Project

Aircraft Recycling – A Literature Review

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Abstract

Purpose – The report summarizes the state-of-the-art in aircraft end-of-life strategies. A focus is on latest aircraft types with a high percentage of composite materials.

Methodology – A literature review is the basic research method utilized. Apart from books, journals, conference proceedings, and dissertations, also technical reports and industrial news have been included into the search results. The field of aircraft end-of-life is still comparatively small, resulting in a manageable amount of literature addressing the topic directly.

Findings – Research has been done on the topic by Airbus, Boeing, other industrial companies, and academic institutions. A market for recycled material is missing. Regulations about aircraft recycling are strongly needed but are not foreseeable in the near future. Nevertheless, the trend goes to extended producer responsibility. The aircraft recycling industry starts to build up now by the launch of several recycling plants. The aircraft recycling market will slowly mature with associations like the Aircraft Fleet Recycling Association (AFRA) and with the publication of guidance material for best practices. The significant higher percentage of composites in modern aircraft types is a challenge for aircraft recycling.

Research limitations – The study provides only an overview on the aircraft end-of-life sector. Further research needs to be done on individual specific aspects.

Value – The paper gives a year 2020 update on the state-of-the-art of aircraft end-of-life handling, including an overview on composite recycling regarding latest aircraft types.

Aircraft Recycling – A Literature Review

Task for a Project

Background

The term "sustainability" gained new importance over the last years. Manufacturers are urged to improve all phases of their product's lifecycle and reduce their environmental impact. Accordingly, the subject of recycling is increasingly investigated. Recycling in the case of airplanes has not happened in the past, as retired aircraft have simply been stored on so-called airplane boneyards. The extend of this aircraft storage is nowadays even visible with GoogleEarth. With the increasing importance of sustainability this process has to be replaced by environmentally friendly and yet economic recycling methods. Ribeiro (2015) sees a "deficiency of knowledge and lack of total management for the aircraft life cycle from cradle to grave." Today aircraft like the B787 and A350 are built with a higher percentage of CFRP and a lower percentage of metal. This saves weight and fuel, but causes problems at the end-of-life when disposal of carbon fiber components has to be managed. Johanning (2017) has considered aircraft recycling as part of Life Cycle Assessment (LCA) in conceptual aircraft design.

Task

Task of this project is to summarize aircraft end-of-life handling strategies und the progress this subject experienced so far. The task has to be approached with a literature review. Based on existing literature and other sources, following subtasks have to be considered:

- Describe the methods used for a literature review.
- Report about state of the art with respect to aircraft end-of-life processes.
- Explain legal aspects that need to be considered when examining aircraft recycling.
- Investigate aims and challenges of aircraft recycling.
- Provide information on composite material recycling and its application in aviation.

The report has to be written in English based on German or international standards on report writing.

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List of Abbreviations

AELS	Aircraft End of Life Solutions – a company recycling airplanes (Netherlands)
AFRA	Aircraft Fleet Recycling Association
AiMeRe	Aircraft Metal Recycling – a Clean Sky project
AMARC	Aircraft Maintenance And Regeneration Center (United States)
AMM	Aircraft Maintenance Manual
APU	Auxiliary Power Unit
ASI	Air Salvage International – a company recycling airplanes (United Kingdom)
BMP	the AFRA Best Management Practice for Management of Used Aircraft Parts and Assemblies and for Recycling of Aircraft Materials
CFRP	Carbon Fiber Reinforced Plastics
CFRTS	Carbon Fiber Reinforced Thermoset
CNRS	Centre national de la recherche scientifique (France)
CRIAQ	Consortium for Research and Innovation in Aerospace in Québec
EADS	European Aeronautic Defence and Space – became Airbus Group in 2013
ECROM	a German company established for mechanical recycling of composites
ELA	End of Life Aircraft
ENVISA	an international environmental research and consultancy company
EPSRC	Engineering and Physical Sciences Research Council (United Kingdom)
GLARE	Glass Laminate Aluminium Reinforced Epoxy
IEC	International Electrotechnical Commission
ISO	International Standardization Organization
LCA	Life Cycle Assessment
LIFE	a UK-based pro-life educational and caring charity
MIT	Materials Innovation Technologies, LLC (United States)
OEM	Original Equipment Management
PAMELA	Process for Advanced Management of End-of-Life of Aircraft
RCF	Recycled Carbon Fibre Ltd (United Kingdom)
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals
SCF	Supercritical Fluids
Tarmac	Tarbes Advanced Recycling and Maintenance Aircraft Company (France)
UQAM	Université du Québec à Montréal
WEEE	Waste Electrical and Electronic Equipment

