardous (special) wastes are signified by entries where the six-digit code is marked with an asterisk.

Dismantling organisations usually take care of the disassembling of the various **parts** that the aircraft owners require them to take out for reuse as spare parts. They remove these parts, inspect[103] them, and send them back to the aircraft owner. They do not usually own the aircraft, as they are often still under the property of the airlines, leasing companies or have been sold to aircraft parts dealers, although in some cases the original aircraft owners sell the aircraft to an asset management/dismantling company. The aircraft owners provide dismantling organisations or MRO companies (if the latter perform this task) with a "harvest list" of parts to be used for their own fleet. Then, based on the agreement, sometimes the rest of the parts and materials could potentially be kept by the dismantlers. It can happen that the aircraft owners ask to destroy the materials and parts outside of their harvest list to prevent parts linked to their company arriving on the black market. When the first cut is given to an aircraft, it automatically loses its certification, and so do all its parts and components that are still installed in the aircraft. It is usual practice nowadays to create an electronic data base for the client of the parts harvested in 'real time.'

Although some disassembling companies (which do asset management business) may buy aircraft and then proceed to carry out the dismantling, **disassembling is usually done for the aircraft owners**, who will receive the most valuable disassembled parts that have still value and will either reuse them or sell them. Usually, aircraft owners hire companies that carry out the parts removal for them. They take the parts that can still be serviceable, pack them and send them back to the aircraft owners, who can use them back for other aircraft from their fleet or sell them.

It is not mandatory to hold a Part 145 for disassembling activities, although parts harvested without a Part 145 company carrying out the work would have to be tagged 'as removed'. These parts would also have to go through a Part 145 overhaul workshop to be recertified and to be able to be reused on an aircraft.

In order to keep their certification (i.e., to avoid recertification as described in the previous paragraph), parts must be removed from the aircraft with a proper part 145 organisation while it is still registered. Removed parts are serviceable if the records are ok and inspection is done, meaning that the full traceability can be established and is valid.

Once the aircraft lands in the **disassembling facility**, the status has to be recorded to ensure that the correct aircraft is being treated – this is done by checking the data plate and the registration the logbook is also checked and removed from the aircraft.

Usually, the **records of the parts** are not kept by disassemblers when they are not the owners of the parts. These records are only asked for when it is needed to check how the parts got damaged. However, for instance, in the case of the engine shops, they do hold the records, following the EASA guidelines.

The **aircraft parts removed as part of the disassembling process** are intended to be returned to the aviation market as far as possible to maximise the recoverable value. These parts need to go through maintenance and/or recertification, depending on their status and on the proposed use in the aviation system. Parts that are destined to disposal are treated differently, since a destructive cut is made, and a certificate of destruction is issued. In addition, paper copies of the back-to-birth records are kept. The flow of part is governed by the certifying authority and the company Maintenance organisation. Parts that are taken off "as removed" have to go for overhaul in an approved workshop.

[103] When done by a dismantler, the part is removed and tagged "as removed" needing to go through under an MRO organisation before re-entering the aerospace business and being reused in another aircraft.

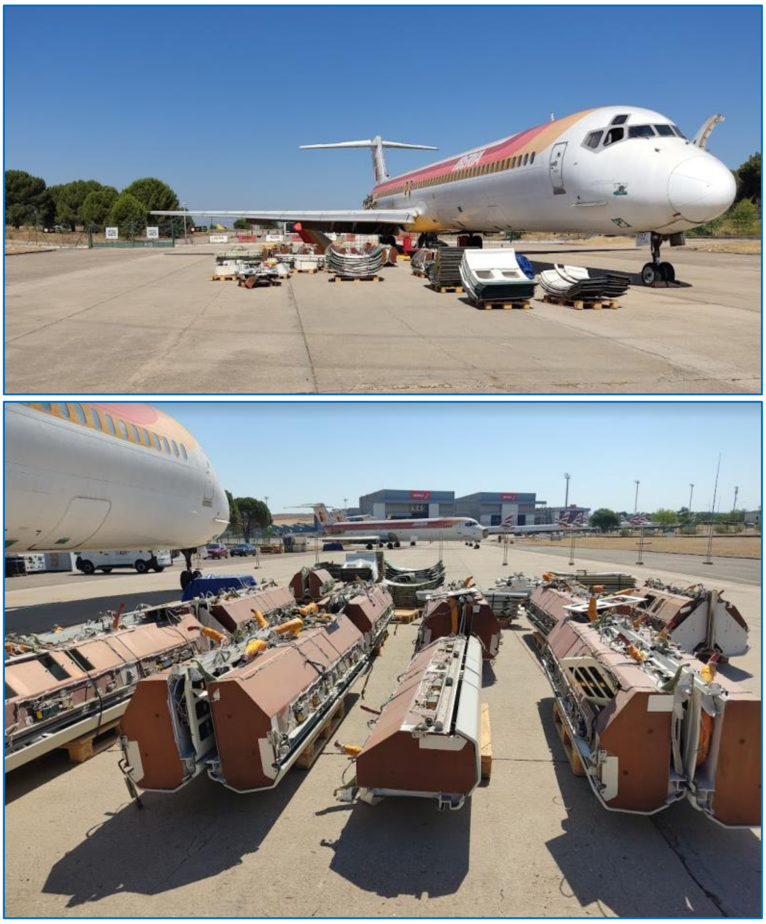

Figure 41. Aircraft going through disassembling (Envisa, 2022)

Chemicals, adhesives, rivets etc cannot be reused in the aviation industry but can be donated, for instance, to an aircraft museum that have static aircraft to restore. On some occasions, **interior materials** of the aircraft are usually not worth to be separated, since the man hours employed for such a task are more expensive than the value of the material and parts obtained as a result.

Figure 42. Aircraft cabin during disassembling (left) and recovered part (right). (Envisa, 2022)

The disassembling performed in advance to the dismantling phase is based on a **“harvest list”** provided by the aircraft owner. This list includes all those parts that are required to be disassembled and sent back to the owners. These are the parts with the highest economic value, and which will still be used within the aerospace industry. After these parts are disassembled, they are labelled, cleaned, stored, and sent to the aircraft owners. This activity is supported in some cases by electronic databases that serve to keep track of the parts recovered. Most of the value from the aircraft parts is constituted by a relatively small number of parts, such as the engines, landing gear and avionics, which represents most of the total value of the aircraft. Inventories of the parts are commonly created among disassembling companies in order to keep records of all the recovered parts and to inform their clients.

Case study: Electronic platform for parts inventories

AIR is a company based in Zaragoza (Spain) whose main activity is aircraft dismantling and recycling. It holds the triple accreditation under the AFRA Best Management Practices for demolition, disassembling and recycling.

As part of their activities, AIR identifies each of the disassembled parts with electronic tags with their part number, serial number, aircraft identification, including pictures, their weight, etc. These electronic platforms are valuable as well for the tracking of sustainability KPIs and the efficiency of the aircraft EoL pathways (reuse, alternative reuse, recycling, and landfill).

The creation of accurate inventories of the parts that are disassembled are essential for the activities of disassemblers. An example of the use of this type of inventories is as well the company AirSalvage, that creates parts inventories for their clients that include the list of disassembled parts with their identification numbers and pictures. This information is uploaded to their clients' system, so they can access this information.

Only after all the valuable airworthy parts have been recovered, aircraft will be dismantled. This process is known as "**parting out**." On some occasions, an aircraft in a fleet might be retired from service with the aim to provide spare parts for the rest, or due to failing a major maintenance check. Parts to be reused on aircraft have to be removed by an approved EASA MRO with the correct approval for the aircraft/engine type. Any parts destined for disposal are tagged and recorded, the destructive cut made, and a certificate of destruction is issued. After the disassembling has been completed and the required parts have been sent back to the aircraft owner, the company that carried it out can do an offer to acquire what is left in the aircraft. After disassembling all parts of the aircraft that are still valuable, the rest of the materials are sent to dismantling. During the **dismantling**, materials and parts can be used either for alternative reuse, recycling, energy recovery or finally sent to landfill.

As part of the full disassembling and dismantling process, checklists are created for reference, as the one indicated below.

Table 19. Example of a disassembling and dismantling checklist (Source: GJD Services Ltd.)

Action	Date	Signed
Aircraft check		
Aircraft registration and Data plate		
Details entered onto Aircraft Board		
Aircraft made safe		
Sumps, drainage, covers, and bunds put in place		
Aircraft made onto breaking pan		
Aircraft is de-fuelled into a bowser		
Non-useable fuel drained through a drain rig		
Hydraulic fluid drained		
Deflate pressure vessels		
Identify and remove Asbestos if fitted		
Identify and remove radioactive substances if fitted		
Parts removed as per list		
Authorisation to scrap for signed by customer		

Action	Date	Signed
Ensure all fluorescent tubes are removed		
All non-recyclable material removed and loaded into covered skips		
Final destruction, cutting fragmenting of aircraft		
Metal loaded onto skip and removed from site		
Breaking pan swept clean and cleansed using scrubber dryer		
Concrete seals and kerbing checked		
Sumps, drainage covers, and bunds removed		

As indicated in Chapter 2, **AFRA** developed **Best Management Practices (BMP) for organisations performing aircraft disassembling activities**. These best practices represent a collection of recommendations for the management of parts that get removed from the aircraft or its parts during the disassembly of the asset at the end of its service life. Examples of the practices included are:

- Creation of a BMP Manual
- Designation and preparation of a proper and secure area to perform the disassembling
- Creation of procedures for inventory accounting and audits
- Providing relevant training
- Use of disassembling identification tags for each of the parts removed
- Use of proper storing and shipping containments and packing materials for the materials that are handled
- Preparation of a methodology to protect the environment from unanticipated releases of fluids and hazardous materials that are used during the processing or that might escape from the Asset during disassembly.
- Coordination with recyclers to ensure that parts intended for recycling are processed in a manner that supports the recycling goals of the Facility.

3.2.3 Alternative reuse

Alternative reuse refers to operations by which products or components that are not waste are used for different purposes from the ones they were conceived for. Alternative reuse provides much **higher added values** to those parts and materials that could not be recovered for aviation use and that would otherwise be sent to recycling facilities to recover the materials. Therefore, this activity is quite important from a sustainability perspective, since it significantly extends the lifetime of the parts and materials, enhancing circularity and since it increases the economic value of the materials taking this pathway. Alternative reuse takes place during the dismantling phase, after aircraft valuable parts have already been disassembled and before materials and parts left are sent for recycling.

Any **parts and components that are recovered for alternative reuse** are first put through a process which ensures they cannot go back into service. After this process is completed, they can be supplied to several non-aviation related companies. Examples of these companies are furniture manufacturers and the film industry, R&D activities, decoration, creation of training material, etc. When providing components and parts for alternative reuse, the purchaser signs a document indicating that it will not be used in the aerospace business any longer. In any case, destructive cuts are given to parts so they would not work.

Examples of alternative reuse are:

- training and education,
- filmmaking, and TV productions,
- seats as furniture,
- Use of aircraft parts, as visualisation for lectures and courses,
- creation of suitcases with metal from aircraft,
- creation of offices areas from a section of the aircraft cabin,

- metals from old aircraft to manufacture small model,
- trophies,
- signs,
- old unusable parts sold to aviation enthusiast/collectors.
- Use of parts in some other industries in particular cases (an example can be the use of engine turbine blades that can be integrated into land-based gas turbines).

Alternative reuse solutions can be taken forward for some of the outputs of the aircraft dismantling. Although the alternative reuse allows to have a remarkably high added value to the dismantled materials, it might be difficult to find a market for all of them. It is important then to have access to alternative reuse and recycling fates for each of the components and materials that are outputs of the dismantling phase, thus allowing for the reduction of the waste fraction to the minimum.

Dismantling companies would try to focus on alternative reuse, when possible, due to the much lower benefits obtained from recycling. For example, sections of the fuselage that can be used for festivals, offices, etc, can reach values of 18,000 € per section. These same sections would be sold for 800€ if they had been treated as waste. However, alternative reuse pathways focus on specialised market niches, as described above, and therefore apply to relatively small fractions (today below 10%) of the materials that go through the dismantling process. This could be improved to a certain degree **by extending the market niches for the alternative reuse business**. A small number of companies work with dismantled aviation materials and parts and the volume of materials required are therefore small. In addition, when these activities happen, they are usually restricted to a very local scope, with organisations using alternative reuse activities contacting nearby dismantling facilities to get the materials they need. It is a very visible but small market. However, the demand for such products is very irregular, which makes it difficult for dismantlers to plan workforces to produce the alternative reuse products; rationalisation of the production process is also normally not possible. Thus, there is a potential for increasing the importance of this pathway, which would require increasing the awareness of the benefits of these activities to both sellers (dismantlers) and buyers (any organisation creating the alternative reuse products, such as designers, furniture manufacturers, etc.).

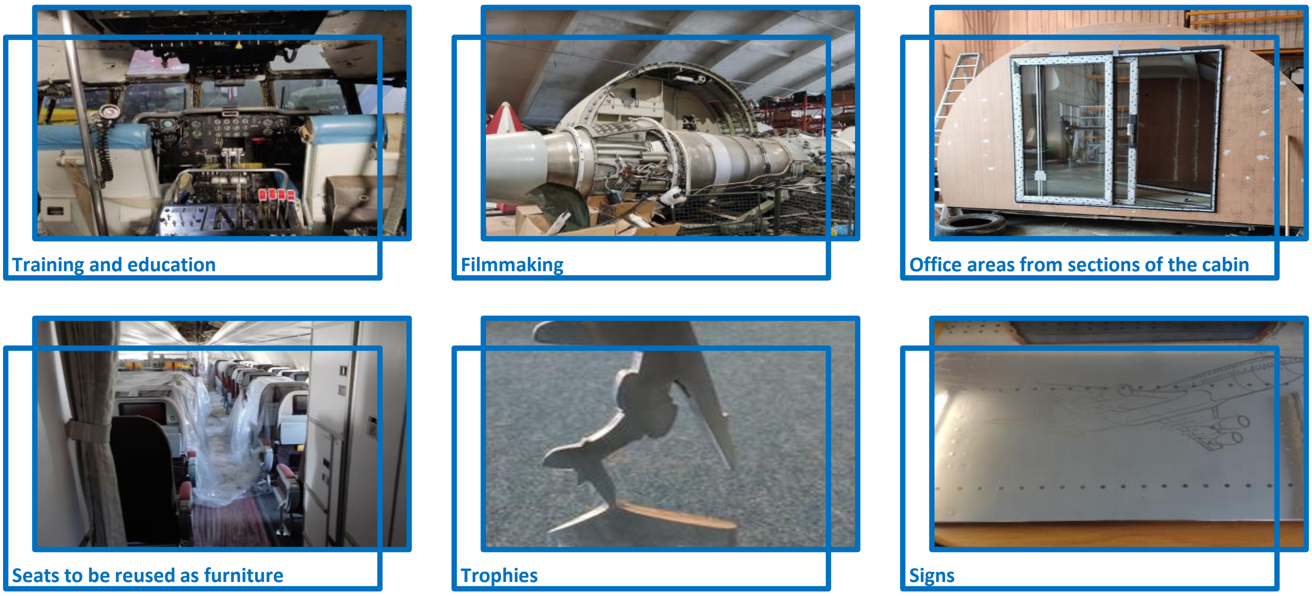

Figure 43. Examples of alternative reuse products (Envisa, 2022)

Case study: GJD Aviation Museum

GJD Services Ltd. provides material for an aviation museum next to its facilities. This museum has several aircraft that can be visited. There are information panels available and guided visits are organised, including school excursions. The museum includes various civil and military aircraft. This constitutes an **example of alternative reuse for old aircraft parts and materials**.

Rests of an accidented aircraft

Old aircraft cabin

Old aircraft

Figure 44. Some pieces of the aviation museum

3.3 Elements within the waste business

In this subchapter, the focus is given to the **waste business**. This involves that the aircraft parts and materials are not employed anymore with their original objectives and applications, in contrast with the previous subchapter of this report. More details of the units and processes that constitute the waste business within the aircraft lifecycle can be found in Chapter 2.

