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Economic and Environmental Aspects of Aircraft Recycling

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Abstract

Aircraft recycling can be considered as an important step on the path to sustainable aviation, as valuable resources used in aircraft construction can be returned for use in a circular economy by these activities. Our results have shown that the market for aircraft recycling is emerging with great future relevance due to the increasing number of aircraft retirements expected in the future. The costs of recycling per aircraft vary by aircraft class and number of engines. The costs range from USD 109,000 for a twin-engine regional jet to USD 268,000 for a four-engine widebody jet. The costs for a twin-engine narrowbody jet lie in between at USD 138,000. In this paper, we investigated the economic efficiency of aircraft recycling expressed as the ratio of average dismantling and recycling costs per aircraft and engine in USD compared with the achieved environmental benefit in average tons recycled material or re-used parts. This ratio revealed that aircraft recycling leads to notable environmental benefits as a large share (60%) of the total structural weight is being re-used at given costs. The average economic efficiency is estimated at 1,666 USD/ton for a widebody aircraft, 3,531 USD/ton for a narrowbody jet and 6,693 USD per ton for a regional jet. In future, aircraft recycling will be facing a number of major challenges as the number of retired aircraft will increase and the share of composite material to be recycled will rise significantly in the medium and long term - for which material no satisfying technological recycling solution exists today. In addition, the environmental pressure from politics and society is expected to be increasing in future. Against this background, we recommend to effectively enforce ambitious recycling standards for retired aircraft on a global level. Furthermore, as recycling technologies for aircraft composite materials are not mature currently, significant R&D investments are needed for these technologies.

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Keywords: aircraft recycling; aircraft recycling market; future of aircraft recycling

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1. Background

The recycling of aircraft and their components is a topic with great future relevance. Currently, around 600 - 1000 commercial airliners are decommissioned worldwide every year (ICAO, 2019; Scholz, 2022). Over the next 20 years, the International Civil Aviation Organization (ICAO) and Airbus estimate that there will be a total of around 12,000 (Airbus, 2022a) to 20,000 (ICAO, 2019) retired aircraft. In addition, a large number of components will be replaced on an ongoing basis during commercial operation as part of routine maintenance activities. Figure 1 presents the process of aircraft decommissioning in schematic form.

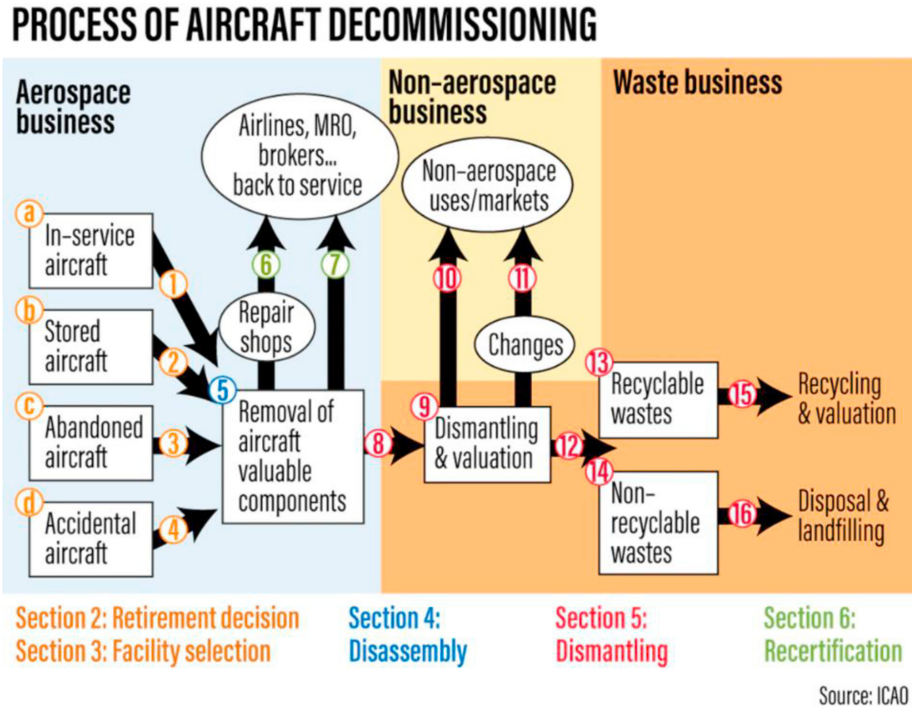

Fig. 1. Process of aircraft decommissioning. Source: ICAO (2019).