1 Introduction

1.1 Motivation

The environmental awareness is increasing in all fields of life. People increasingly try to avoid environmentally polluting products and services. The government in many countries already passed laws on different fields of the industry, forcing them to acknowledge the whole lifecycle of their products and improve their sustainability. Since the year of 2000 for example, the European automotive industry is directly addressed by the European Directive 2000/53/EC ma-king manufacturers responsible for their products end-of-life. Until now, there is no regulation directly addressing the aircraft end-of-life, which is commonly justified by a small number of retired aircraft.

Yet, with a look at forecasts of aircraft manufacturers, this justification will lose its fundament in the coming years. With an expected air traffic growth of at least 4.3 % annually, around 40 000 commercial aircraft deliveries are expected until the year 2038. Boeing expects 56 % of these to accommodate the market growth while the remaining deliveries will replace around 75 % of the current fleet over the next two decades. This leads to an amount of approximately 19 000 commercial aircraft retiring from service during the next 18 years. (Boeing 2019, Airbus S.A.S. 2019 and Embraer 2019)

The increasing expectation of a regulation and an increasing civil and market pressure led to a change in the aviation industry where OEMs (Original Equipment Manufacturers) began to consider the aircraft end-of-life already during the design and research on aircraft recycling is being pushed by the industry and academic institutes. The recent years brought up new technologies, processes and a whole new recycling market. To not lose track of it, there is the need for a summarizing update on aircraft end-of-life strategies, the state-of-the-art aircraft recycling and the next generation aircraft models. These new models are built with a high amount of composite materials (> 50 %) to reduce weight and hence, save fuel as well as emissions during operation. Composite materials, nevertheless, are highly challenging to deal with during design, manufacturing and recycling. The topic of composite recycling in context with the aviation industry completes the summarization on the aircraft end-of-life.

1.2 Title Terminology

Aircraft End-of-Life

The end-of-life represents the last phase in the lifecycle of a product. The original product has lived its useful life and is now going to be reused, recycled or disposed. The aircraft end-of-life, hence, describes processes executed after an aircraft has retired from service. This includes the stowage of the aircraft, as done for many years, and any other process, such as disassembly or recycling.

State of the Art

“The most recent stage in the development of a product, incorporating the newest technology, ideas, and features.” (Lexico 2020)

Composite

Composites can be defined as construction materials, made up of recognizable constituents (**Lexico 2020**). The combination leads to changed, commonly improved characteristics, while each material has its own functionality in the composite.

Recycling

“The action or process of converting waste into reusable material.” (Lexico 2020).

1.3 Objectives

The main goal of this study is to give a comprehensive update and summary on current end-of-life handling strategies and improvement researches. To supplement the current situation a regulatory observation along with a comparison to other transportation industries is contributed. Moreover, due to an increasing amount of composite materials used in aircraft manufacturing another objective is to examine aspects of composite recycling in connection with the aviation industry. As there is a lack of documentation and free access to industrial information only a vague relation can be drawn between composite recycling and the aviation by now. Furthermore, this review only covers the basics of the aircraft life cycle and other life cycle phases except for the end-of-life phase. The lifecycle analysis, which is important to aircraft manufacturers nowadays, is not implemented as the topic delivers a large amount of literature itself. In consequence, this study pursues to recap most aspects of the aircraft end-of-life but is not able to cover every aspect in detail. It can be used as introduction to the topic and start point for further, more specialist research.

1.4 Previous Research

A summarizing work was published by Asmatulu 2013b, investigating the progress, environmental benefits and marketability of recycled aircraft materials. Towle 2004 described several aircraft recycling projects and technologies. Regarding legislation, analogies to other industries and driving forces, Feldhusen 2011 released a comprehensive document. These researches manage to describe certain aspects of the aircraft end-of-life in detail but fail to provide an overview on all important subjects.

With reference to composite materials, Yang 2012 presented a comprehensive overview on composite recycling issues and technologies. A first approach to relate composite recycling with aviation concerns was given by Wong 2017.

Both topics, the aircraft end-of-life and composite recycling, experiences fast progress during the last 20 years, giving the urge for a summarizing study.

1.5 Structure

The report is structured as follows.