3.3.1 Dismantling

Aircraft **dismantling** constitutes the entry of the aircraft parts and materials to the waste business, meaning that they cannot be reused in the aerospace sector, are considered as waste, and are under the general regulations covering waste treatment. The two main steps during the dismantling phase are:

- The removal of any left liquids and hazardous materials, as well as any other **“unwanted” fraction** (any materials or parts that are either unrecyclable or for which the recycling is not worth the time and effort required for their separation). This fraction is then prepared to be sent to energy recovery and/or landfill. From this unwanted fraction certain materials and parts can be reused in other sectors.
- The preparation of those sections and **parts that will go through recycling**, which require their shredding and transportation to the recycling companies. Usually, parts and materials are prepared to be sent to the metal recycling facilities when the prices are high, as far as possible (when price fluctuations are predictable, waiting times are not too long, and enough material storage space is available).

Case study: TARMAC Aerosave

TARMAC Aerosave was created in 2007 by the founders: Airbus, Safran Aircraft Engines, SUEZ and Equip'Aéro. At that time, TARMAC Aerosave was an extension of the PAMELA-Life project. TARMAC Aerosave provides disassembling activities, obtaining the required parts for the aircraft owners, dismantling, sorting, and provision of the sorted materials to recyclers. In addition, they also keep aircraft parked with minimum maintenance between leasing periods or before disassembling. To be able to achieve proper recycling, they invest on the proper separation of the dismantled materials. The recycling itself (the production of the manufacturing materials via remelting, for instance) is done by recycling companies. TARMAC do the part-out and dismantling for engines as well.

Several initiatives take place to enhance sustainability at TARMAC:

- TARMAC AIR. Project on the new industrial recycling. Looking at improving the disassembling process,
- Collaboration with FAIRMAT on carbon recycling,
- Collaboration with CORAC, French Aeronautic Research Council, funding R&D programme to assess full lifecycle,
- Collaborations with material recyclers, OEMs, and National Authorities,
- Sustainability trainings.

Most of the **value from the parts and materials that enter the aircraft EoL** comes from the reuse of parts in the aerospace business. Therefore, the pure dismantling is performed when all that potential value was already obtained. For instance, a ton of dismantled materials can have a value of a few hundred euros when not used for an alternative reuse activity. Therefore, the effort put in this activity is lower than in the proper disassembling.

Materials above the cabin floor are usually very neat, so these are relatively easy to be used efficiently in recycling. Insulation materials in the cabin can be separated to be reused either in aviation or in other industries.

Regarding the **engines' parts and components**, these follow a particular process, considering their remarkably high value. Engine components are separated to recycle precious metals, such as Au and Pt, if present in sufficient concentration. Engine discs contain rare earths that can be remelted and employed in new turbines. Parts can be reused as well in other industries on some occasions, such as engine turbine blades that can be integrated into land-based gas turbines.

After the harvest list is dealt with, the rest of the parts are separated as much as possible in order to obtain an alternative reuse for them or to send them to different recycling pathways. They focus on separating as many materials as possible to increase the percentage that can be recycled. Before obtaining the fractions to be sent to recycling, the **aircraft** are **cut**. These activities are performed with specialised machinery that is sent to the required locations. Certificates of destruction are released to demonstrate that the parts will no longer be used in the aviation industry. Afterwards, parts and materials to be recycled are transported to the recycling facilities for the separation and processing.

Figure 45. Engine parts separated before dismantling (Envisa, 2022)

Safety and Quality initiatives come from national legislation which apply as well to the aviation industry. These initiatives get complemented with the use of toolbox talks and on the job trainings.

Aircraft cutting procedures as well as **health instructions** are important as part of the dismantling process. An example of the health instructions is to wear masks when cutting carbon fibre. In particular, these are crucial when dealing with materials such as carbon fibre reinforced polymers, which can release dangerous fine particles during their treatment. The principal health hazards of carbon fibre handling are due to mechanical irritation and abrasion. Carbon fibres can easily become a fine dust during cutting, machining and mechanical finishing which can be released to the surrounding atmosphere. These micro fibres can pose health risks when sticking into human skin or the mucous membranes in the respiratory system. Use of heavy gloves, full googles and dust mask is fundamental to prevent dust inhalation. Protective clothing is required as well so the fibres do not enter in contact with the skin. It is also especially important to cut the aircraft in an accurate way. In order to perform the cutting, usually machinery as portal saws and claws are used.

In order to **work with carbon fibres**, workers need to be trained in their use. Examples of the aspects that need to be considered are:

- Use of specific extraction or ventilation systems
- Minimisation of dust generation while machining
- Use of emergency washing stations
- Use of first aid kits

Figure 46. Dismantled aircraft sections (left) and interiors preparation for dismantling (Envisa, 2022)

There are several **risks and precautions in aircraft dismantling**:

- Direct risks for the operator, such as the existence of hazardous pieces of metal.
- Risk of fire since some Jet A1 could remain. This is especially important while cutting. Fire extinguishing measures (hoses) must be available at any time of work.
- FOD (Foreign Object Damage), therefore most activities are carried out in a "tunnel."
- Parts lose traceability, are sold on the black market, and get back into service on the black market ("bogus parts" or unidentified parts).
- Materials not identified. Unidentified materials (asbestos or other that can be dangerous) that can create risks during dismantling.

The last point regarding the non-identification of materials leads to the importance of knowing an **aircraft mapping** during dismantling activities in order to facilitate and improve them. It would be useful to have chapters in the documentation of the parts identifying the materials. Aircraft and engine manufacturers prefer to keep this information as confidential, as some components, especially in engines, are produced out of special alloys that are kept secret; however, this would be quite helpful for dismantlers when given for the airframe and engines.

The **environmental data records** in dismantling varies from country to country and business to business. Some companies record recovery of material by weight and others do by volume, so there is a discrepancy in reporting. The data recorded is particularly important from a sustainable point of view since it helps to estimate the efficiency of the aircraft EoL. As part of the dismantling activities, related companies can keep track of the value generated per aircraft, as well as the fractions sent to recovery and landfill. Labour hours and fuels/machinery employed in the process might as well be registered.

Employment records, specialist training and induction training are all recorded as part of the ISO 9001:2015 Quality Management System in companies that follow this standard. Most companies have similar systems that depends on each nation rules.

Case study: GJD Environmental reporting

GJD Services Ltd. creates a **"cradle-to-grave" analysis** for each aircraft processed which captures the types and quantities of the materials processed during decommissioning and disposal. They follow the waste streams and record what happens to every element. They also capture the labour hours and fuels/machinery employed in the process from beginning to end. As part of their continual improvement, they evaluate each 'job' (aircraft disposal) and have meetings with stakeholders to determine if/what could be improved going forward. Suggestions are taken from staff and clients alike. They also follow the waste streams and record what happens to every element.

Training on the treatment of dangerous materials, such as the carbon fibres, which can release harmful particles, is given to workers to avoid health risks, as well as for example training on how to perform the aircraft cutting. Dismantling facilities can also include specific induction programmes that are given to staff and that are helpful to analyse all the different materials that are part of the aircraft that is going to be dismantled, as well as how to make use of them.

Induction programmes are given at some dismantling facilities for new employees and contractors. Employees are usually encouraged to carry out continuing professional development and it is mandatory to have the correct training and licences prior to using specialist equipment. Quality, Environmental, Health and Safety procedures are normally registered.

Reporting Employment records, specialist training and induction training are all usually recorded as part of the ISO 9001:2015 Quality Management System. Most companies have a similar system as it is required under Health and Safety Legislation, but each Nation will have its own rules.

One of the issues found during dismantling activities has been the **existing legislation**, which for example sets that waste cannot be used as new raw material. This is an issue with the kerosene present at the moment of aircraft decommissioning. Another issue found during the dismantling is the **scale of the recycling for aero grade materials**. Since usually aircraft individually cannot provide the amounts of material required for smelters to produce aero grade aluminium, the metals from aviation tend to be downcycled in other industries.

3.3.2 Recycling, energy recovery and landfill

3.3.2.1 Recycling

After the disassembling has been completed, the **airframe** is usually cut into pieces with sizes that are suitable for transportation into recycling facilities that can be sorted depending on the materials. Metals are mostly recycled through smelting.

Figure 47. Materials to be sent to recycling

Electronic waste is sent to external recycling. Small amounts of precious materials, e.g., gold coatings on electric pins, are not worth being separated mechanically at some dismantling areas, but this is left to the metal recycler. For **engines**, precious materials (e.g., rare earths) are present in larger concentrations in some parts and worth to be separated.

Table 20. Electronics and avionics scrapping outputs sample (Outputs from two typical narrow bodies plus one wide body). Source: interview with aircraft dismantling company

Component/material	Weight (Kg)	Value percentage (%)
PCB's	13	30.3
Mixed Relays & Connectors	209	35
Mixed Cable	357	2.8
Misc Al/Ti	1520	0.5
Platd Ti (wing pipes)	46	29.1
Avionics boxes	1610	2.3
Total	3755	100

Regarding **metals that arrive to EoL phase**, for a typical narrow-body aircraft, around 17 tons of Aluminium, 2 tons of Titanium and 3 tons of mixed metals are obtained. These amounts are not large enough by themselves to allow the upcycling (recycling to raw materials to be used with the same original purpose) to aero grade metals, being therefore necessary to group metals scrapped from several aircraft to feed enough volumes to the smelters and to produce materials that can be used again in the aviation industry.

Currently, most of the aircraft that enter the EoL phase contain high percentages of aluminium alloys (ranging around 60-80%), constituting one of the biggest **potentials of recyclable materials in aviation**. The amount of primary energy required to obtain 1 kg of aluminium that is extracted as primary resource can be averaged around 47 MJ of primary energy, in contrast to the 2.4 MJ that are required when using recycled aluminium. This constitutes approximately a 95% reduction in the amount of energy required. In terms of CO_2 emissions in a typical US average electricity mix, 3.83 kg are released when producing 1 kg of primary sourced Aluminium, in comparison with the 0.29 kg that are released when obtaining the same amount from recycled one[104].

One of the largest **problems in the aircraft materials recycling** is the existence of various alloys, which makes complicated to keep the aero grade when working with their recycling, since additional effort is needed to separate the materials accordingly. Moreover, the aviation legislation includes strict requirements for the materials employed during aircraft manufacturing, which poses challenges for the recycling of materials to be used again in the aerospace industry and leading to much higher percentages of downcycled parts and materials.

High **recovery rates** are reported by manufacturers for the case of aircraft that have been retired in the last decade. For aircraft reaching their EoL during the last decade (with a high share of metals in their structure), recovery rates of around 95% can be achieved by recyclers. These high recovery rates involve the use of downcycling and dealing with aircraft that have a high percentage of metallic parts. Thus, for the case of recent aircraft models containing a significant percentage of composite structural parts, which will enter the EoL phase in the future, new recycling technologies will be required in order to keep the high reusability and recyclability rates. Therefore, there is a good basis, although the situation could be improved increasing the alternative reuse, potentially recycling metals with aero grade that could be used in the aerospace sector again, as well as developing pathways for the carbon composite materials that are becoming increasingly predominant in newer aircraft types.

Table 21. Aircraft fuselage disposal outputs sample (Outputs from two typical narrow bodies plus one wide body). Source: interview with aircraft dismantling company

Component/material	Weight percentage (%)	Value percentage (%)
Ferrous 3b	5.76	3.5
Zorba	50.78	96.1
Oversize materials	4.76	1.7
Titanium	1.04	1.6
Stainless steel	1.48	2.7
Mix cable	2.02	3.7
Fines & Waste	33.14	-9.1
Loss	1.02	-0.3
Total	100	100

The **composition of aircraft structure** has been significantly modified during the previous decades, the latest change being the substitution of Aluminium alloys in fuselages and wings with composite materials. This substitution is carried by the goal of manufacturers to reduce operational costs and emissions, therefore leading them to use lighter and stronger composite materials. Even though these changes constitute additional challenges for the aircraft EoL, the reduced operational impacts compensate the currently higher difficulties

[104] Asmatulu et al. (2013). Evaluation of recycling efforts of aircraft companies in Wichita

during the aircraft EoL. For example, a modern twin aisle aircraft can contain more than 30 tonnes of CFRP composites, made with approximately two thirds of carbon fibre. By weight, the material contents are 50% composite, 20% aluminium, 15% titanium, 10% steel, and 5% other.

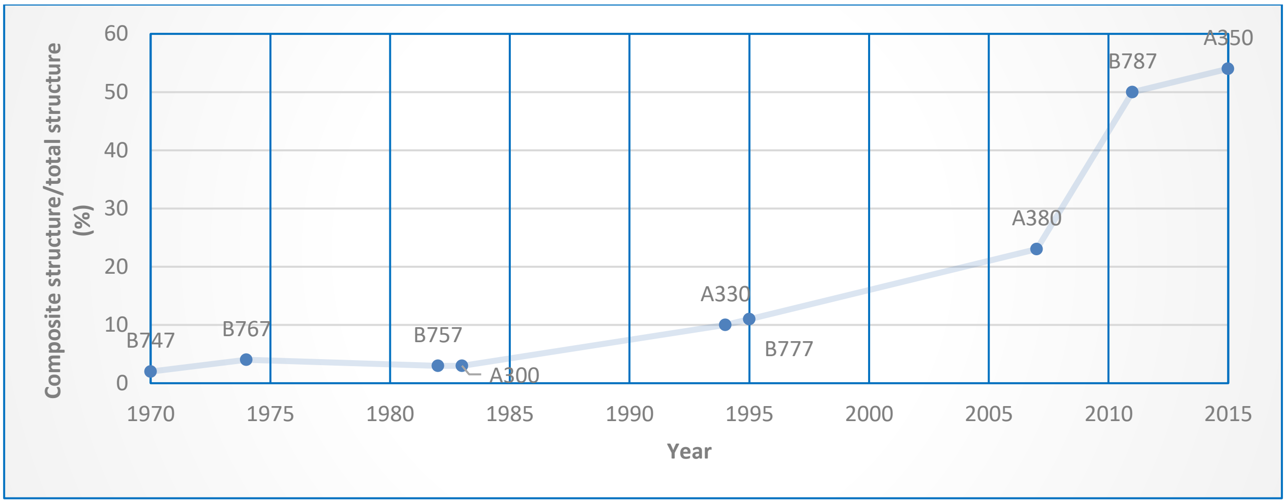

Figure 48. Share of composites in aircraft structure materials (values from Woidasky 2017[105], Wong 2017[106], and Towle 2004[107])

As it can be in the Figure above, the **volume of composite materials that will reach EoL and that will require suitable EoL paths**, such as reuse and recycling, will increase more in the following years. Even though most of these materials are expected to reach the EoL in 20-25 years, the technologies to ease this situation are to be developed in the following years, in order to reach an evolved status when moment requires it.