Due to a number of developments, recycling of aircraft and their components is becoming increasingly important for aircraft manufacturers and policymakers in the future. Particularly noteworthy are the partly shorter lifetimes of commercial aircraft - with a growing overall fleet size - and the increasing use of fiber composites and material composites in aircraft production. This will increase the recycling effort in the future.

2. Legal Aspects of and Current Market for Aircraft Recycling

From a legal point of view, it is up to the aircraft owner whether or not a retired aircraft is being recycled or permanently parked on an airfield as there is no legal obligation for aircraft recycling. However, if a retired aircraft is being recycled, the ‘aircraft dismantling activities have to comply with existing rules and regulations based on ICAO’s Standards and Recommended Practices (SARPs) relating to aircraft air-worthiness, general and hazardous waste management, and recycling activities. ICAO’s Committee on Aviation Environmental Protection (CAEP) has gathered existing ICAO SARPs, as well as other material of a regulatory nature from various international bodies, including from non-aviation organizations’ (ICAO, 2019). Furthermore, regional rules and regulations provided by regional air safety authorities such as the FAA or EASA have to be applied. In addition, recycling industry and airline associations such as the ‘Aircraft Fleet Recycling Association AFRA’ and the ‘International Air Transport Association IATA’ have published ‘Best Management Practices (BMP)’ guidelines for these activities which can be applied on a voluntary basis.

The re-use of disassembled aircraft parts in aviation is strictly regulated by safety regulations. In principle, these aircraft parts have to maintain their airworthiness status before being re-installed in another aircraft. Parts that have been deemed non-airworthy have to be recertified by an approved maintenance organization before re-entering service (ICAO, 2019).

From an economic point of view, aircraft decommissioning, disassembly and dismantling has become increasingly relevant in the last two decades. In 2006, in the USA, the Aircraft Fleet Recycling Association AFRA was founded on the initiative of Boeing and ten other aviation companies. AFRA's goal is to improve the end-of-life management of aircraft. Today, AFRA's members consist of around 52 recycling companies, 20 research institutions and 15 airlines, mainly from the USA (AFRA, 2022). In Europe, the research project 'Process for Advanced Management of End of Life of Aircraft PAMELA' was carried out by Airbus in 2006. PAMELA led to the founding of TARMAC Aerosave, which is still the largest European company for the recycling of retired aircraft. TARMAC was founded as a joint venture of Airbus, Safran and Suez-Sita.

The number of companies active in aircraft recycling in the world is hard to determine. Adding to the difficulty is the fact that some of these companies are also active in other business areas, such as traditional metal recycling, MRO activities or trading in used aircraft parts. It is note-worthy that there is a large concentration of companies in the US market; more than 50% of the turnover in aircraft recycling carried out worldwide are currently realized in the United States (Global Market Insights, 2021).

The European market for aircraft recycling is significantly smaller. Well-known companies in this field are TARMAC Aerosave, Aircraft End-of-Life Solutions (AELS), Air Salvage International (ASI) and eCube Solutions. A number of, mostly smaller, companies have also been able to establish themselves in Germany. These include MoreAero, Roth International and Cronimet.

In principle, there are two business models for recycling aircraft (Scholz, 2022):

- During dismantling, all parts of the aircraft remain the property of the original aircraft owner. I.e. the recycler receives only a remuneration for the disassembly,

or

- the entire aircraft, i.e. all aircraft parts, become the property of the recycler. The recycling company can therefore recognize the revenue from the sale of parts.