Chapter 2	defines the research methods used in this paper.
Chapter 3	explains the aircraft lifecycle and the practice of storing retired aircraft at places where enough space is given. These explanations are important for a better understanding of the following chapters.
Chapter 4	deals with aircraft end-of-life progress pushed by the two largest aircraft manufacturers: Airbus and Boeing. It includes the Process for Advanced Management of End-of-Life of Aircraft project launched by Airbus and the Aircraft Fleet Recycling Association founded by Boeing and partners.
Chapter 5	presents different researches regarding the aircraft end-of-life including different tools and strategy improvement efforts. Furthermore, the recent progress of the aircraft recycling market is highlighted in this chapter.
Chapter 6	describes the legislative environment of aircraft recycling and draws a comparison between the aviation and other transport industries (shipping, railway and automotive industry) with respect to the end-of-life handling.
Chapter 7	derives advantages and problems of the aircraft end-of-life.
Chapter 8	provides information about composite materials, focusing on recycling technologies and associating it with the aircraft transport sector.
Chapter 9	summarizes conclusions that can be drawn from this literature review.

2 Research Methodology

The foundation of every scientific work should be a qualitatively high literature research to ensure a comprehensive knowledge of the field of work. The research methodology used in this paper therefore is the literature review. Several strategies for performing a scientific literature research exist. Universities like the TU Dresden in Germany release guidelines which can be useful in school, studies and working life. The goal of a literature research, however, is not to simply copy existing knowledge but to have a critical look on the work done previously and to deal with those scientific issues associated with the own project (Kache 2015). For a proper research thus, appropriate literature needs to be found.

The type of the planned research requires a certain quality of references. Based on the quality of information and the accessibility of the source, references are roughly dividable into primary, secondary and tertiary references. Slightly differing criterions for this separation exist. Scholz 2006 for example shows a separation by the origin and another separation by the type of publication. In contrary, Kache 2015 mixes these criterions up. Table 2.1 displays literature examples for these separation approaches.

Table 2.1 Separation of references and literature with different approaches

	Primary reference / literature	Secondary reference / literature	Tertiary reference / literature
Kache 2015	Measurement and test reports	Reference books Dissertations Journals	Textbooks Compilations Encyclopedias
Scholz 2006 (by origin)	Experiments, calculations and simulation results generated by the author	Literature Professional's interviews Information from the internet	References from secondary references (e.g. if the originally referenced literature can't be found)
Scholz 2006 (by publication type)	Books Scientific articles Dissertations Regulations	Journal articles Newspaper articles Research reports	Lecture notes Business booklets

As the subject of aircraft end-of-life is comparatively new to the scientific world and only few data are gained through analysis and experiments, raw data are close to impossible to find. Even other literature such as papers, dissertations and industrial reports cannot be found in a large number. Nevertheless, the literature available contains enough information to perform a broad summarization of the aircraft end-of-life.

To accumulate the available literature three research methods were used in this paper. The first two methods are described in Kache 2015 as the method of concentric circles and forward searching (refer to Figure 2.1). Both methods are in the need of a central document, e. g. a central paper. The method of concentric circles evaluates the references of the central document. References of interest are listed and replace the main document in its function for the next steps. Then, the references of these documents, are being assessed. This sequence is followed until no relevant documents can be found any longer. The counterpart to this method is the forward search. Modern databases offer the ability to find documents citing a certain other document. By following the forward search method, the literature citating the central document is evaluated, before documents citing the citing documents are rated. Just like the method of concentric circles these steps are repeated until no relevant documents appear anymore. The forward search, though, can be problematic in the case of a central document, that was published only a few years before performing the research, as there might be a lack of newer publications in the field of interest. Figure 2.1 illustrates both methods with the method of concentric circles to the left and the forward search to the right of the central document.