Composite scrap, which can be seen to increase its importance in the following years, is not only produced during the aircraft EoL, but as well during the manufacturing process itself. This waste is produced during the cutting of the original rolls containing the composites that are used for manufacturing. This scrap is however easier to deal with, since it is "pure," in contrast to the composite scrap of aircraft EoL, which can include as well metallic inserts, honeycombs, etc. as well as being possibly contaminated with chemicals. The production of new Carbon fibre reinforced thermosets requires around 234 MJ/kg energy and generates 12 kg CO_2/kg, while the production of the recycled one requires 33 MJ/kg energy with a generation of 2 kg CO_2/kg.[108]

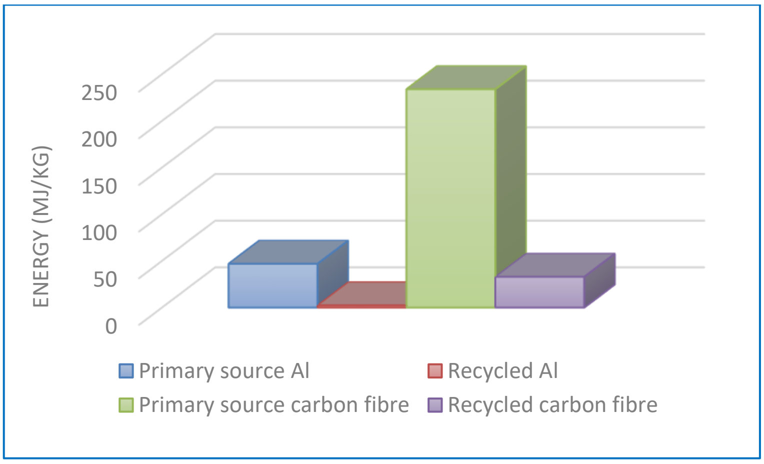

Figure 49. Energy savings from the use of recycled Al and carbon fibre (Data from Asmatulu et al., 2013)

105 Woidasky et al. (2017). Materials Stock of the Civilian Aircraft Fleet
106 Wong et al. (2017). Composites recycling solutions for the aviation industry.
107 Towle et al. (2004). The Aircraft at End-of-Life Sector: A Preliminary Study
108 Asmatulu et al. (2013). Evaluation of recycling efforts of aircraft companies in Wichita

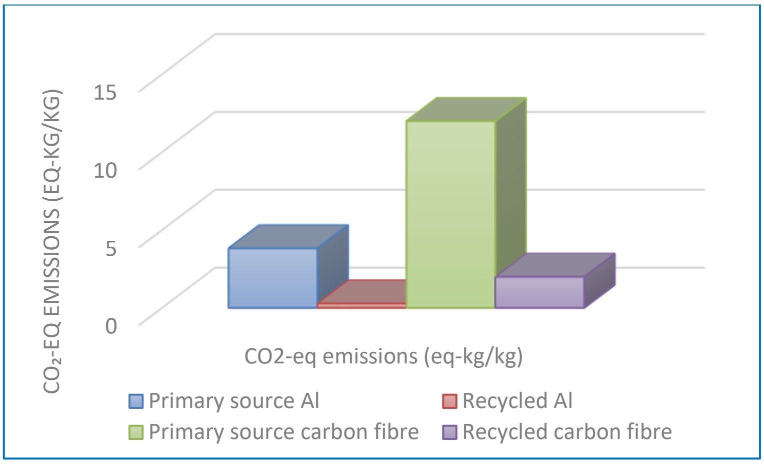

Figure 50. GHG savings from the use of recycled Al and carbon fibre (Data from Asmatulu et al., 2013)

The recycling of composites is a complex process, mainly due to their structure, and a chain of processes need to be carried out in order to obtain reusable recycled materials. The **most often employed composite materials** are the following:

- Thermoset matrices,
- Thermoplastic matrices, and
- Other composites

Each of these types require different **recycling processes**. The main recycling techniques for them are:

- Mechanical recycling, including shredding, crushing, milling and other similar processes. These processes results in the obtention of short fibres with degraded mechanical properties.
- Thermal recycling, which involves the use of elevated temperatures.
- Chemical recycling, which includes the chemical dissolution of the matrix that exposes the fibre.

Case study: Aerocircular activities

Aerocircular was a Belgium-based company which stopped its activities in 2021 and that worked on introducing the circular economy in the sector of end-of-life aircraft dismantling. The company was based at the International Airport of Ostend-Bruges. Dismantling services covered both aircraft landing at the dismantling facility at the Ostend-Bruges airport, as well as remote location dismantling of non-airworthy airframes

Aerocircular managed to obtain close to zero landfill when treating aircraft EoL. The following results were obtained by them for the case of a typical A320 type that has already gone through the disassembling of the valuable parts:

- Close to zero landfill, since only isolation matting was left, corresponding with approximately. 200kg.
- Incineration with heat recovery for the interior composites including sandwich/nomex.
- Carbon fibre materials that are pure monolithic go to break-even recycling, meaning that the transport costs just cover value, which are typically around 200 € per ton.
- 17 tonnes of Aluminium for recycling
- 2 tonnes of Ti (excluding landing gear) for recycling
- 3 tonnes of mixed metal for recycling
- For the rest of the materials, alternative reuse fates were obtained, representing 10% of revenue.

The **composites recycling** is still a field which is being currently under development, and which is expected to gain more importance due to the change in the material composition of the newer aircraft types that are entering the market, and which will need to be recycled in the next decades.

Some materials that are obtained as part of the aircraft dismantling are not recyclable, such as the insulation matting and nomex. They cannot be recycled nor used for energy recovery. These materials can be tackled and employed as part of alternative reuse.

In the case of **engines**, these are a source of rare earths with high values. However, not all these elements are separated and recycled, due to the difficulties to obtain them. For example, smelters usually pay for the Ni, but not for the Co which is present in jet engines. The Platinum coating is a valuable section of the engines as well that is not being used for the moment due to extraction costs. Therefore, there is potential to improve its efficiency and to increase the recyclability of the engines.

Table 22. Dismantling outcomes of an A330. Source: Interview with an aircraft dismantling company

Material	Tonnes	Percentage
Zero fuel weight	68.04	100
Parts reused	21.44	32
recovered metal	40.6	60
Recovered oils and fuel	1	1
Rest (carbon fibre elements)	5	7

Table 23. Average EoL pathways of an average single aisle aircraft (A320, B737 technology level). Source: Interview with an aircraft dismantling company

Pathway	Percentage
Reuse	30
Recycling	60
Energy recovery	8
Landfill	2

AFRA released Best Management Practices that cover aircraft recycling activities. Examples of the initiatives to be implemented by aircraft recycling organisations are the following:

- Designation and preparation of areas to perform the recycling activities.
- Segregation of the recycling materials that are intended to be transferred as aerospace materials from those that are not intended to be used in this way.
- Implementation of internal audits.
- Creation of safe procedures for transportation of materials.
- Use of appropriate storing and shipping containments and packing materials for the articles and materials handled.
- Proper management of drained fluids and disposal according to local jurisdictional requirements.

Case study: Green Earth Recycling Solutions

Green Earth Recycling Solutions is an UK-based company that provides recycling services that cover materials as well obtained from aircraft EoL:

- They hold ISO 14001, ISO 9001 and guarantee zero to landfill.
- They send materials on some occasions to be recycled in other countries, such as China, India, Spain, etc.
- Regarding Aluminium from aircraft, when there is enough volume, it can be used again in aviation. Aircraft grade is tried to be kept, when possible, otherwise it is recycled but used for other purposes.
- The recycling is not a standard process, in the sense that depending on the volumes and characteristics of the materials that reach their facilities, the demands of the customers, logistics, etc. the way to deal with the recycling and the outputs obtained will vary.
- They keep an exhaustive record of all flows. They get audited every 6 months and get regular visits every 2 months.
- They are involved in the commercial phase of the rare earths, but their recovery goes to other specialists.

3.3.2.2 Energy recovery

Energy recovery is defined as a form of resource recovery in which the organic fraction of waste is converted to some form of usable energy. Recovery may be achieved through the combustion of processed or raw refuse to produce steam through the pyrolysis of refuse to produce oil or gas; and through the anaerobic digestion of organic wastes to produce methane gas. In each form (paper, plastic, rubber, communal waste) there is a component with high energy potential and through the recycling process they could be used as a source to perform energy recovery actions. Energy recovery can be applied to waste that otherwise would end-up in a landfill. This process at this stage is not aviation-specific and is therefore applied for aviation waste in the same way as for waste originated from other industries and sectors. There are several advantages of recovering energy from waste, such as providing local source of energy and decreasing the volume of solid waste dumped in landfills, which in turn may have positive effects on carbon emissions since this process avoids methane emissions from landfills and carbon dioxide from fossil fuels. However, it is important to keep in mind that waste incineration itself is as well a carbon-intensive process and undermines the general efforts of carbon emissions reductions in aviation and which can also lead to LAQ issues. In addition, since both non-recyclable and recyclable waste can be used as a feedstock to a waste incinerator, waste prevention and recycling can be discouraged.

3.3.2.3 Landfill

A **landfill** area is a site for disposal of waste materials. According to the EU's waste hierarchy, landfilling is the least preferable option and should be limited to the necessary minimum, therefore, the EU rules aim to limit the amount of waste sent to landfill to the necessary minimum. As it is the case for energy recovery, **the process of sending aviation waste to landfill is not aviation specific**.

EU waste codes are employed to identify the waste types. These documents indicate what was sent if it was collected, who did the collection, etc. Waste carriers must be companies that are certified as well. Permits are required for the transportation of the waste. The EU Waste Directive has the basics for this framework.

Detailed documentation is required for the transportation of waste, which indicates for example:

- Where the waste is taken from
- Where it is transported to
- The description of the waste
- The quantity of each waste type
- The details of the waste producer
- The details of the transporter

Sending waste to **landfill** implies **costs** for aircraft dismantlers. These costs vary depending on each region. For example, these costs can be around 40€ per m^3 of waste that is sent to landfill. If bigger volumes are sent, higher costs are derived. There are requirements to what can be sent to landfill.

It has been proved that current aircraft that go through the EoL process can reach close to zero landfill. For instance, in the case of the company Aerocircular, they managed to reduce the number of materials that went to landfill to around 200 kg for a typical A320 type. Only the isolation matting was left to be disposed.

The main applicable regulation after it is decided that the aircraft is not going to be flown any longer is the European Waste Directive. Countries in Europe have applied this **regulation** in diverse ways, leading to different requirements within the different countries. This inconsistency in the approach to apply the Directive is to be addressed.

3.4 Scale of the business

The **scale of the activities** described for the different areas, units, and processes of our scope can be estimated with the following information:

- The **aircraft manufacturing and current fleet**, which directly influences the maintenance and production steps.
- The **aircraft retirement**, which constitutes the input to the aircraft EoL steps of the aircraft lifecycle.

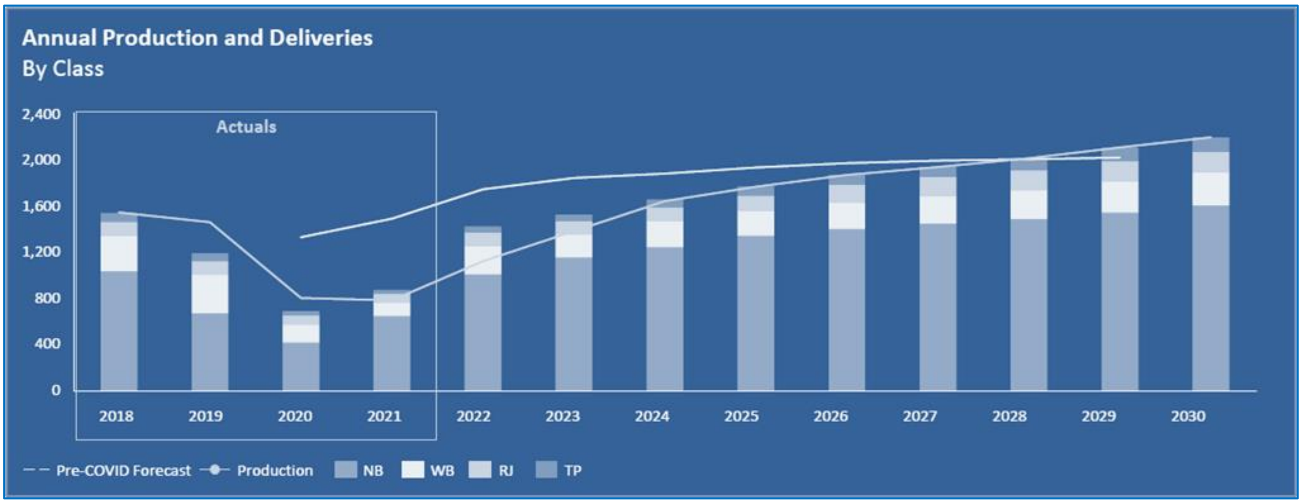

Figure 51. Aircraft annual production and deliveries. (Oliver Wyman, 2022)

Regarding **manufacturing**, a decrease in the annual aircraft production and deliveries took place in 2019 in comparison to the year 2018. This decrease continued during 2020, affected as well by the Covid-19 pandemic. In 2021 and 2022, these figures are increasing, and it is forecasted that, by 2024, the 2018 levels will be recovered, leading to a continuous yearly rise of the produced and delivered aircraft. The majority of the production will correspond to narrow bodies.

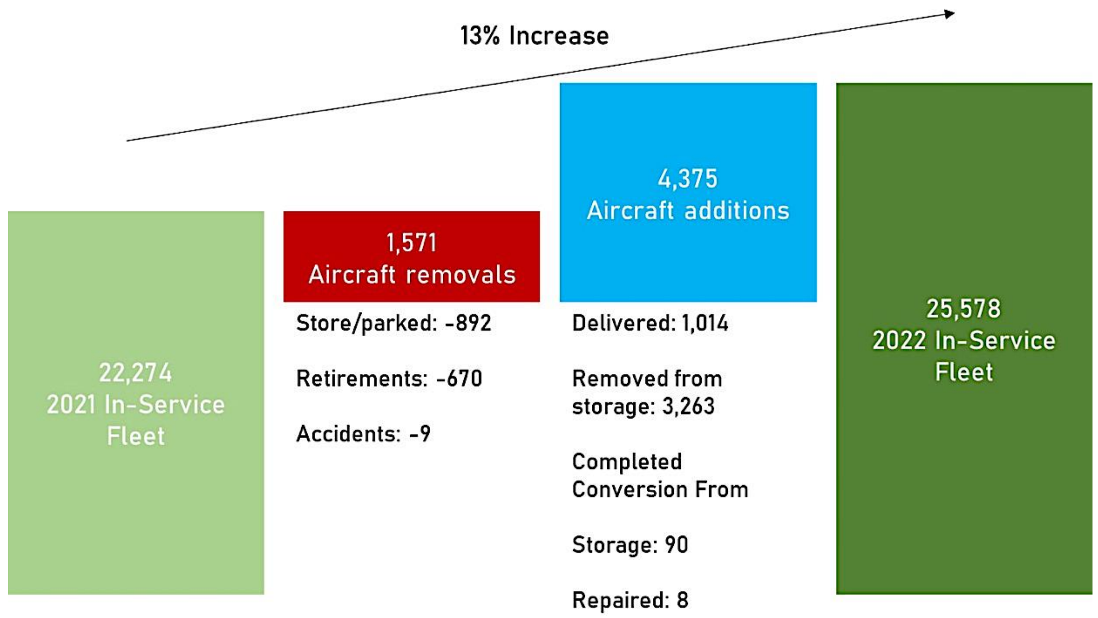

Figure 52. Global in-service fleet changes from 2021 to 2022. (Oliver Wyman, 2022)

As it can be observed in the previous Figure, a 13% increase in the global fleet has occurred from 2021 to 2022. In addition, when looking at the **global fleet forecast** up to 2030, a rising trend has been estimated, reaching 35,700 aircraft. These figures are roughly 10% lower than those obtained before the start of the Covid-19 pandemic.

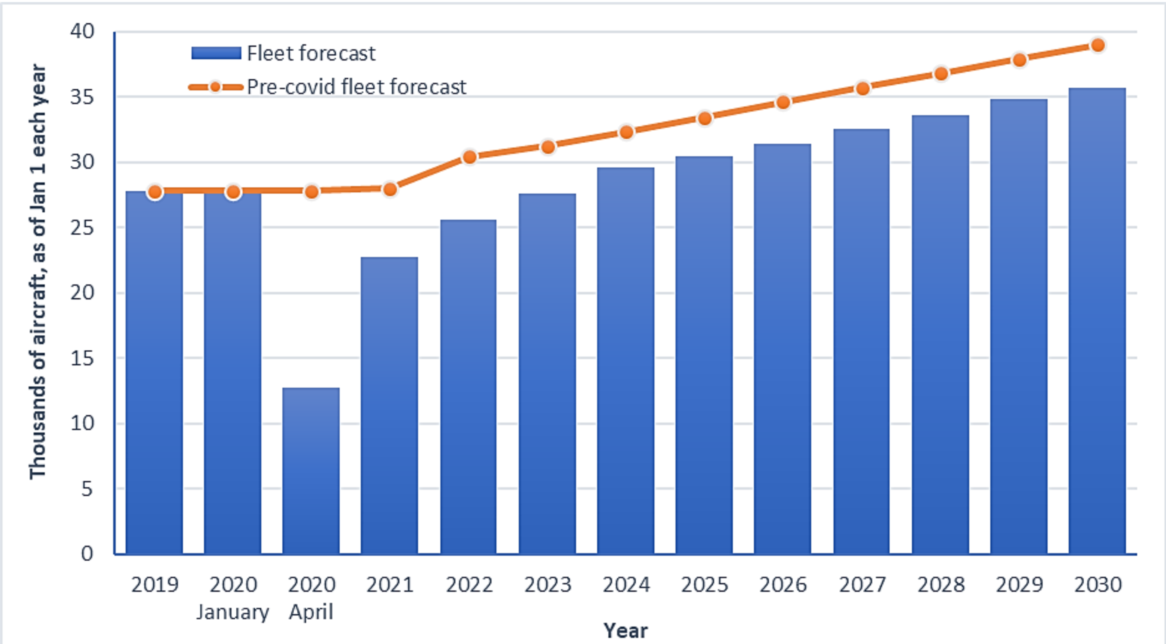

Figure 53. Global in-service fleet forecast, including cargo and passenger fleet. (Oliver Wyman, 2022)

The forecasted increase in the global fleet will lead to an **increasing market for MRO activities**. After an initial decrease due to the Covid-19 pandemic, the market is expected to recover by 2023.