If dismantled aircraft parts are resold, engine components represent the most valuable components, accounting for 60% - 80% of the total value, which can lead to significant revenues for the companies (Zhao et al., 2021, Zhao et al., 2020 and Asmatulu et al., 2012). These high-value components, along with other reusable equipment such as navigation systems, can be reused by airlines or MRO companies after reprocessing and recertification, if necessary. Other components can be returned to both the aviation and non-aviation markets after the recycling process (ICAO, 2019).

The cost of aircraft recycling varies by aircraft class and number of engines. Table 1 shows the average dismantling/teardown cost per aircraft and per engine for regional, narrowbody, and widebody jets. The costs are based on the average costs reported by AFRA members in a 2014 survey (TeamSAI, 2014) and have been inflation-adjusted to 2020 using the corresponding US producer price index. As shown in Table 1, the costs range from USD 57,000 to 116,000 depending on the size of an aircraft. Including the dismantling/teardown cost for the engines, this results in USD 109,000 for a twin-engine regional jet to USD 268,000 for a four-engine widebody jet. The costs for a twin-engine narrowbody jet lie in between at USD 138,000. For 2022, an AFRA-accredited aircraft recycler based in Europe quoted an amount of around EUR 100,000 for dismantling and disposal of an Airbus A320 narrowbody jet, which is in the order of magnitude of the aforementioned value for narrowbodies.

Table 1. Average cost to dismantle/teardown an aircraft/engine by aircraft class (USD 2020)

	Regional Jet	Narrowbody Jet	Widebody Jet
Cost per aircraft	57,000	84,000	116,000
Cost per engine	26,000	27,000	38,000

Source: TeamSAI (2014), inflation-adjusted to 2020 prices using the producer price index WPU5711 (Machinery and Equipment and Parts and Supplies Wholesaling) from St. Louis Fed. Note: Rounded to the nearest thousand USD.

The total global costs of the aircraft recycling industry for dismantling and disposing of commercial aircraft (turboprop, regional jet, narrowbody jet, widebody jet) are, according to our estimates, USD 108 million in 2020. For the estimation, we use the average costs per aircraft and engine shown in Table 1 as well as data on previously retired aircraft from the aviation data provider Cirium (Cirium, 2022). Due to a lack of data, we assume that the recycling costs for a turboprop aircraft approximate those for a regional jet. The number and types of recycled aircraft in 2020 are modelled as the annual average of retired aircraft in 2018 to 2020.

Aircraft recycling is relatively labor-intensive, as many processes have to be carried out by hand. Considering a moving average of the last three years using the Cirium data leads to a total of approximately 720 aircraft retired in 2020. Using the total costs calculated above and our input-output model, we roughly estimate the global number of employees to be 1,100 for that year. We make the admittedly strong assumptions that all of the costs estimated above are labor costs and that the labor compensation per employee in the corresponding US industry is the global average for the sector.

The total revenue of the aircraft recycling industry from the sale of parts and materials is estimated by the authors at USD 6.0 billion in 2020. For the estimation, we used Cirium data on the retired aircraft in 2018 to 2020, analogous to the estimation of total costs. The average values of parts and materials per aircraft are taken from the 2014 survey of AFRA members (TeamSAI, 2014). The average USD values were then adjusted to 2020 prices using the corresponding US producer price index. Due to a lack of data, we assumed that the parts and material value of a retired turboprop is equivalent to that of a retired regional jet. For comparison, the market research firm Visiongain estimates the market size of the aircraft recycling market at 6.6 billion USD in 2020 (Visiongain, 2022). However, as this is a result from a report not freely available, the underlying methodology cannot be assessed.

3. Environmental Aspects of Aircraft Recycling

In order to determine the current and future environmental relevance of aircraft recycling, it is important to be able to map the entire environmental effects during the whole life cycle of an aircraft (Howe et al., 2013). In this life cycle analysis of aircraft, the use of resources and energy should be analyzed in particular. In this context, it must be considered that many high-quality materials for aviation are subject to complex development and qualification processes and are currently intended primarily for one-time use. In addition, lightweight structures and fiber composites are increasingly being used, which on the one hand can make a decisive contribution to reducing fuel consumption in aviation, but on the other hand can only be recycled with greater effort.