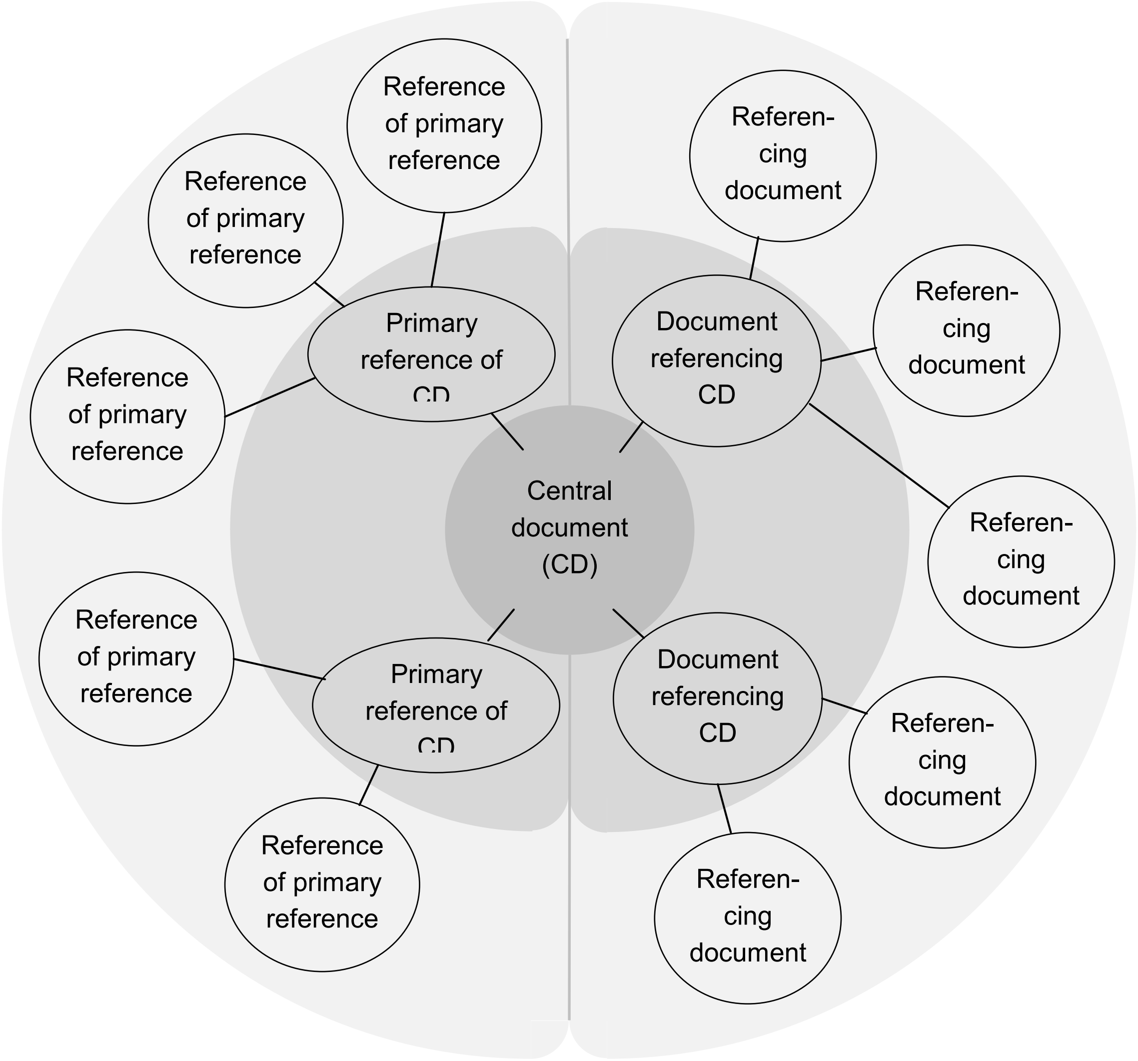

Figure 2.1 Method of concentric circles (to the left) and forward search (to the right)

The third research method used is a workflow described by Bergheimer 2018. It can be called "strategic research" and is divided into six steps, shown in Figure 2.2.

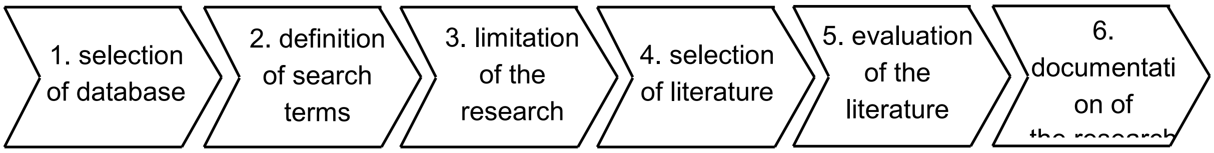

Figure 2.2 Strategic research workflow (adapted from Bergheimer 2018)