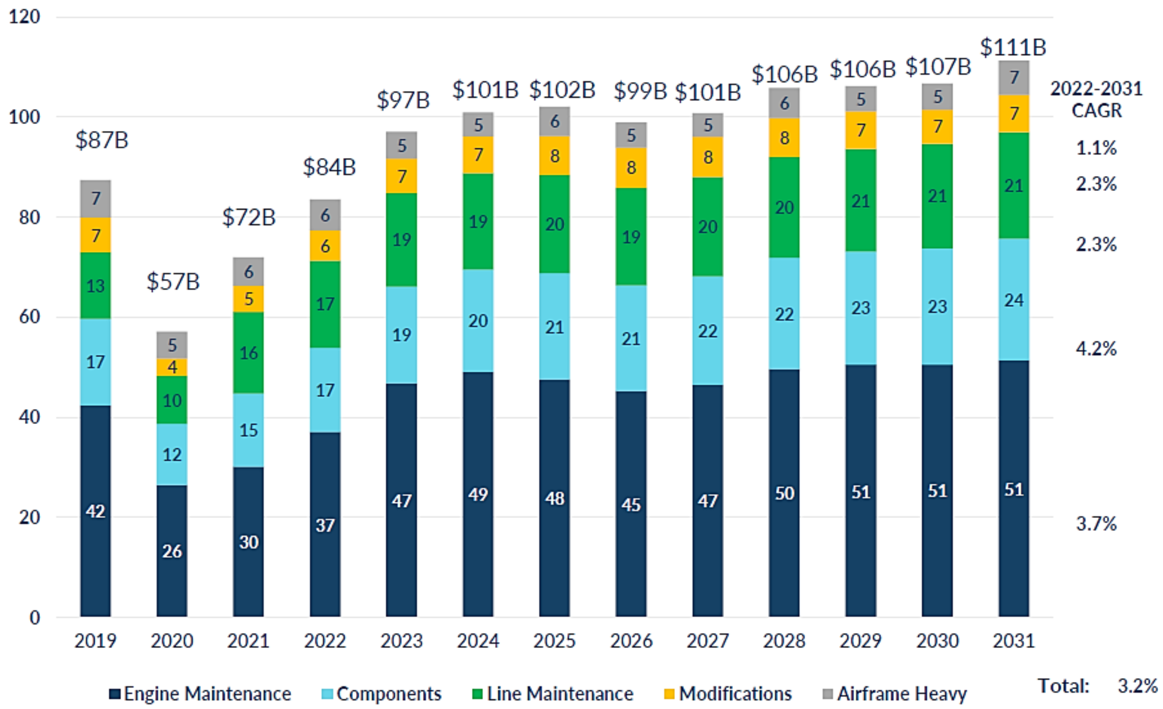

Figure 54. Air Transport MRO Market Forecast, 2019-2031 by MRO Category (Naveo Consultancy, 2022).

Regarding **aircraft retirement**, an average of 650 aircraft were retired yearly during the previous decade. This average is forecasted to increase during the current decade, and after recovering from the effects of the covid-19 pandemic, reaching approximately 800 retired aircraft per year. In addition, more than 30% of the current fleet in Europe is expected to retire over the next decade. (Oliver Wyman Fleet and MRO Forecast, 2022).

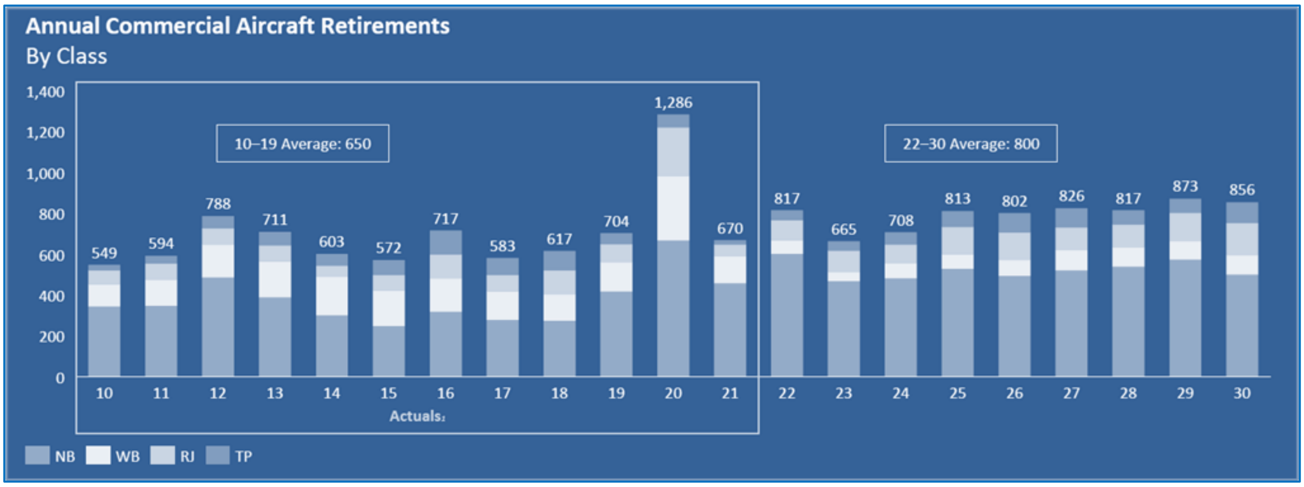

Figure 55. Annual Commercial Aircraft Retirements. (Oliver Wyman, 2022)

In the following table, a **summary of the scale of the business per aircraft lifecycle area and unit** is provided, both for the current situation as well as for the forecasted values.

Table 24. Scale per area and unit

Area	Unit	Source for scale	Pre-pandemic scale (Approximate number of aircraft in 2019)	Recovering crisis scale (Approximate number of aircraft in 2021)	Forecasted Scale (approximate number of aircraft in 2030)
Aerospace business	Design	Aircraft annual production and deliveries	1,200	900	2,000
	Manufacturing				
	Operation and maintenance	Global in-service fleet forecast	27,800	22,000	35,000
	Parking				
	Decommissioning	Yearly aircraft retirement	650	420	800
	Disassembly				
Waste business	Dismantling				
	Recycling				
	Energy recovery				
	Landfill				
Non-aerospace business	Alternative re-use				

4. Initiatives and recommendations to enhance sustainability in the aircraft lifecycle

In this chapter, different **initiatives, and recommendations to enhance the sustainability in the aircraft lifecycle** are presented. These suggestions come from the status quo analysis presented in Chapter 2, as well as from the investigation of the technical culture elements and day-to-day practices (Chapter 3). In addition, feedback from aviation stakeholders have been considered. The initiatives and recommendations are classified following the same structure used for the analysis in Chapter 3. First, solutions for "general elements" are provided, which focus on those initiatives and recommendations that, due to their holistic nature, cover several areas, units, and processes of the aircraft lifecycle. Following the general elements, initiatives targeting specific areas of the aircraft lifecycle are given, starting from those that belong to the aerospace sector and alternative reuse, before specifying those that are part of the waste business.

Note: Envisa is not directly providing solutions to be implemented by EASA. This chapter provides a potential list of initiatives and recommendations that EASA can decide to further investigate and consider based on their criteria.

4.1 Summary of the initiatives and recommendations

In the following table, a list with the summary of the proposed possible initiatives and recommendations by area and subgroup can be consulted.

Table 25. Summary of the initiatives and recommendations

ID	Group	Subgroup	Initiative or recommendation
1	**General elements**	**Regulation aspects**	Consider the option to set EoL regulations for aircraft
2	**General elements**	**Regulation aspects**	Analyse the inclusion of aircraft in the EoL Vehicles Directive
3	**General elements**	**Regulation aspects**	Application of the European Waste Directive to parts/components of dismantled aircraft
4	**General elements**	**Work on incentives**	Possibility to include the generation of carbon credits from sustainable aircraft decommissioning and recycling activities
5	**General elements**	**Work on incentives**	Push for more recognition of sustainable practices, for example, by setting the requirements for aircraft lifecycle activities within the EU Green taxonomy
6	**General elements**	**Use of charges**	Use of environmental charges to foster recycling
7	**General elements**	**Increasing collaboration among stakeholders**	To increase national collaboration
8	**General elements**	**Increasing collaboration among stakeholders**	To increase collaboration among knowledge institutions
9	**General elements**	**Increasing collaboration among stakeholders**	Suggestion for Clean Aviation to launch a call on Circular Economy
10	**General elements**	**Increasing collaboration among stakeholders**	To create industrial partnerships

ID	Group	Subgroup	Initiative or recommendation
11	**General elements**	**Increasing collaboration among stakeholders**	To develop an international framework
12	**General elements**	**Promotion and implementation of sustainable management practices**	To promote the use of environmental management systems
13	**General elements**	**Promotion and implementation of sustainable management practices**	To promote the use of sustainability declarations (labels)
14	**General elements**	**Promotion and implementation of sustainable management practices**	To increase the use of sustainability reporting
15	**General elements**	**Promotion and implementation of sustainable management practices**	To increase the use of sustainability monitoring
16	**General elements**	**Promotion and implementation of sustainable management practices**	To increase the use of sustainable business models
17	**General elements**	**Promotion and implementation of sustainable management practices**	To generate sustainability roadmaps and use for aircraft lifecycle activities
18	**General elements**	**Training of personnel in sustainability and circular economy**	To promote specific training on sustainability aspects could be proposed to be provided to the staff working in the different units and processes of the aircraft lifecycle
19	**General elements**	**Communication activities to increase the visibility of the sector**	Effectively communicate the efforts of the aviation sector on improving sustainability, keeping in mind the key messages and the key stakeholder groups that need to be addressed
20	**General elements**	**Communication activities to increase the visibility of the sector**	To extend the coverage of the aircraft lifecycle and circular economy in the European Aviation Environmental Report
21	**General elements**	**Communication activities to increase the visibility of the sector**	To create a European Aircraft Lifecycle Sustainability White Paper
22	**Aerospace industry and alternative reuse**	**Best practices**	To include of eco-design and "design for decommissioning" principles

ID	Group	Subgroup	Initiative or recommendation
23	**Aerospace industry and alternative reuse**	**Best practices**	To reduce the volume of non-recyclable materials
24	**Aerospace industry and alternative reuse**	**Best practices**	To include the concept of commonality in aircraft eco-design
25	**Aerospace industry and alternative reuse**	**Best practices**	To include the consideration of sustainability criteria when choosing suppliers and services in the aerospace industry
26	**Aerospace industry and alternative reuse**	**Best practices**	Inclusion of sustainability criteria to choose disassembling and dismantling facilities
27	**Aerospace industry and alternative reuse**	**Best practices**	To foster the alternative reuse of aircraft parts and materials that could not be reused in the aviation industry for their original purpose
28	**Aerospace industry and alternative reuse**	**Industry policy**	Increase strategic independence of the EU regarding the acquisition of materials important for the aeronautical sector
29	**Aerospace industry and alternative reuse**	**Regulation aspects**	Study the option to create legislation on aircraft eco-design
30	**Aerospace industry and alternative reuse**	**Regulation aspects**	Inclusion of the principle of "Extended Producer Responsibility" in aviation
31	**Aerospace industry and alternative reuse**	**Regulation aspects**	Use of fluids from aircraft decommissioning

ID	Group	Subgroup	Initiative or recommendation
32	**Aerospace industry and alternative reuse**	**Standards**	Use of dismantling information (Digital Material Passports) for parts disassembled and materials dismantled
33	**Aerospace industry and alternative reuse**	**Standards**	More stringency in the noise, emissions, and CO_2 standards for in-service aircraft[109]
34	**Aerospace industry and alternative reuse**	**Standards**	Implementation of serialisation, electronic records, and digital back-to-birth traceability for aircraft parts
35	**Aerospace industry and alternative reuse**	**Publication of materials and components of the aircraft**	To provide aircraft mapping/cartography to help performing dismantling activities
36	**Aerospace industry and alternative reuse**	**Publication of materials and components of the aircraft**	To include a waste/material treatment manual indicating the materials used in each of the aircraft components, as well as their potential hazardousness and need for specialised treatments
37	**Aerospace industry and alternative reuse**	**Decommissioning registry**	Creation of a registry, probably at ICAO level, which includes the decommissioned aircraft
38	**Aerospace industry and alternative reuse**	**Decommissioning registry**	Creation of a certificate of aircraft retirement
39	**Aerospace industry and alternative reuse**	**Aircraft decommissioning decision recommendations**	To include Economic analysis to decide on the aircraft decommissioning decision

[109] This initiative has an indirect effect on aircraft decommissioning, since it would increase the retirement of older generations aircraft.

ID	Group	Subgroup	Initiative or recommendation
40	**Aerospace industry and alternative reuse**	**Aircraft decommissioning decision recommendations**	To include Environmental analysis to decide on the aircraft decommissioning decision
41	**Waste business**	**Improving recyclability and reuse of parts and materials**	Development of recycling scenarios for today's non-recyclable fractions
42	**Waste business**	**Improving recyclability and reuse of parts and materials**	To enhance carbon fibre and other new materials recycling
43	**Waste business**	**Improving recyclability and reuse of parts and materials**	To consider take-back schemes for those components and materials that arise with the use of electric and hydrogen aircraft
44	**Waste business**	**Increase of aero grade metals upcycling**	To foster volume grouping and consolidation to create the scale required for economically feasible recycling streams
45	**Waste business**	**Increase of aero grade metals upcycling**	Setting of upcycling targets by aircraft manufacturers
46	**Waste business**	**Wider application of current best practices handbooks**	Wider application of AFRA BMP for disassembling and recycling
47	**Waste business**	**Set the aspirational goal to eventually reach zero landfill**	Consideration of a final target for the treatment of the aircraft EoL that should be to reach zero landfill

4.2 General elements

4.2.1 Regulation aspects

As it has been indicated in the previously, **there is currently no regulation worldwide about EoL specifically targeting aircraft**. There is, however, regulation that affects aircraft EoL, such as the waste legislation, which enters into play after the dismantling process has started, when the different aircraft parts and materials become waste. There is as well a Regulatory Position Statement from the UK Environment Agency regarding the removal of airworthy parts from waste aircraft.

In the EU, the EoL Vehicles Directive is in force, although it is focused on road vehicles. **Setting related regulations** would help changing the current situation, in which aircraft disassembling customers (leasing companies rather than airlines) often do not tend to include sustainability and circular economy considerations into their decision to choose a particular company to take care of their EoL aircraft. It is important to keep in mind that when designing this type of solution, the **perspectives and experiences from other sectors are beneficial and useful**. For example, experiences from the automotive industry, as well as the maritime transportation are relevant for the implementation of specific solutions for the aviation industry.

In addition, when proposing **solutions**, these **should be considered from the perspective of the global system**. International aspects need to be considered, otherwise there is the risk to, for instance, establish comprehensive and strict legislation in Europe that can lead to the relocation of the aircraft disassembling and dismantling activities into other countries where these regulations would not apply.

The inclusion of any of these **regulation aspects are to be discussed in detail among all relevant stakeholders before taking definitive decisions** (for instance, AFRA, GAMA, IATA, etc.). Regulations are important but are one of the many measures available. Therefore, a balanced approach should be taken, including regulatory aspects when required and to the extent which is found to be necessary and/or supporting stakeholders' work towards sustainability and circular economy.

As part of the EU Circular Economy Action Plan (adopted March 2020), there will be **upcoming legislation on eco-design** (but only for specific groups of products, which do not include aircraft). Textiles, construction, and electronics are the priority under the scope of the EU. Therefore, it is recommended to consider integrating aircraft into these groups. Aircraft sector is to lead by example, translating eco-designs into the aviation business.