According to a thorough review of the relevant literature (see for example Howe et al., 2013; Vasco de Lopes, 2010, Liu, 2013 and Scholz, 2022), 99.9% of environmental relevant emissions occur during the commercial operating phase of commercial aircraft. For this purpose, the entire life cycle of common aircraft types such as the Airbus A319, A320, A330, and Boeing 737-800 was considered. In other words, both aircraft development and production as well as the decommissioning, disassembly and dismantling of aircraft result in a very low proportion of environmental impact compared with their operational phase. This can be explained by the fact that the processes at the beginning and end of the life cycle are one-time events, whereas the commercial operation of an aircraft takes place on a daily basis with high usage times over decades (Scholz, 2022). However, in view of the expected aircraft retirement numbers in the next 20-30 years, these processes should also be carried out in an environmental and economically efficient manner.

The material recycling rate of end-of-life aircraft that are taken out of service today is around 60% in relation to the weight of the aircraft (DLR, 2022). However, this only applies to those aircraft that are also disassembled and dismantled. In the USA in particular, several thousand aircraft have been permanently parked at so-called aircraft cemeteries since the 1950s. Such cemeteries also exist in Europe, but on a much smaller scale. Currently, there are about 6,000 aircraft stored at aircraft cemeteries worldwide (DLR, 2022). If, on the other hand, an aircraft is dismantled and disassembled, the recycling processes are relatively simple up to now, since older aircraft types were mainly made of metal. In addition, many components can still be resold.

In the medium term, a higher share of retired aircraft produced with composites and an increase in the total number of aircraft decommissioned per year can be expected. Figure 2 shows that the share of composite materials in common widebody commercial aircraft has increased significantly, particularly in recent years. While almost no composites were used in the production of the Boeing 747 in the 1970s, a good 50% of composites by total weight have been used in the production of the latest generation of Boeing 787s and Airbus A350s since 2010. Although many of these aircraft will continue to be used commercially for at least another 20 years, an efficient recycling approach must also be found for these aircraft types in the long run. It should be noted that there are two groups of composite materials that require separate recycling processes: Composite waste generated during aircraft manufacturing (production residues, offcuts, etc.) and composite parts generated at the end of the commercial use of the aircraft (Scholz, 2022). Currently, no satisfying recycling concepts are available for composite materials (DLR, 2022). Against this background, considerable research and development activities are still necessary.

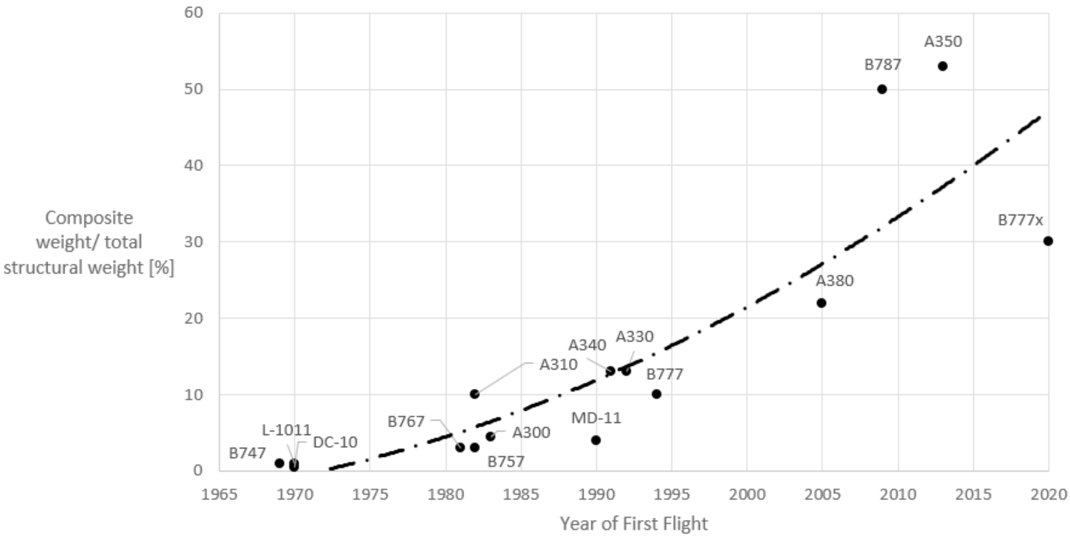

Fig. 2. Share of composite material used in wide-body aircraft, 1965 – 2020. Source: DLR, based on Government Accountability Office (2011).

4. Future Market/Economic Developments in Aircraft Recycling

How will the market for aircraft recycling develop in the future? Within the scope of the scenario project DEPA2050 (DEvelopment Pathways for Aviation up to 2050), a traffic forecast and fleet model for the timeframe up to the year 2050 has been set up in order to forecast the future fleet structure in passenger air transport (Leipold et al., 2021). Individual aircraft retirement had been modelled using the ICAO Committee on Aviation Environmental Protection (CAEP) methodology of logistic survival curves for each aircraft category (turboprops, regional jets, narrowbody jets and widebody jets). The same methodology is e.g. applied in the European Union's Clean Sky 2 Technology Evaluator (Gelhausen et al., 2022). Figure 3 shows that for instance about 50% of widebody aircraft are retired before reaching the age of 24 years. Narrowbody jets have a slightly longer half-life of about 25 years, while half of the regional jet fleet is retired before reaching an age of 22 years.

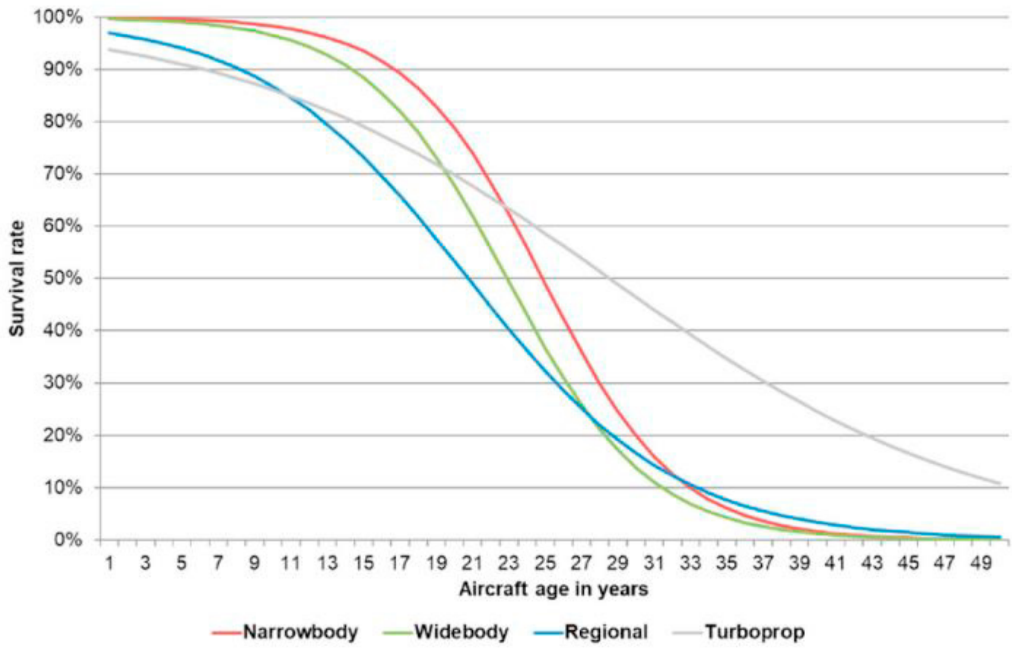

Fig. 3. Survival curves of different aircraft categories in ICAO CAEP/12 (Gelhausen et al., 2022).