In addition, **the inclusion of aircraft in the EoL Vehicles Directive could be analysed**, in order to provide clear aviation targets for reuse, recycling and recovery of aircraft parts and materials, and mechanisms for its monitoring. This inclusion would have to consider the evolution of materials and in aircraft manufacturing over the years, as well as the new technologies, such as electric or hydrogen-powered aircraft. It is important to note that the current End-of-Life Vehicles Directive places the responsibility on manufacturers, importers, and distributors to collect the road vehicles and provide systems for their reuse and recycling – this responds to the "polluter pays" principle, indicated in the EU Waste Framework Directive. The application of this responsibility to the aviation counterparts would have to be discussed, in order to assess which stakeholders (manufacturers, distributors, owners, etc.) should hold it. The application of this Directive should always be adapted in a way to optimise environmental benefit without incentivising the relocation of the aircraft disassembling and dismantling activities into other countries.

Also, **the European Waste Directive is to be harmonised among the different European countries**. The current application leads to differences within the different EU members, which is required to be solved in order to reach equality. This is a general recommendation to ensure the harmonisation of the Directive, not to make aircraft owners carriers of waste, which would be troublesome, and which would not reflect the fact that many parts and components would re-enter the aerospace sector to be re-used.

4.2.2 Work on incentives

Incentives to enhance sustainable practices in the aircraft lifecycle would be useful. An example of incentive could be that sustainable aircraft decommissioning and recycling could generate carbon credits usable for EU-ETS (or CORSIA). The costs of the ETS would thus flow back into the aviation industry.

It would now be a **suitable time to push for more recognition of sustainable practices**, as sustainable behaviour is becoming a competitive advantage also in the finance sector. For instance, by setting a financial requirement for disassembly companies to be AFRA-certified. The currently observed trend in the finance sector towards giving more weight to sustainability aspects is expected to make such requirements more likely than in the past when decisions were dominated by pure profitability aspects. In this regard, it is relevant to mention the EU taxonomy for sustainable activities, which defines business sectors eligible for preferential financing and which foresees decommissioning of an old aircraft as a prerequisite for favourable conditions for purchasing a new one.

Some points to be clarified on the application of the EU Green Taxonomy in aviation:

- What would the consequences be of "non-compliance" with the criteria'
- What is the scope of the taxonomy? Does it apply only to EU airlines, to only aircraft decommissioned in the EU, or also elsewhere?
- Maximum parking period of an aircraft before decommissioning to comply with the taxonomy.
- Understanding of the replacement rate between decommissioned and newly built aircraft to obtain access to "green financing."

4.2.3 Use of charges

It could also be considered the **use of environmental charges to foster recycling**, energy recovery, reuse, etc as part of the aircraft EoL. This environmental charge would then be applied to the manufacturers to improve eco-design and to achieve the circularity of their products. As another example, revenues from EU ETS could be used to enhance aircraft recycling activities.

4.2.4 Increasing collaboration among stakeholders

Collaboration within the different stakeholders involved is key to advance in the sustainability of the sector and obtain satisfactory results. The list of the different collaboration initiatives, and the stakeholders involved are indicated in the table below.

Table 26. Collaboration initiatives

Collaboration type	Stakeholders involved	Description
National collaboration	National governments and aircraft lifecycle organisations at a national level.	Needed to identify national requirements and mobilise actors at a national level. An example in the field of aviation is the White paper on Research and Development in aviation sustainability in Spain[110].
Industrial partnership	Between companies involved in the same aircraft lifecycle units.	Industrial partners are crucial as well in order to enhance the circular economy of the sector. An example of this collaboration would be the fostering of volume grouping and consolidation among aviation metal recyclers so that volumes become large enough to allow economical recycling of aero grade aluminium to be reused in the aviation industry can be achieved.

[110] SENASA (2020). White Paper on Research and Development of the Aviation Sustainability (in Spanish)

Collaboration type	Stakeholders involved	Description
Knowledge institutions	Universities, Research and Development Institutions, Specialised consultancies, and the relevant aircraft lifecycle organisations.	Advancement in newest techniques through the collaboration between research and day-to-day practices. Advance in the research of new materials and to produce technology building blocks. An important example in this regard is to foster the share of information of currently non-recyclable materials coming out of the aircraft EoL with other organisations and research programmes that explore possibilities for their use. This collaboration is valuable and required to achieve ideally zero-waste as part of aircraft EoL activities. Currently, the amount of non-recyclable materials is not high, but these are expected to increase when newer aircraft types reach the market, due to their higher percentages of carbon fibre materials. It would also be important for R&T funding organisations to launch calls for projects to advance on the technical and scientific aspects of the implementation of these initiatives, as well as on technical/scientific advancements to foster sustainability and circular economy in aviation, to be carried out by the knowledge institutions. In this regard, it could be suggested to Clean Aviation to launch a funding call on Circular Economy, where partnerships along the value chain are explicitly required.
International framework	ICAO and all other aviation international stakeholders	The role of ICAO within the development of an international framework for aircraft EoL is an important consideration that should be addressed in order to establish an efficient and effective global aviation EoL system, working as well towards the global aviation targets, such as the carbon neutrality by 2050. This international framework to manage aircraft EoL activities, could include schemes, best practices, etc[111]. ICAO's role would include the harmonisation of governmental regulations and activities and for instance establishing a worldwide aircraft decommissioning register.

4.2.5 Promotion and implementation of sustainable management practices

Sustainable management considers the fact that taking non-environmentally responsible economic actions makes it difficult to preserve good environmental and social conditions in the future. It aims to run organisations in a way that allows to meet the needs of the company without harming future generations' natural and social resources. Sustainable management includes aiming for long-term profit, circularity, reduction of carbon footprint, ensuring sustainable supply chains, and social sustainability. The inclusion of sustainable management practices in the different organisations involved in the aircraft lifecycle is an important step to achieve sustainability. Different practices are under the framework of what is described as "sustainable management." In the table below, recommended initiatives in this regard are indicated.

[111] An example could be the approach taken by the International Maritime Organization with the recycling of ships

Table 27. Proposed Sustainable Management Practices

Sustainable Management Practices	Description
Use of Environmental Management Systems	Environmental management systems help organisations identify, manage, monitor, and control their environmental issues in a holistic manner. The following EMS can be considered: EMAS, ISO 14001, ISO 9001, AS9100, AS9110 and AS9120, ISO 19011, and ISO 50001. More information about these EMSs can be consulted in Chapter 2.
Sustainability declarations (labels)	Sustainability labels (such as the EASA Ecolabel) are often employed to mark products or processes that fulfil a series of sustainability requirements. Type III declarations are suggested to be employed for those products that are created by the different organisations in our scope. Type III declarations (ISO/TR 14025) consist of quantified product information on the life cycle impacts. In this type, instead of assessing or weighting the environmental performance, the objective data obtained during the sustainability assessment is presented, which facilitates the comparison among products. This aspect includes the integration of LCA and carbon footprint methodologies.
Sustainability reporting	Environmental statements and reports are intended to establish a framework of reference for the integration of the protection of nature and the environment within the strategy of the organisation, as well as its investments and operations. These reports show the main principles of conduct and the priority lines of action that aim to achieve sustainability[112]. In this regard, big OEMs will soon need to report on sustainability efforts as per Corporate Sustainability Reporting regulation[113].
Sustainability monitoring	Sustainability monitoring means the recording, tracking and analysis of the sustainability performance of an organisation. In order to be able to perform this action, sustainability KPIs need to be created in the organisations, targeting different areas and that will allow to follow the performance of the organisation in the way to achieve sustainable development targets. As part of the sustainability monitoring, the use of electronic platforms and dashboards to keep track of the evolution of the KPIs is a useful approach to be implemented.
Use of sustainable business models	Sustainable business models are growing in literature and in the industry, driving companies to search for opportunities to improve their impact on sustainability. They integrate the classical point of view of business models with the three pillars of sustainability[114].

[112] Examples of these sustainability reports are Airbus sustainability reporting, Boeing 2022 Sustainability Report and Lufthansa group sustainability reporting
[113] EU Commission - Corporate sustainability reporting
[114] An example of a sustainability strategy in the aviation sector is ENAIRE's Green Sky

A way to integrate the previous elements is the elaboration and integration of **sustainability roadmaps** for the different organisations. These roadmaps integrate: a description of the organisation, its sustainability activities and targets, a set of KPIs to measure their sustainability performance, and further initiatives and timelines to reach those targets.

4.2.6 Training of personnel in sustainability and circular economy

Specific training on sustainability and circular economy aspects[115] could be proposed to be provided to the staff working in the different units and processes of the aircraft lifecycle. These trainings would include the fundamentals of sustainability, how it applies to their sector, the relevant regulations, and the tracking of the relevant sustainability indicators that correspond to their field.

4.2.7 Communication activities to increase the visibility of the sector

Parts and materials have been regularly reused as spare parts in the aviation sector, although not much communication to a broader public has been used regarding these activities. These messages would help keeping the image of the aviation field in a good position, helping to make people understand that efforts are being made to make it sustainable, while fulfilling all safety requirements. This is a problem to be solved when dealing with groups of people who are hostile to aviation because of its image as a polluting industry. Aviation needs to communicate in a meaningful way to change this perception but being careful to always avoid greenwashing. To summarise, the **aviation sector needs to effectively communicate its efforts on improving sustainability, keeping in mind the key messages and the key stakeholder groups that need to be addressed**.

In this regard, it is also advised to extend the section on **aircraft lifecycle and circular economy in the European Aviation Environmental Report**[116], such as the design, production, and maintenance phases, as well as the alternative reuse and the aircraft EoL.

It is also recommended to produce a European Aircraft lifecycle sustainability white paper. This **white paper**[117] would describe the situation of the sector in Europe and **set goals and objectives to be achieved as well as their timescales**. The white paper would be published as a result of the discussion and agreement of the aforementioned initiatives. **Common definitions** should also be included in this white paper so all stakeholders and the public can have a good understanding of these activities.

4.3 Elements within the aerospace industry and alternative reuse

4.3.1 Regulation aspects

As part of the EU Circular Economy Action Plan[118], adopted in March 2020, there is an action at the European level to create legislation on eco-design. Currently, the Eco-design Directive[119] establishes measures for energy-related products. However, aircraft are not listed as part of the main groups of products included. The goal with the new Circular Economy Action Plan is to widen this Directive to make it applicable to the broadest possible range of products and make it deliver on circularity. In March 2022, an updated version of the **eco-design directive** was published by the Commission, including circular strategies (modularity, repairability,

[115] An example of sustainability aviation trainings is the IATA's Aviation Environment and Fuel courses

[116] Less than half a page in the 2022 edition

[117] As indicated previously, the Spanish Aviation Safety Agency published a White Paper on Research and Development of the Aviation Sustainability White Paper on Research and Development of the Aviation Sustainability (in Spanish), which can be considered as an example of such publication.

[118] European Commission (2020). Communication from the commission to the European Parliament, the Council, the European Economic and Social Committe and the Committee of the Regions. A new Circular Economy Action Plan For a cleaner and more competitive Europe

[119] European Parliament and Council (2009). Directive 2009/125/EC of the European Parliament and of the Council of 21 October 2009 establishing a framework for the setting of eco-design requirements for energy-related products

materials use, recycling, etc.). The directive however is only valid for about 130 product groups. There is a need to design aircraft in a way to envisage end-of-life and circular strategies in mind. This review is expected to build where appropriate on criteria and rules established under the EU Ecolabel regulation, the Product Environmental Footprint approach, and the EU Green Public Procurement Policy. **The aviation sector is then set to lead by example, translating eco-designs into the aviation business**.

In addition, the **principle of Extended Producer Responsibility** that is fostered by the European Waste Directive[120] for certain waste flows **should be extended to include aircraft as well**. This is especially important to be addressed considering the evolution of aircraft materials, which is leading to increasing percentages of carbon fibre, which is a future problem since there is no commercially viable solution at present and the problem is being postponed for future generations to deal with.

Another aspect to be considered from a regulatory perspective is to allow the **use of fluids from aircraft decommissioning**. For instance, the re-use of Jet Fuel A kerosene is nowadays not allowed due to customs regulations. During aircraft decommissioning, several tonnes of Jet A1 can still be on board. Since at this point, the kerosene is considered waste, it is not allowed to be employed in aviation. An option to revert this situation would be to allow selling waste products as long as they were in good condition. The legislation would need to be modified to allow kerosene to be re-used as jet fuel. In addition, other fluid streams could be incorporated.

4.3.2 Best practices

An important approach to increase the sustainability of the aviation industry is to include eco-design principles, which would lead to the use of environmentally friendly materials and the use of materials that are easier to reuse and recycle. The eco-design should include as well "**design for decommissioning"** principles, as this is an important aspect that needs to be addressed by aircraft and engine manufacturers. It is crucial that aircraft are designed in a way that their materials and parts are easy to disassemble and either reused or eventually recycled, considering the inclusion of materials with the same EoL fate in a modular way. Priority should be given to materials that are easily recyclable in the production phase. On the other hand, those that have more difficulties to be recycled should be used less and less, until solutions for their recycling are found. Finally, if no recycling pathways are available for certain materials, these should not be used, and alternatives would need to be found. The inclusion of the eco-design principles would be a voluntary initiative by manufacturers which would require raising awareness, training, etc.

As part of the eco-design principles, **engines** need to be considered with special attention, since they hold a significant part of the total value of the components to be recovered. For jet engines, it would be a great advancement to assure that components with elevated levels of critical raw materials are demountable of separatable. Alloys would be important to be selected allowing enhanced recovery as well.

Finding ways to avoid use of **critical raw materials** in aviation would also be an important aspect to consider lowering this dependence. Alternatively, a circular recycling scheme to recover all back should be adopted.

Another important concept to be included into the promotion of eco-design principles is the "**commonality**" **for aircraft parts and components**, which is linked to the ease to obtain parts. For instance, in the case of the A320-neo, it can employ many parts from the A320ceo version, therefore increasing the access to parts and materials to be reused.

In addition, and from a procurement point of view, it would be helpful to include the **consideration of sustainability criteria when choosing suppliers and services in the aerospace industry**. For example, when manufacturers select providers for certain parts or materials, it would be useful to give priority to those certifying that their products have a lower environmental footprint, following circular procurement policies[121].

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[120] European Parliament and Council (2008). Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives

[121] European Commission (2017). Circular procurement

This choice would also apply, as indicated, to the delivery of services, so, for instance, an aircraft owner would provide priority to send its aircraft to a disassembler that holds an environmental management system.

In the case of the **selection of a decommissioning facility**, it is recommended that not only expenses are taken into consideration, but also the facility location, climate (for storage), storage and maintenance capability if needed, future marketability of the components and available accreditations.

When **selecting disassembling and dismantling facilities**, it is recommended that the facility[27]:

- Holds valid certificates of authorisation from the environmental authorities and an environmental policy,
- Is able to document the decommissioning and disassembling activities (e.g., certificate of destruction, material traceability),
- Is able to meet the aircraft owners'/operators' environmental and corporate goals (e.g., recycling rates, waste minimisation),
- Holds environmental management systems.

Moreover, the **feasibility of banning certain materials which cannot be recycled currently** could be analysed. Examples of these materials are sandwich materials, Nomex, isolation matting, etc. An alternative is to oblige producers to offer recycling process for these materials in order to put them into the market, which is linked to the extension of the Extended Producer Responsibility.

4.3.3 Industry policy

An important topic to be addressed which is connected to the use of materials for aircraft manufacturing is the need for material efficiency, coupled with the interest of the EU to achieve **strategic independence** when it comes to raw materials. The European Commission could work on making the EU more independent from single countries regarding the acquisition of materials.

4.3.4 Standards

The **use of dismantling information (Digital Material Passports)** would be beneficial to be implemented in the case of aviation. For instance, in the case of road vehicles, producers must supply dismantling information for each vehicle type within 6 months of it being placed on the market. Giving transparency on materials used allows dismantlers to optimise sorting and process materials in a correct way. Today, dismantlers do not have this basic materials information and need to run costly analyses to retrieve materials used, often varying per aircraft type. Although the complete aircraft is designed and available digitally in CAD, the digital definition availability usually stops at aircraft delivery.

In addition, the **increase of the stringency levels in the different aircraft noise and emissions standards** is a way to decrease the aircraft operational impacts and is therefore an important way to increase the sustainability of its lifecycle.