Figure 4 shows the expected number of retirements for the timeframe 2025 to 2050. The number of retired aircraft is calculated using a DLR developed traffic forecast and fleet model (Gelhausen et al., 2022). In order to assess the fleet composition accurately, the lifespan of each individual aircraft is considered. By means of a Monte Carlo simulation, based on the survival probabilities shown in Figure 3, the retirement of each aircraft is estimated.

With an overall growth of the global commercial aircraft fleet, also the number of retirements is expected to grow from an average of 800 aircraft per year to more than 1,200 p. a.. It should also be noted that with the growth of average aircraft size, the share of widebody aircraft in the retired fleets is constantly growing. This will increase the mass of materials to be recycled at a higher rate than the number of aircraft and also the value of parts and materials will grow disproportionally.

Based on the expected aircraft retirements by 2030, we estimate the revenues that aircraft recyclers will be able to generate through the sale of parts and materials in 2030. For this purpose, we use the expected number of aircraft retirements (Figure 4) and the average parts and material values per aircraft, which we have taken from the survey of AFRA members (TeamSAI, 2014) and inflation-adjusted to 2020 prices. For 2030, this results in total revenues of USD 8.2 billion, which corresponds to an annual growth of 3.3% between 2020 and 2030. The calculation is based on the assumption that the share of composite materials in retired aircraft remains constant until 2030. As shown in Figure 4, around 50% of the retired/recycled aircraft in 2030 will be narrowbody jets. In the wake of the COVID19 pandemic, a large number of aircraft have been parked permanently by their owners due to low aviation demand. The COVID19 pandemic is expected to lead to strong growth in the recycling market as many of these aircraft will not return to service (Kamel, 2021).

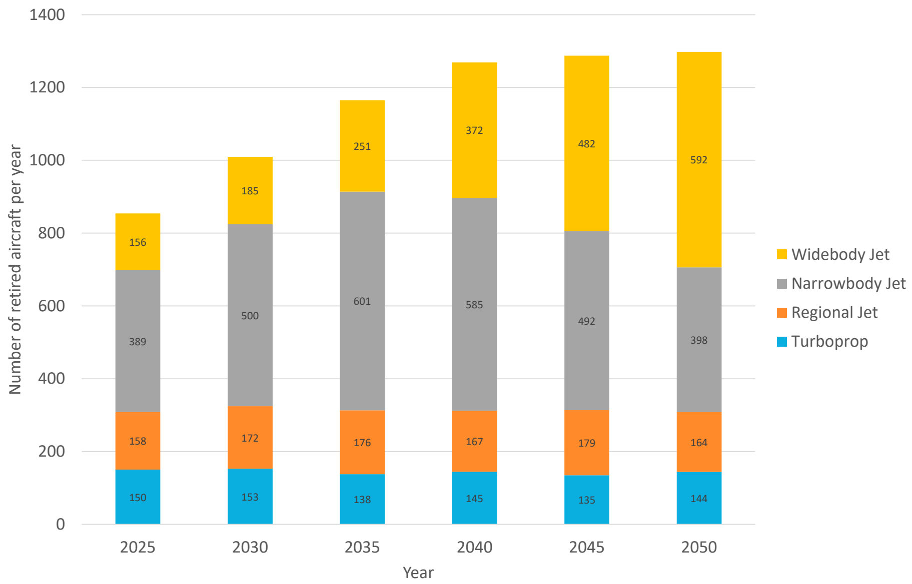

Fig. 4. Expected number of aircraft retirements 2025-2050. Source: Authors modelling results.

Currently, the market for aircraft recycling can be considered as an emerging market. However, in the medium and long term, this market will grow. The main expected drivers (and barriers) of the market in the future are:

- the growth of the global commercial aircraft fleet,
- the global number of aircraft retirements,
- the prices of re-used aircraft parts and materials,
- the environmental political regulations for aircraft recycling and
- the technological options for recycling of aircraft composite parts and materials.