When analysing the day-to-day practices in the aircraft lifecycle, we can realise that there are still **many activities** that **rely on processes that are still done with paper records**. This is particularly valid in the case of MRO organisations, which are still at the beginning of their journey to a complete digitalisation. This digitalisation process requires **teamwork**, and industrial partnerships, as indicated, would be useful to achieve this goal. There are various **processes** that are part of the activities of the organisations **that can be subject of digitalisation** and that are relevant for enhancing their sustainability and circular economy. For instance, in the case of MRO activities, the following are examples of digitalisation elements:

- Paperless operations
- Predictive analysis
- Digital twins
- AI Technologies
- Augmented reality

- 3D printing
- SHM
- Digital records
- Secured digital back-to-birth traceability

In particular, the last two elements of the list of examples: "Digital records" and **"Secured digital back-to-birth traceability"** are quite relevant.

The use of digital records would require a first key step, which is the serialisation (assignation of unique IDs) of all aircraft parts. After performing the serialisation, the digitalisation would constitute the substitution of the current parts documents with electronic ones. These electronic forms could be stored in a digital registry. This registry would allow for an easier access to a part history, to determine if there are any gaps, and to establish a back-to-birth traceability. In this regard, and as explained in Chapter 2, IATA released a Guidance material for the implementation of Paperless Aircraft Operations in Technical operations[122], which could be applied or taken as a basis for further developments. An important aspect of **digitalisation** is that it also **helps to solve the labour problem that many organisations have**. Digitalisation attracts younger generations, therefore making these markets more appealing and demanded by young professionals. In contrast, older generations working in MRO might be more reluctant to be traced and to enter data into apps and other computer software.

A mixture of top-down and bottom-up initiatives are required to establish digitalisation. It could be useful to consider establishing a "**Guidance on the digitalisation of the aviation organisations**." This guidance could be studied to be provided by EASA and FAA, setting a common ground and a standardised system for parts history records for the organisations to follow.

In addition, the "Electronical back-to-birth traceability" would be important to avoid the use of **counterfeit parts**, which are those unapproved parts that are created deliberately to mislead, pretending to have been produced under approved systems and methods. Counterfeit parts can be as well those that initially had been properly produced, but that have reached a design life limit or have been damaged beyond possible reparations, but that are deliberately manipulated to look as acceptable, with the intend to defraud. This electronical way of storing and accessing information from parts would make it easier to follow the parts history and to detect any potential gaps[123].

4.3.5 Publication of materials and components of the aircraft

Having the **aircraft materials mapping/cartography** during dismantling activities would be helpful to increase the reusability and recyclability rates. With that goal in mind, it would be useful to have chapters in the documentation of the parts identifying the different materials and their locations.

Aircraft and engine manufacturers prefer to keep this information as confidential, as some components, especially in engines, are produced out of special alloys that are kept secret; however, providing this information would be helpful when it comes to increase the efficiency of the aircraft EoL phases, reducing the amount of material that would end as landfill.

[122] IATA (2017). Guidance Material for the implementation of Paperless Aircraft Operations in Technical Operations (PAO:TO)

[123] In this line, ICAO included guidance material on the use of Electronic Aircraft Maintenance Records (EAMR) and continuing airworthiness records in the unedited 4th edition of the Airworthiness Manual – Doc9760.

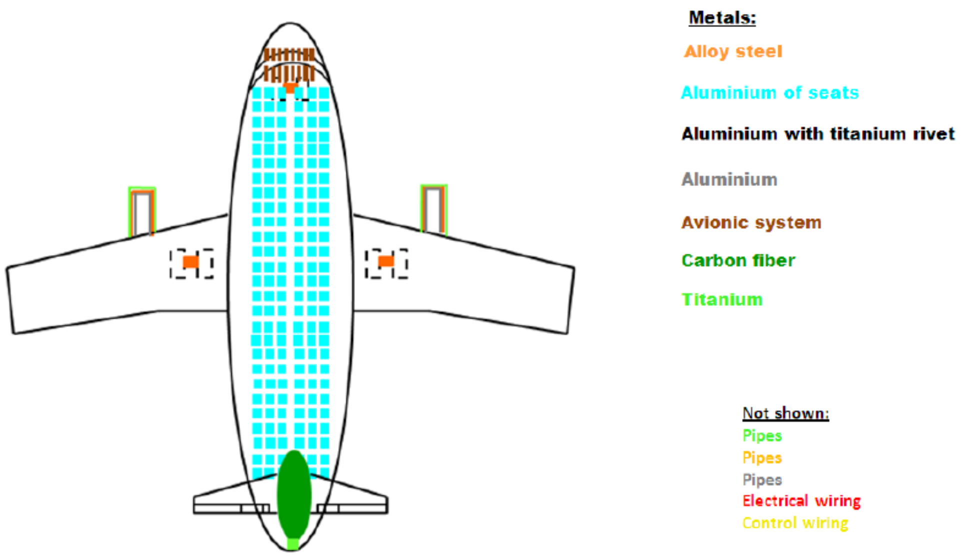

Figure 56. Aircraft metals mapping (Aimere project, 2014)

A potential improvement would be as well to **include a waste/material treatment manual** indicating the materials used in each of the aircraft components, as well as their potential hazardousness and need for specialised treatments. These manuals would be transferred from the aircraft manufacturer to the owner, maintainer, and aircraft dismantler.

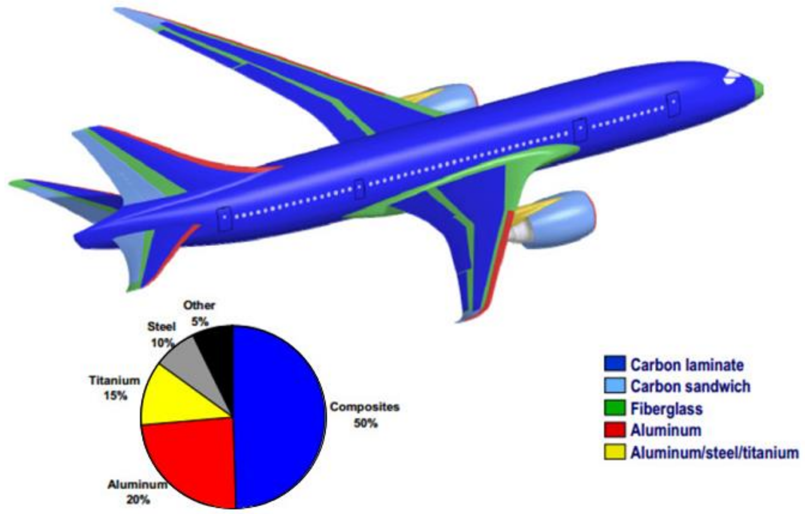

Figure 57. Aircraft materials mapping (Aimere project, 2014)

4.3.6 Decommissioning registry

It is suggested to study the possibility of creating a **registry**, probably at ICAO level, **which includes the decommissioned aircraft**, therefore constituting an important source of information regarding aircraft EoL. Aircraft included in this registry could have as well a **certificate of aircraft retirement**[124] available that includes

[124] For instance, in the case of the End-of-Life Vehicles Directive, there is a certificate of destruction that is issued with the following requirements: 2002/151/EC: Commission Decision of 19 February 2002 on minimum requirements for the certificate of destruction issued in accordance with Article Directive 2000/53/EC of the European Parliament and of the Council on end-of-life vehicles (Text with EEA relevance)

that parts are treated properly, therefore, not only targeting the deregistration, but also the disassembling and dismantling phases.

4.3.7 Aircraft decommissioning decision recommendations

Currently, the **decommissioning decision is mainly driven by economic and safety factors**, the main reasons being the increase in the operational costs, fuel consumption, rise of fuel prices, new regulatory requirements, and difficulties to obtain spare parts. When costs are expected to become excessive, or due to safety issues, the aircraft owner usually decides to retire it from the fleet. Therefore, the decommission decision depends on the point in time when the value of the individual parts of the aircraft is higher than keeping the aircraft itself.

In order **to improve the decision making concerning the moment when to decommission an aircraft, from the economic perspective**, it is recommended to[125]:

- Fully understand the influence and risks of the factors impacting aircraft decommissioning (fleet planning, operational life, maintenance cycle, technological improvements, economic conditions, accounting principles and aircraft value concepts).
- Continuously track these influencing factors.
- Assess the maintenance investment required on the aircraft, such as major airframe structural checks, components (e.g., engine), shop visits and other modifications. If the return on investment on maintenance is not positive, it may be considered a good opportunity to disassemble the aircraft.
- Assess the development of new aircraft types, as well as the differences and commonalities with current models.
- Revisit the accounting principles (e.g., depreciation method) used by the company, especially the useful life and the residual value, at least once a year. Adjust the residual value of the aircraft in accordance with the market value to avoid unanticipated gap in the values.
- Assess the market value and scrap value of the aircraft, together with the potential future operational profit generated by the aircraft, when considering disassembling an aircraft.

In addition, regarding **environmental aspects**, some general **recommendations** when deciding to decommission an aircraft are:

- Evaluate the environmental impacts, direct and indirect, of aircraft decommissioning.
- Identify the planning - control measures related to the risks identified.
- Analyse the environmental consequences and benefits (CO_2 emissions, waste production, regulations) of the decision as to whether to decommission an aircraft or fleet.

4.4 Elements within the waste business

4.4.1 Improving recyclability and reuse of parts and materials

The **development of recycling scenarios for today's non-recyclable fractions** is crucial to enhance the sustainability of the sector. Examples of these non-recyclable fractions are the isolation matting/ Nomex sandwich material/ PMMA windows, and the CFRP fractions. In the case of these types of materials, research is to be done to find recycling or alternative reuse solutions for them. If no solution is available, the proposal would be to study their ban.

The **carbon fibre recycling** is a key research pathway to be developed during the following years, since the volume of these materials that will reach the aircraft EoL will increase due to the new compositions of new

[125] IATA (2018). Best Industry Practices for Aircraft Decommissioning (BIPAD)

aircraft types, which favour these materials against the older configurations that had higher amounts of metals. The use of these types of materials have benefits during the use phase. However, they pose recycling challenges during the EoL phase, in comparison with older aircraft types that have much bigger percentages of metallic compounds that are much easier to recycle. Importance is to be given as well to the **reuse of carbon fibre reinforced polymers**. This is due to the current difficulties to recycle these materials and the health risks they produce. In order to solve this situation, there is effort to be done to find recycling pathways, as well as to increase the possibilities to reuse these materials, therefore avoiding waste that would end up as landfill.

When **reusing carbon fibre**, the requirements for these materials to be used in aircraft are to be considered in the dismantling process to facilitate their potential reuse in the aerospace industry.

Regarding the **recycling of new materials,** it is important to work on the research about thermoplastics recycling, as well as to characterise and certify new materials such as the recyclable Carbon Fibre Reinforced Polymers, bio-based materials for interiors, etc.

An important aspect to be explored to enhance aircraft EoL is the **recycling and reuse of materials and parts located in the aircraft interiors**, which tend to go unseparated to recycling, since the labour required to separate the different elements is more costly than the value of the recovered parts and materials. The solution to this issue is linked with the improvement of the eco-design and materials mapping.

In the particular case of engines, it is important to work on assuring that **components with high levels of critical raw materials** as Co, Ni, Re are demountable and separable, thus allowing for an efficient reuse and recycling.

It is also important to consider take-back schemes for those **components and materials that arise with the use of electric and hydrogen aircraft**, which are expected to have an important influence on the future of the sector. For example, in the case of electric aircraft, batteries are expected to be a hotspot in the overall environmental impact of the aircraft. Therefore, it is necessary to establish pathways to carry out the batteries' uptake and their proper treatment to avoid these environmental impacts[126].

The reuse and recycling of the materials and components is key as well to work towards the **independence of the European Union regarding materials acquisition**, which have important environmental, economic, and social implications.

4.4.2 Increase of aero grade metals upcycling

Keeping the aero grade of recycled metals requires to have volumes large enough so that they can be processed together. Therefore, an important and interesting measure to upcycle aero grade metals is to foster **volume grouping and consolidation**[127], to create the scale required for economically feasible recycling streams, therefore having a higher potential of achieving high upcycling rates.

It would also be interesting if aircraft manufacturers set **upcycling targets**, meaning the percentages of recycled materials from their own industry that would get back to manufacturing. For instance, setting a target of 1% aviation aluminium recycled into the aviation business would be useful to increase the upcycling rates in aviation.

4.4.3 Wider application of current best practices handbooks

The AFRA BMP constitute a document that collects recommendations concerning **best practices for the parts removal during disassembling and for aircraft recycling**. The application of these practices helps to increase the sustainability of the aircraft EoL and should be considered.

[126] In this regard, there is a proposal for a new EU Batteries Regulation which was published on 10th December 2020. This proposal includes in its scope electric vehicle batteries, and proposes collection, and recycling targets, as well as the repurposing of batteries from electric vehicles, among other initiatives.
[127] For example, the European Ship Recyclers Group.

4.4.4 Set the aspirational goal to eventually reach zero landfill

The final target for the treatment of the aircraft EoL should be to reach **zero landfill**. This requires finding alternative reuse and recycling processes for all the materials that end up as landfill from current aircraft dismantling projects and for the new materials that are used in newer aircraft types that are currently entering the fleet and that will eventually go through their EoL.

4.5 Analysis of the recommendations

In this subchapter, a **qualitative analysis of the recommendations** is provided. This analysis is based on a set of categories that represent important aspects to assess their benefit and ratings given to them. The higher the scores, the more interesting (in terms of benefit and/or implementability) the application of the recommended measures is expected to be.

It is important to note that these scores are given based on the personal considerations of aviation experts. Therefore, they are not derived from scientific analysis, but nevertheless help to have an estimation of the expected benefits of each of the initiatives in the different categories and can be helpful to plan priorities and next steps.

4.5.1 Categories of the analysis

The following table indicates the different **categories and the meaning of the possible ratings** given to them.

Table 28. Description of the qualitative analysis categories and ratings

Category	Description of the category	Ratings description		
		1	2	3
Environmental benefits	Benefits from an environmental point of view. How much can the initiative help to achieve a good conservation of the environment. Linked with reduction of waste, use of natural resources, emissions, carbon footprint, etc.	**No or negligible environmental benefits** Initiative not directly linked with environmental improvements	**Significant environmental benefits** The reduction in waste, use of natural resources, emissions, etc. is significant	**High environmental benefits** Important reductions of environmental impacts. It can include positive impacts
Economic benefits	Benefits from an economic point of view for the stakeholders involved in the application. Potential value of the savings that arise from the implementation of the initiative	**No or negligible economic benefits** The initiative leads to higher costs or no significant economic benefits	**Significant economic benefits** The initiative provides costs savings and/or additional income	**High economic benefits** The initiative is expected to provide substantial reduction of costs and/or additional income

Category	Description of the category	Ratings description		
		1	2	3
Social benefits	Benefits from a societal point of view. Linked with jobs creation, attitude of the society towards the initiative, sustainability education, etc.	**No or negligible social benefits** The initiative is not directly linked to social aspects	**Significant social benefits** The initiative provides additional jobs, contributes to more sustainability awareness, etc.	**High social benefits** The initiative has strong positive social implications
Technical benefits	Benefits from an aviation technical point of view. For example, increase in the efficiency of the technical operations, increase in safety, etc.	**No technical benefits** Initiative not directly linked with technical benefits	**Significant technical benefits** The initiative involves a significant improvement of the aviation technical activities. For example, resource savings in those operations	**High technical benefits** The initiative or recommendation involves strong technical benefits. For example, going from paper maintenance records to electronical databases
Geographical scope	How large is the geographical extension of the initiative	**Local scope** The initiative is expected to be pushed mostly at a local/regional scope, or at individual companies	**National and EU scope** The initiative is to be targeted at national and/or at EU level	**International scope** The initiative has a worldwide application
Ease to implement	How easy to implement would this initiative be. It considers technological, regulatory, and societal difficulties	**Difficult to implement** The initiative has strong difficulties to face	**Moderate effort to implement** The initiative is not particularly easy to implement, but it is also not expected to face strong difficulties	**Easy to implement** The initiative is expected to be straight forward, with no strong difficulties and with interest of the different involved stakeholders to promote it
Speed to implement	Time that is expected to be required to fully implement the initiative	**Long timeframe** The initiative is expected to require 10 years or more to be implemented	**Medium timeframe** The initiative is expected to require from 3 to 10 years to be implemented	**Short timeframe** The initiative is expected to be able to be implemented in less than 3 years.

4.5.2 Qualitative analysis

In the table below, the list of the different **initiatives and recommendations** given in the previous subchapters are included, **together with the first qualitative analysis assessment** that follows the ratings indicated previously. These ratings have been based on initial qualitative estimations of selected users in order to provide a "proof of concept," and more in-depth analyses would be required in following steps.