While most of these expected drivers and barriers are of global nature, environmental political regulations for aircraft recycling may well differ from country to country or confederation of states in the future. This will lead to different market conditions for the aircraft recycling industry in the world. If, for instance, aircraft recycling will become mandatory for EU airlines in the future while non-EU airlines will not have this obligation, the EU aircraft recycling industry will benefit economically from these political regulations compared to the non-EU recycling companies. However, any regulations planned for the future should avoid aircraft operators using evasive strategies to reduce costs at the expense of the environment, for instance by selling aircraft shortly before retirement to countries outside the scope of a strict environmental regulation on aircraft recycling. Similar strategies can be observed already today in the maritime business, where vessels are dismantled in countries with low standards under highly questionable conditions for workers and the environment.

One of the forthcoming major drivers and challenges of the aircraft recycling industry are the technological options for recycling of aircraft composite parts and materials. On the one hand, technological progress has to be achieved on this issue as explained above. On the other hand, from an economic point of view, the recycling activities of aircraft with a high share of composite materials should be conducted in an economically efficient way.

Here, economic efficiency is understood as a situation in which every resource (capital, labor, environment, e. g.) is optimally allocated to serve each individual or entity in the best way while minimizing gaseous emissions, waste and other environmental impacts. One common approach to measure economic efficiency is defined as (Koskela and Vehmas, 2012; see also Čuček et al., 2015):

- The ratio between environmental impact and economic performance
  or
- The ratio between economic performance and environmental impact.

For aircraft recycling, no reliable quantitative data on the environmental benefits of these activities on a global scale exists to date to our knowledge. This is also due to the complexity of the processes and the plethora of different materials used in aeronautics. Asmatulu et al. (2013) point out that the environmental benefits of recycling can be substantial. For instance, recycled aluminum is said to consume 90% less energy than that produced from raw materials. With the increased usage of more precious materials (e.g. titanium alloys) and increasing prices for energy and raw materials, recycling becomes more important from an environmental and economic perspective.

Against this background, new analyses and methodologies are urgently needed to investigate the environmental benefits of aircraft recycling. In general, re-used parts or recycled materials can be considered more energy friendly than newly produced parts and materials (source?).

Nevertheless, as a starting point for discussion, we provide some initial quantifications of the economic efficiency by calculating the environmental benefits as the average cost of the industry per ton of recycled aircraft parts and materials. The economic efficiency can be calculated based on the available data. To do this, we use the dismantling and recycling costs per aircraft and engine (Table 1) as well as the average number and the operating empty weight (OEW) of the retired aircraft between 2018 and 2020, which we obtain from Cirium. It should be noted, that, as in Zhou et al. (2020), an APU has not been considered as an additional engine. The resulting ratio indicates the current economic efficiency of the aircraft dismantling and recycling activities of the sector. Interestingly, this leads to large differences in the ratios for different aircraft types. Table 2 presents these results.

Table 2. Economic efficiency of achieving environmental benefits by the aircraft recycling industry (in USD per average ton recycled material or re-used parts)

Aircraft Type	Regional Jet	Narrowbody Jet	Widebody Jet
Economic Efficiency (USD/ton)	6,693	3,531	1,666

A Table 2 shows, for the year 2020, we calculated a ratio of 6,693 USD/ton recycled material/re-used aircraft parts for regional jet, a ratio of 3,531 USD/ton for a narrowbody jet and of 1,666 USD/ton for a widebody jet. The cost per ton decreases by the size of the aircraft type as a result of economies of scale. For example, as shown in Table 1, the average disassembly cost for a widebody engine is a good 40% higher than the costs for a narrowbody engine, but the weight of the former can be more than twice of the latter. For instance, the Rolls Royce Trent 700 engine popular on the twin-engine Airbus A330-300 is a good 150% heavier at 6,160kg than the CFM-56-5B engine popular on the twin-engine Airbus A320CEO at 2,455kg.