Table 29. Qualitative analysis of the recommendations

ID	Initiative or recommendation	Environmental benefits	Economic benefits	Social benefits	Technical benefits	Geographical scope	Ease to implement	Speed to implement	Average
General elements									
Regulation aspects									
1	Consider the option to set EoL regulations for aircraft	3	1	2	2	2	1	1	1.7
2	Analyse the inclusion of aircraft in the EoL Vehicles Directive	2	1	2	1	2	1	1	1.4
3	Application of the European Waste Directive to parts/components of dismantled aircraft	2	1	1	1	2	1	1	1.3
Work on incentives									
4	Possibility to include the generation of carbon credits from sustainable aircraft decommissioning and recycling activities	3	3	2	1	2	2	3	2.3

ID	Initiative or recommendation	Environmental benefits	Economic benefits	Social benefits	Technical benefits	Geographical scope	Ease to implement	Speed to implement	Average
5	Push for more recognition of sustainable practices, for example, by setting the requirements for aircraft lifecycle activities within the EU Green taxonomy	3	2	1	1	2	2	2	1.9
Use of charges									
6	Use of environmental charges to foster recycling	2	1	2	1	2	2	2	1.7
Increasing collaboration among stakeholders									
7	To increase national collaboration	2	2	2	2	1	3	3	2.1
8	To increase collaboration among knowledge institutions	2	2	2	3	3	3	3	2.6
9	Suggestion for Clean Aviation to launch a call on Circular Economy	3	2	1	2	2	3	3	2.3
10	To create industrial partnerships	2	2	2	2	1	2	2	1.9
11	To develop an international framework	2	2	2	2	3	1	1	1.9

ID	Initiative or recommendation	Environmental benefits	Economic benefits	Social benefits	Technical benefits	Geographical scope	Ease to implement	Speed to implement	Average
Promotion and implementation of sustainable management practices									
12	To promote the use of environmental management systems	3	2	2	2	3	2	2	2.3
13	To promote the use of sustainability declarations (labels)	3	1	2	1	3	2	2	2.0
14	To increase the use of sustainability reporting	2	1	2	1	3	2	2	1.9
15	To increase the use of sustainability monitoring	2	1	2	1	3	2	2	1.9
16	To increase the use of sustainable business models	3	2	2	1	3	2	2	2.1
17	To generate sustainability roadmaps and use for aircraft lifecycle activities	3	2	2	2	3.0	3	2	2.4
Training of personnel in sustainability and circular economy									
18	To promote specific training on sustainability aspects could be proposed to be provided to the staff working in the different units and processes of the aircraft lifecycle	2	2	3	2	3	2	2	2.3

ID	Initiative or recommendation	Environmental benefits	Economic benefits	Social benefits	Technical benefits	Geographical scope	Ease to implement	Speed to implement	Average
Communication activities to increase the visibility of the sector									
19	Effectively communicate the efforts of the aviation sector on improving sustainability, keeping in mind the key messages and the key stakeholder groups that need to be addressed	1	1	3	2	3	3	3	2.3
20	To extend the coverage of the aircraft lifecycle and circular economy in the European Aviation Environmental Report	1	1	2	1	2	3	3	1.9
21	To create a European Aircraft Lifecycle Sustainability White Paper	2	1	2	2	2	3	3	2.1
Aerospace industry and alternative reuse									
Best practices									
22	To include of eco-design and “design for decommissioning” principles	3	1	1	3	3	1	1	1.9

ID	Initiative or recommendation	Environmental benefits	Economic benefits	Social benefits	Technical benefits	Geographical scope	Ease to implement	Speed to implement	Average
23	To reduce the volume of non-recyclable materials	3	2	2	2	3	1	1	2.0
24	To include the concept of commonality in aircraft eco-design	2	2	1	3	3	2	1	2.0
25	To include the consideration of sustainability criteria when choosing suppliers and services in the aerospace industry	2	1	2	1	3	2	3	2.0
26	Inclusion of sustainability criteria to choose disassembling and dismantling facilities	3	1	2	1	3	2	3	2.1
27	To foster the alternative reuse of aircraft parts and materials that could not be reused in the aviation industry for their original purpose.	3	2	2	2	3	2	3	2.4

ID	Initiative or recommendation	Environmental benefits	Economic benefits	Social benefits	Technical benefits	Geographical scope	Ease to implement	Speed to implement	Average
Industry policy									
28	Increase strategic independence of the EU regarding the acquisition of materials important for the aeronautical sector	2	3	2	3	2	1	1	2.0
Regulation aspects									
29	Create legislation on aircraft eco-design	3	1	2	2	2	1	1	1.7
30	Inclusion of the principle of “Extended Producer Responsibility” in aviation	3	1	2	1	2	2	1	1.7
31	Use of fluids from aircraft decommissioning	1	2	1	2	3	2	2	1.9

ID	Initiative or recommendation	Environmental benefits	Economic benefits	Social benefits	Technical benefits	Geographical scope	Ease to implement	Speed to implement	Average
Standards									
32	Use of dismantling information (Digital Material Passports) for parts disassembled and materials dismantled	1	1	1	3	2	2	2	1.7
33	More stringency in the noise, emissions, and CO2 standards for in-service aircraft	3	1	2	2	3	1	1	1.9
34	Implementation of serialisation, electronic records, and digital back-to-birth traceability for aircraft parts	1	2	2	3	3	2	1	2.0
Publication of materials and components of the aircraft									
35	To provide aircraft mapping/cartography to help performing dismantling activities	3	3	2	3	3	1	2	2.4
36	To include a waste/material treatment manual indicating the materials used in each of the aircraft components, as well as their potential hazardousness and need for specialised treatments.	3	2	2	3	3	2	2	2.4

ID	Initiative or recommendation	Environmental benefits	Economic benefits	Social benefits	Technical benefits	Geographical scope	Ease to implement	Speed to implement	Average
Decommissioning registry									
37	Creation of a registry, probably at ICAO level, which includes the decommissioned aircraft.	2	1	2	2	3	2	1	1.9
38	Creation of a certificate of aircraft retirement.	2	1	1	2	3	2	2	1.9
Aircraft decommissioning recommendations									
39	To include Economic analysis to decide on the aircraft decommissioning decision	1	3	1	2	3	3	3	2.3
40	To include Environmental analysis to decide on the aircraft decommissioning decision	3	2	1	2	3	3	3	2.4

Waste business									
Improving recyclability and reuse of parts and materials									
ID	**Initiative or recommendation**	**Environmental benefits**	**Economic benefits**	**Social benefits**	**Technical benefits**	**Geographical scope**	**Ease to implement**	**Speed to implement**	**Average**
41	Development of recycling scenarios for today's non-recyclable fractions	3	2	2	3	3	1	2	2.3
42	To enhance carbon fibre and other new materials recycling	3	2	2	3	3	1	2	2.3
43	To consider take-back schemes for those components and materials that arise with the use of electric and hydrogen aircraft	3	2	2	2	3	2	2	2.3
Increase of aero grade metals upcycling									
44	To foster volume grouping and consolidation to create the scale required for economically feasible recycling streams	2	2	2	2	3	3	3	2.4
45	Setting of upcycling targets by aircraft manufacturers	3	1	1	1	3	3	3	2.1

ID	Initiative or recommendation	Environmental benefits	Economic benefits	Social benefits	Technical benefits	Geographical scope	Ease to implement	Speed to implement	Average
Enhancement of current best practice handbooks and their application									
46	Wider application of AFRA BMP for disassembling and recycling	3	1	2	2	3	3	2	2.3
Set the aspirational goal to eventually reach zero landfill									
47	Consideration of a final target for the treatment of the aircraft EoL that should be to reach zero landfill	3	2	2	2	2	1	1	1.9

In the following table, the **average scores per group** can be consulted. As it can be observed, significant improvements with average scores of 2 or higher can be expected for each of the groups.

Table 30. Average scores per group

Group	Average score
Waste business	2.3
Aerospace business and alternative reuse	2.0
General elements	2.0

When analysing the **average scores obtained per subgroup**, the highest average scores were obtained for the publication of materials and components of the aircraft initiatives linked to the publication of materials and components of the aircraft, aircraft decommissioning decision recommendations, and the enhancement of current best practice handbooks and their application.

Table 31. Average scores per subgroup

Subgroup	Average score
Publication of materials and components of the aircraft	2.4
Aircraft decommissioning decision recommendations	2.4
Enhancement of current best practice handbooks and their application	2.4
Improving recyclability and reuse of parts and materials	2.3
Increase of aero grade metals upcycling	2.3
Training of personnel in sustainability and circular economy	2.3
Increasing collaboration among stakeholders	2.1
Promotion and implementation of sustainable management practices	2.1
Communication activities to increase the visibility of the sector	2.1
Work on incentives	2.1
Best practices	2.0
Industry policy	2.0
Decommissioning registry	1.9
Set the aspirational goal to eventually reach zero landfill	1.9
Standards	1.9
Use of charges	1.7
Regulation aspects	1.7

When looking at the **average scores per category**, geographical scope and environmental benefits have been estimated to be the most important among the criteria included. The economic and social benefits are significant as well on average, although they do not reach the environmental benefits average impacts.

Table 32. Average scores per category

Category	Average score
Geographical scope	2.6
Environmental benefits	2.4
Ease to implement	2.0
Speed to implement	2.0
Technical benefits	1.9
Social benefits	1.8
Economic benefits	1.6

In the following table, the **initiatives that are expected to be easier to implement** are indicated. These are the individual initiatives or recommendations that received the maximum score in the "Ease to implement" criteria and therefore could be considered as "quick-wins."

Table 33. Initiatives expected to be easier to implement

ID	Group	Subgroup	Initiative or recommendation
7	**General elements**	**Increasing collaboration among stakeholders**	To increase national collaboration
8	**General elements**	**Increasing collaboration among stakeholders**	To increase collaboration among knowledge institutions
9	**General elements**	**Increasing collaboration among stakeholders**	Suggestion for Clean Aviation to launch a call on Circular Economy
17	**General elements**	**Promotion and implementation of sustainable management practices**	To generate sustainability roadmaps and use for aircraft lifecycle activities
19	**General elements**	**Communication activities to increase the visibility of the sector**	Effectively communicate the efforts of the aviation sector on improving sustainability, keeping in mind the key messages and the key stakeholder groups that need to be addressed
20	**General elements**	**Communication activities to increase the visibility of the sector**	To extend the coverage of the aircraft lifecycle and circular economy in the European Aviation Environmental Report
21	**General elements**	**Communication activities to increase the visibility of the sector**	To create a European Aircraft Lifecycle Sustainability White Paper
39	**Aerospace industry and alternative reuse**	**Aircraft decommissioning decision recommendations**	To include Economic analysis to decide on the aircraft decommissioning decision
40	**Aerospace industry and alternative reuse**	**Aircraft decommissioning decision recommendations**	To include Environmental analysis to decide on the aircraft decommissioning decision

44	**Waste business**	**Increase of aero grade metals upcycling**	To foster volume grouping and consolidation to create the scale required for economically feasible recycling streams
45	**Waste business**	**Increase of aero grade metals upcycling**	Setting of upcycling targets by aircraft manufacturers
46	**Waste business**	**Enhancement of current best practice handbooks and their application**	Wider application of AFRA BMP for disassembling and recycling

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5. Conclusions

5.1 Introduction

1. This report presents the outcome of the research study mandated by EASA to Envisa to perform an **Assessment of the environmental sustainability status in the Aviation Maintenance and Production Organisation (M&P) Domain**. The study has been structured into three parts[128]: Overview of the status quo (Chapter 2), Elements of the aviation system and technical culture which could support the implementation of sustainability (Chapter 3), and Initiatives and recommendations to enhance sustainability in the aircraft lifecycle (Chapter 4).
2. **Sustainability** constitutes a balance between economic, environmental, and social elements, which is known as the "triple bottom line," achieving the needs of current generations without compromising the needs of future ones. In addition, especially for the case of aviation, safety and security are important aspects that are connected to the three main sustainability pillars.
3. Another important concept is **circular economy**, which tries to achieve an improved resource management throughout the lifecycle of systems. It is characterised by closed loops, promoting maintenance, reuse, remanufacturing, and recycling, and reducing waste to the minimum.
4. Sustainability and the achievement of sustainable development have become major goals at international level. A reflection of this ambition has been the 2030 Agenda for Sustainable Development, adopted by all United Nations Members States in 2015. This Agenda includes the 17 **Sustainable Development Goals**, which are a call for action by all countries in a global partnership. **The global aviation sector has a role to play in 15 of the 17 SDGs**, contributing to a safe, efficient, and cost-effective mobility strategy.
5. **Sustainability is a priority in the EU as well as the application of sustainable practices in aviation for EASA.**
6. There are several **methods to measure sustainability aspects**, such as LCAs, CBAs, MCAs, EIAs, etc, that could be employed in the aviation sector.
7. Aviation is a complex sector which causes different sustainability impacts. The main direct **impacts coming from the aircraft operational phase** are noise, pollutant emissions, and greenhouse gas emissions. In addition, all the interlinked activities, such as airport operations or aircraft manufacturing pose additional impacts, such as waste generation, or land-use changes.
8. During the last years, the implementation of renewable energies together with electrification has shown the potential of how emissions can be significantly reduced by the introduction of **new technologies**. Currently, air mobility implies a large use of fossil fuels. Therefore, the integration of sustainable energy sources in the aviation sector represents a challenging and necessary objective to meet the various sustainability goals.
9. The **generation of waste** is one of the main sustainability impacts of the aviation sector. As we are seeking to achieve climate neutrality by 2050, there should be a focus as well on the implementation of circular economy principles in the sector. There are currently no requirements for the aviation industry to design new products considering the recovery of materials when aircraft are scrapped.

[128] For each of the three parts of the study, a separate internal report has been produced as deliverable to EASA. The present overall report constitutes a merged version of these three deliverables.

Another challenge in this area is that it is not mandatory for manufacturers to publish manuals that identify the materials of each component, the type of treatment that can be used in their recovery, or the hazard that the unproper management of the linked waste can produce to the environment.

10. A crucial element among the aviation sustainability challenges is the **aircraft EoL phase**. More than 15,000 commercial aircraft had been retired worldwide in the period from 1980 to 2017. During the years before the beginning of the Covid pandemic, around 700 aircraft were being retired annually, having an average age of 27 years. In addition, it was estimated that 12,000 aircraft would be retired in the next two decades (IATA, 2018). Due to the pandemic, this trend has been altered. Only around 420 aircraft were officially retired in 2021 (Naveo Consultancy, 2022), which represents the lowest level since 2007. The reason for this modification is that parking and long-term storage are relatively cheap, therefore Airlines and lessors favour waiting and seeing how traffic recovers. Various airlines have taken the opportunity of the low demand period to retire their entire fleets of old aircraft models (e.g., 747, A340). Aircraft retirements are expected to increase in the coming years to 20-25% compared to previous decades (Oliver Wyman, 2022).

5.2 Overview of the status quo

1. In order to structure the whole aircraft lifecycle study, **areas, units, and processes** have been identified:
    a. **Areas** refer to the use of the parts and materials at that stage of the lifecycle.
    b. **Units** indicate individual steps or subareas. These are differenced by the nature of the processes that take part in them and the stakeholders involved.
    c. **Processes** are actions or activities that take place within the identified units.
2. The **aircraft life cycle** can be divided into 3 principal areas: the aerospace business, the waste business, and the non-aerospace use.
3. The **aerospace business** is constituted by all units in which aircraft and their parts keep being used with their original purpose, serving air traffic operations. In this area, aircraft components are still certified for airworthiness. This area begins with the **design phase**, which, amongst others, defines the materials and construction for the **manufacturing** of the aircraft and its parts. When the parts are completed, they enter the **use and maintenance phase**. These two phases belong to **M&P**. Another important flow from this area is the **production of waste** during the operational phase of the aircraft, which will enter the waste business, meaning maintenance as well as cabin and catering waste.
4. At some point of the aircraft lives, when the continuation in their use is not economically viable or due to safety issues, aircraft owners take the **decision to decommission** and prepare them for disassembling. After **disassembling**, parts can be reused and employed as spare parts for other aircraft (still in the aerospace business) or taken to **alternative reuse** in the non-aerospace business, for instance with educational or decoration purposes.
5. After disassembling, aircraft enter the **waste business**, starting with the **dismantling**, where they are shredded and their materials are prepared to be either recycled, used for energy recovery, or sent to **landfill** when none of the previous options are available any longer. From **recycling**, there is a process of re-entry of materials into manufacturing in other non-aerospace businesses, as it can be the case of recycled metals, for instance.
6. The phases covering the time from the decommissioning decision to the waste business, belong to the **EoL**.
7. **Composite materials** have been employed increasingly during the recent years in aviation, even though recycling technologies for these materials are still not fully developed and available.

8. The development of **electric aircraft and hydrogen-powered aircraft** constitute options to increase the sustainability of the sector, although additional challenges may arise from their use, in particular the manufacturing and disposal of batteries.
9. **Structural Health Monitoring** may constitute a way to optimise maintenance activities and lower the impact of these activities, therefore enhancing sustainability.
10. Various **initiatives linked with sustainability** are available and affect aviation:
    a. Standards and regulations
    b. Handbooks
    c. Sustainability projects
    d. Other studies

    All these initiatives contribute or have contributed to the sustainability of the sector and are important to be considered when setting the ground for the proposal of new recommendations.
11. Sustainability practices need to be considered from the very beginning in the **design phase**, selecting the right materials and using them as efficiently as possible during production.
12. Another important action to be taken from design and manufacturing is to establish a **sustainable supply chain**, meaning that the materials selection targets ethical and environmentally friendly options.
13. It is crucial as well to consider **sustainable practices during the operation phase**, for instance, with the production and use of sustainable alternative fuels and with air traffic management solutions that help to increase fuel savings during the aircraft's entire service life.
14. **Decommissioning and disassembling** constitute the entry into the EoL phase, being this decision made mainly by economic and safety factors. The main reasons for the retirement of aircraft are:
    a. increasing operational costs,
    b. high fuel consumption,
    c. steady or sudden rises in fuel prices,
    d. new regulatory requirements such as expensive technology upgrades,
    e. and difficulties in obtaining spare parts.
15. The **disassembly** key points are the physical disassembling process with the equipment and parts removal, the sorting and storage of parts and materials, and the material diagnosis. All parts intended for reuse must be removed before the aircraft loses its certification, to avoid costly recertification.
16. **Alternative reuse** refers to: "Any operation by which products or components that are not waste are used for a different purpose from the one they were conceived for." This EoL pathway is especially useful, since it provides significantly higher added values to materials and parts the dismantling phase and that would otherwise be used for recycling or, in the worst case, sent to landfill. For the moment, alternative reuse pathways are applied to relatively small fractions of the materials that go through the dismantling process.
17. Aircraft **dismantling** constitutes the entry of the aircraft parts and materials to the waste business, meaning that they cannot re-enter the aerospace business, are considered as waste, and are under the general regulations covering waste treatment. Aircraft dismantling consists of the following steps: the final draining of the systems, the categorisation of the materials that are left and the end-of-life fates that they will follow, the removal of hazardous materials, removal of non-recyclable materials, shredding, and transportation to recycling and recovery facilities.

18. After dismantling, the **recycling, energy recovery, and landfill** steps take place. Following the removal of all valuable components, the remaining fuselage is broken up into small pieces and processed by a metal recovery company. Those materials that allow energy recovery are taken to incineration facilities to extract energy from their combustion. Ultimately, materials that cannot be either recycled or used for energy recovery are sent to landfill.
19. It is expected that **recovery rates** of current and future aircraft types will decrease, unless recycling solutions are given to the rising share of composite materials that are used to build them.
20. **Energy recovery** is defined as a form of resource recovery in which the organic fraction of waste is converted to some form of usable energy. It is important to keep in mind that waste incineration itself is as well a carbon-intensive process that can undermine the efforts to decrease carbon emissions and to reach carbon neutrality on time.
21. **Aviation waste** is subject to no aviation-specific legislation and will be treated and if required sent to landfill following similar processes as in other sectors and industries.

5.3 Elements of the aviation system and technical culture which could support the implementation of sustainability

5.3.1 General elements

1. **Planning and management** are fundamental to any organisation. Sustainability involves different pillars: environment, economy, and society. All these pillars are influenced by the planning and management of the organisations involved. Therefore, sustainability should be included in the planning and management in order to achieve its practical implementation and improvement.
2. The **sustainability of the aviation industry** has to be tackled at all stages of the aircraft lifecycle to achieve global improvements. Therefore, more initiatives targeting the design phase, supply chain, manufacturing, the operational phase, and the EoL phase are needed.
3. A tool that aviation organisations use in the area of sustainable management is the **publication of environmental statements and reports**. The **use of these reports and the involved monitoring of KPIs and advancements is a useful tool, although it is still not widely applied**, and its implementation requires to be improved in some cases. Therefore, it would be beneficial to stimulate the inclusion of these activities.
4. In the case of **planning meetings**, sustainability aspects can also be included into them to enhance the sustainability of the organisations. However, **sustainability aspects are traditionally considered from the perspective of the economic performance** of the activities, not giving as high priority to the other two sides of sustainability: environmental and social aspects. Therefore, it would be beneficial to include these aspects as well in the scheduled planning meetings of the organisations that participate as stakeholders during the aircraft lifecycle.
5. The **use of electronic platforms** to manage the activities carried out by the different organisations is widespread.
6. **Even though various sustainability projects and initiatives exist, there is still room for improvement**. In fact, many of the currently existing initiatives are not broadly included by the stakeholders, especially by small organisations.
7. **Cooperation between the different organisations** that participate in the whole aircraft lifecycle is crucial to ensure the proper and successful performance of the business in general and to implement the various sustainability initiatives.

8. When analysing the general cooperation between the identified organisations, **two main groups can be established: those organisations within the M&P domain and those linked to the aircraft EoL and non-aerospace business**. Within these two main groups, the cooperation actions are widespread. For example, within the aircraft EoL area, intense cooperation happens between disassemblers, dismantlers, and recyclers to work with the different aircraft parts and materials and allow their reuse or recycling. However, there are less interactions between these two groups, except for the cases in which large MRO organisations perform as well disassembling activities.

9. **Cooperation with research centres and universities** occurs between the different stakeholders. This cooperation allows for the development of innovative techniques.

10. Regarding the legal elements, there is **currently no regulation worldwide about EoL specifically targeting aircraft** (note that for example the EU vehicle EoL Directive is applicable to road vehicles, but not to aircraft). There is, however, regulation which indirectly impacts aircraft recycling. Once an aircraft has irreversibly lost the ability to fly, it is considered an assembly of pieces of waste, therefore being affected by the general waste regulation. Depending on the materials used, different existing regulations apply. These, however, make no distinction whether the materials originate from aircraft or other previous uses. There is as well a Regulatory Position Statement from the UK Environment Agency regarding the removal of airworthy parts from waste aircraft.

11. The **environmental benefits from improving the aircraft EoL** include the savings of materials and energy, as well as a reduced environmental footprint of the EoL activities. These benefits lead to a lower environmental impact, including a mitigation of GHG emissions. The savings on materials and energy have therefore economic effects as well, since the recycled materials can generate revenues, and expenses for the production or acquisition of new materials are saved. Although additional costs are created with improved EoL practices, such as the labour costs, and the disposal of the remaining materials that cannot be recycled, the positive economic impacts can outweigh them.

5.3.2 Elements within the aerospace industry and in the alternative reuse

1. Starting from the beginning of the aircraft lifecycle, **eco-design activities** are crucial as a first step to lower the total environmental impacts produced during the rest of the phases of the lifecycle. Among the eco-design activities, we can find the use of innovative materials and structures. Manufacturers invest on the evolution of their designs, involving environmental and economic benefits.

2. The **environmental impacts from the aircraft manufacturing phase** originate from different steps, such as the extraction of raw materials, their transportation, production and casting, and their use to produce the different components until the final assembly. During each of these steps, energy and water is consumed, and waste is produced. From the different aircraft components, **the engine is the structure containing resources with the highest scarcity**.

3. The **operational phase** is the source with the largest proportion of impacts, such as noise, air pollution and climate change, as well as the production of waste. However, in this report we focus on the rest of the areas of the aircraft lifecycle, targeting M&P, aircraft EoL and alternative reuse, which have traditionally been studied less than the operational phase of the aircraft lifecycle.

4. During **aircraft maintenance, environmental impacts** are produced due to the energy use, the production of maintenance products and spare parts, and the waste produced. The production of spare parts and maintenance products have impacts that are comparable to those that happen during the aircraft production phase. On the other hand, the waste production is very similar in the case of aircraft decommissioning and disassembling, including for instance the disposal and recycling of parts that are no longer usable and the draining of fluids.

5. **In the MRO business**, which is driven by time pressure, safety and reliability concerns, **sustainability is usually not yet a main topic being addressed**. The MRO organisations comply with the regulations for waste management but additional measures to increase sustainability are still not broadly extended. They partner with specialised dismantling companies when dealing with aircraft reaching their EoL phase, although sustainability considerations are not necessarily a main part of the decision to choose these partners.
6. There is a **slight general trend towards lower age of retiring aircraft**.
7. During **decommissioning**, aircraft cleaning and decontamination of hazardous substances, draining of tanks and piping, and the implementation of safety procedures take place. Besides, the list of aircraft parts which could be disassembled and re-used is prepared.
8. **Dismantling organisations usually take care of the disassembling of the** various **parts** that the aircraft owners require them to take out. They do not usually own the aircraft, as they are normally still under the property of the airlines, leasing companies or have been sold to aircraft parts dealers, although in some cases the original aircraft owners might sell the aircraft to a dismantling company.
9. The **aircraft parts removed as part of the disassembling process** are intended to be returned to the aviation market as far as possible to maximise the recoverable value. These parts need to go through maintenance and/or recertification, depending on their status and on the proposed use in the aviation system. This flow of parts is governed by the certifying authority and the maintenance companies.
10. The disassembling performed in advance to the dismantling phase is based on a **"harvest list"** provided by the aircraft owner. This list includes all those parts that have been requested to be disassembled and sent back to the owners. These are the parts with the highest economic value, and which will still be used within the aerospace industry. It is usual practice nowadays to create an electronic data base for the client of the parts harvested in 'real time.'
11. Only after all the valuable airworthy parts have been recovered, aircraft will be dismantled. This process is known as "**parting out**."
12. **Alternative reuse** refers to operations by which products or components that are not waste are used for different purposes from the ones they were conceived for. Alternative reuse provides **higher added values** to those parts and materials.
13. The **alternative reuse business is currently not broadly extended**. A small number of companies work with dismantled aviation materials and parts and the volume of materials required are therefore small. Furthermore, when these activities happen, they are usually restricted to a local scope, with organisations using alternative reuse activities contacting nearby dismantling facilities to get the materials they need. It is a visible but small market.

5.3.3 Elements within the waste business

1. Aircraft **dismantling** constitutes the entry of aircraft parts and materials into the waste business, meaning that they cannot be reused in the aerospace sector, are considered as waste, and are under the general regulations covering waste treatment.
2. **Materials above the cabin floor** are usually very neat, so these are relatively easy to be used efficiently in recycling.
3. Regarding the **engines' parts and components**, these follow a particular process, considering their remarkably high value.

4. **Safety and Quality initiatives** come from national legislation which apply as well to the aviation industry.

5. Dismantling and recycling activities fall under the **AFRA Best Management Practices handbooks**.

6. It would be interesting to expand as well on **circular economy value loops**, including alternative reuse, re-manufacturing, and recycling on aero grade.

7. **Recycling** of end-of-life aircraft is a voluntary action, which is not regulated by legislation.

8. In the case of aircraft reaching their EoL during the last decade (with high share of metals in their structures), recovery rates of around 95% are being claimed. These high **recovery rates** involve the use of downcycling and dealing with aircraft that have a high percentage of metallic parts.

9. The **composition of aircraft structure** has been significantly modified during the previous decades, being the latest change the substitution of Aluminium alloys with composite materials. Thus, for the case of current aircraft that will enter the EoL phase in the future, new recycling pathways will be required in order to keep high recovery rates.

10. **Some materials that are obtained as part of the aircraft dismantling are not recyclable**, such as the insulation matting and nomex. They cannot be recycled nor used for energy recovery. These materials can used as part of alternative reuse.

11. In the case of **engines**, these are a source of rare earths with high values.

12. As it is the case for energy recovery, **the process of sending aviation waste to landfill is not aviation-specific**, since at this point of the aircraft lifecycle, this waste has no specific legislation and follows the same steps as waste from other industries and sectors.

13. It has been proved that **current aircraft that go through the EoL process can reach close to zero landfill**.

5.3.4 Scale of the business

1. Regarding **manufacturing,** it is forecasted that by 2024 the 2018 levels will be recovered, leading to a continuous yearly rise of the produced and delivered aircraft. The majority of the production will correspond to narrow bodies. In addition, when looking at the **global fleet forecast** up to 2030, a rising trend has been estimated, reaching 35,700 aircraft (Oliver Wyman, 2022).

2. The forecasted increase in the global fleet will lead to an **increasing market for MRO activities**. After an initial decrease due to the Covid-19 pandemic, the market is expected to recover by 2023 (Naveo Consultancy, 2022).

3. Regarding **aircraft retirement**, an average of 650 aircraft were retired yearly during the previous decade. This average is forecasted to increase during the current decade, reaching approximately 800 retired aircraft per year. More than 30% of the current fleet in Europe is expected to retire over the next decade (Oliver Wyman Fleet and MRO Forecast, 2022).

5.4 Initiatives and recommendations to enhance sustainability in the aircraft lifecycle

1. **Initiatives and recommendations are categorised into general elements, elements within the aerospace industry and alternative reuse, and elements within the waste business**. *As indicated previously, **Envisa** is not directly providing solutions to be implemented by EASA. This chapter provides a potential list of initiatives and recommendations that EASA can decide to further investigate and consider based on their criteria.*

2. The following **subgroups of initiatives** can be found **within the general elements**: regulation aspects, work on incentives, use of charges, increasing collaboration among stakeholders, promotion and implementation of sustainable management practices, training of personnel in sustainability and circular economy, and communication activities to increase the visibility of the sector.

3. Within the **aerospace industry and alternative reuse** group, the following **subgroups** of initiatives have been proposed: regulation aspects, best practices, industry policy, standards, publication of materials and components of the aircraft, a decommissioning registry, and aircraft decommissioning decision recommendations.

4. Concerning the recommendations given for the **waste business** group, the following **subgroups** have been considered: improving recyclability and reuse of parts and materials, increase aero grade metals upcycling, enhancement of current best practice handbooks and their application, and set the aspirational goal to eventually reach zero landfill.

5. More **information and examples for each of the previous subgroups** and their initiatives is provided in Chapter 4 of this document.

6. A **first qualitative analysis** of the recommendations has been carried out and presented in Subchapter 4.5. This analysis is based on a rating system that includes the following categories: Environmental benefits, economic benefits, social benefits, technical benefits, geographical scope, ease to implement, and speed to implement. A score from 1 to 3 is given for each of these categories and for each recommendation. The higher the scores, the more interesting (in terms of benefit and/or implementability) the application of the recommended measures is expected to be.

7. **Scores** can be consulted per individual recommendation, group, subgroup and per category.

8. In addition, those **initiatives that are expected to be the fastest to implement** can be found in the analysis of the recommendations.

9. An especially important aspect to be kept in mind in general for these recommendations and initiatives, is that **aviation is a global business**. Therefore, any initiatives should be taken forward and supported by stakeholders at an international level.

10. Chapter 4 therefore provides a **comprehensive set of initiatives and recommendations that**, based on the information gathered throughout this project, **can significantly improve sustainability, and enhance circular economy along the aircraft lifecycle**.

6. Next steps

The following next steps are suggested:

1. To analyse the information and outcomes of this research study and **agree on the initiatives and recommendations that would be most interesting to be taken forward**.
2. Initiate an internal (within EASA) and external (with all relevant stakeholders) **dialogue to find agreement on the initial list of envisaged initiatives** and to transmit them to the relevant organisations and institutions.
3. Once the key action points are decided, **in-depth analyses on the implementation of the different initiatives** are to be taken forward. These in-depth analyses are to be organised by the organisations involved in each of the respective chosen initiatives.
4. An **expected calendar for the inclusion of the initiatives could be established**, and recurrent meetings to analyse its implementation could be set.

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