These ratios will be subject to change in the future as the share of aircraft composite material will rise. This is especially true for the ratio of wide-body aircraft such as the Airbus A350 and the Boeing 787 as these aircraft types have the largest share of composite material while narrowbodies such as the Boeing 737 MAX or the Airbus A320neo still consist of metals to a large extent. However, the proportion of composite materials will also increase for narrowbody aircraft in the long term. For example, parts of the wing, empennage and rear fuselage of the Airbus A220 (formerly Bombardier CSeries) are already constructed by the use of composite materials (Airbus, 2022b). As Airbus is also conducting research on sustainable wings based on composite materials according to its “Wing of tomorrow” program which started in 2021 (Airbus, 2021), an increase in composite materials can therefore be expected for a large part of its global aircraft fleet in the long run.

Currently, the recycling costs of these composite materials are unknown as no technologically satisfying recycling technology exists to date. There is much reason to believe that the recycling costs will be rising while the environmental benefit will be stable or even decreasing, at least if the benefits are measured by weight of recycled materials. This is because the recycling technologies for aircraft composite materials are not mature and will need significant R&D investments in the future.

5. Conclusions

Aircraft recycling can be considered as an important step on the path to sustainable aviation, as valuable resources used in aircraft construction can be returned for use in a circular economy by these activities.

Our results have shown that the market for aircraft recycling is emerging with great future relevance due to the increasing number of expected aircraft retirements expected in the future. For 2020, global revenues form aircraft recycling activities were estimated at USD 6.0 billion. These revenues, especially the revenues from trading in used aircraft parts create an economic incentive for airlines to recycle retired aircraft instead of permanently parking them on so-called aircraft cemeteries. However, the aircraft recycling market is currently fragmented with a large concentration in the US market. The number of aircraft recycling companies is hard to determine as some of these companies are also active in other business areas, such as trading in used aircraft parts. The costs of recycling per aircraft vary by aircraft class and number of engines. The costs range from USD 109,000 for a twin-engine regional jet to USD 268,000 for a four-engine widebody jet. The costs for a twin-engine narrowbody jet lie in between at USD 138,000.

In this paper, we investigated the economic efficiency of aircraft recycling expressed as the ratio of average dismantling and recycling costs per aircraft and engine in USD compared with the achieved environmental benefit in average tons recycled material or re-used parts. This ratio revealed that aircraft recycling leads to notable environmental benefits as a large share (60%) of the total structural weight is being re-used at given costs. The average economic efficiency is estimated at 1,666 USD/ton for a widebody aircraft, 3,531 USD/ton for a narrowbody jet and 6,693 USD per ton for a regional jet. The differences in economic efficiency can be explained by economics of scale. For example, the average disassembly cost for a widebody engine is a good 40% higher than the costs for a narrowbody engine, but the weight of the former can be more than twice of the latter.

The main expected drivers of the aircraft recycling market in the future are:

- the growth of the global commercial aircraft fleet,
- the global number of aircraft retirements,
- the prices of re-used aircraft parts and materials,
- the political regulations for aircraft recycling and
- the technological options for recycling of aircraft composite parts and materials.

In the future, aircraft recycling will be facing a number of major challenges:

- Air traffic is expected to grow and the number of retired aircraft will increase in the medium and long term. Therefore, capacities in aircraft recycling will have to be expanded by the recycling companies worldwide. The market for aircraft recycling will be growing accordingly. Between 2020 and 2030, the revenues from aircraft recycling are estimated to grow by an average of 3.3% annually.
- In the medium term, a higher share of retired aircraft produced with composite materials can be expected. However, no technologically satisfying recycling technology exists to date for composites. Therefore, the recycling costs of these composite materials are unknown. There is much reason to believe that the recycling costs will be rising while the environmental benefit will be stable or even decreasing, at least if the benefits are measured by weight of recycled materials. As a consequence, the economic efficiency of aircraft recycling will be decreasing. This can lead to a smaller economic incentive for aircraft recycling for airlines compared to the situation today.
- As the environmental pressure from politics and society is expected to be increasing in the future, a stronger public awareness will be on recycling activities not only but also in the aviation sector.

Against this background, we recommend to effectively enforce ambitious recycling standards for retired aircrafts on a global level. Furthermore, as recycling technologies for aircraft composite materials are not mature currently, significant R&D investments are needed for these technologies.

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