Steps one and two represent preparations, while steps three to five function as the actual research. The final step ensures transparency. First of all choosing the appropriate database is important as most databases are specialist and commonly list literature on different specific topics. Hence, databases focusing on medical topics shouldn´t be chosen when examining an engineering question. After selecting appropriate databases, search terms are defined. These terms can be expanded at any time of the process, if necessary. Next, these terms are used in the selected databases to accumulate literature. In order to not aggregate too many findings during research, limits need to be defined before evaluating the results. Limiting factors can be the appearance of certain combinations of words in the title of a document or the whole text, the year of publication or keywords. In contrary, this step can also be turned around to generate more findings, by using less words to find or widening selection filters. Moving on to step four, the evaluation of the yield literature is executed but does not call for perusal of the whole text of every finding. The first evaluation step is set by reading only the title. If the title is not of interest, neither abstract nor the whole text need to be read. Conversely, if the title is interesting the abstract is evaluated in terms of relevance. If the document is again chosen to be relevant, the whole text is perused quickly. Afterwards, the literature is given a careful peruse in step five which constitutes the basis for writing the literature review. Despite the arrangement in Figure 2.2 the documentation of the research process needs to be done during all phases of the research to not lose track of the progress. Step six therefore represents the structured and comprehensible documentation of all steps and results. With this transparency being ensured, the research work is traceable and repeatable. Due to the largely done research performed for this review, the documentation is not shown in this document. An exemplary documentation of a research is shown in Bergheimer 2018.

Further information on literature research in terms of literature characteristics and strategies is published by many universities, such as Charles Sturt University 2020, University of Leeds 2020, Obst 2011 and Rauchmann 2019.

For this study, all three research methods and the databases Scopus, Scholar.Google and the conventional Google search engine were combined. This led to a sufficient amount of literature to perform a summarization in a qualitatively adequate way. The focus was placed on the aircraft end-of-life. Besides, the subject of composite recycling is not investigated in the same quality but is examined precisely enough to give an overview on the current situation.

3 Background Information

The aircraft is a complex product, not only due to technological aspects but also from an economic and logistical point of view. In addition, the aviation sector is sensitive to social hypes. For a long time, flying was told to be dangerous, while nowadays the aircraft transport sector is said to be pollutive. Over the past two decades the term "green" gained importance representing an environmentally friendly lifestyle. The pressure on the industry to "go green" and decrease the environmental impact of their products increases. This pressure is also applied on the aviation, which is commonly associated with rather poor environmental sustainability. This urged the aircraft industry to make a change and improve the social image of flying. Operators began to ask for aircraft models with better sustainability and aircraft manufacturers had to follow their request. Thus, these manufacturers began to analyze the lifecycle of their products and soon discovered that the aircraft end-of-life was a comparatively polluting part. The reason for this was the common practice to simply park retired airplanes and leave them without any deconstruction. The following two subchapter build fundamentals on the aircraft lifecycle and the aircraft storage in order to enable a better understanding of the urge to overcome the past practices.

3.1 Aircraft Lifecycle

Every system and product undergoes different stages of development or use during their life, from the initial idea of creation to the disposal at the end of the useful life. In most cases the lifecycle of a product is investigated when performing lifecycle assessment or lifecycle management. The basic goal of these techniques is to gain insight on properties like quality, measurability and emissions. The lifecycle defined by the International Standard ISO / IEC / IEEE 15288 is divided into six basic stages:

- Stage of design,
- Stage of development,
- Stage of production,
- Stage of use,
- Stage of support and
- Stage of disposal.

This division can, in general, be applied to almost every product, hence, also to the product aircraft. Nevertheless, the stages defined by the International Standard are neither tailored towards the aircraft nor to a special use case. To improve the significance, the aircraft lifecycle can either be simplified to only four phases or be broken down to a higher, more detailed number of stages. Schmidt 2013 for instance divides the aircraft life cycle for the purpose of a life cycle cost assessment into four main phases:

- Research & development, planning & conceptual design, preliminary design & system integration, detail design;
- manufacturing & acquisition;
- operation & support; and
- disposal.

In contrast to this a more exact division is explained in Soumalainen 2014. For a long time, the aircraft end-of-life stage was not considered important as only few airplanes retired every year. The concept of parking old, uneconomic aircraft originates from that time and led to airplanes being parked for years before and if ever being dismantled. Another reason for this concept of aircraft storage is presented by the lack of an aircraft dismantling industry. Soumalainen 2014 incorporates this stage into an idealized aircraft lifecycle, shown in Figure 3.1.

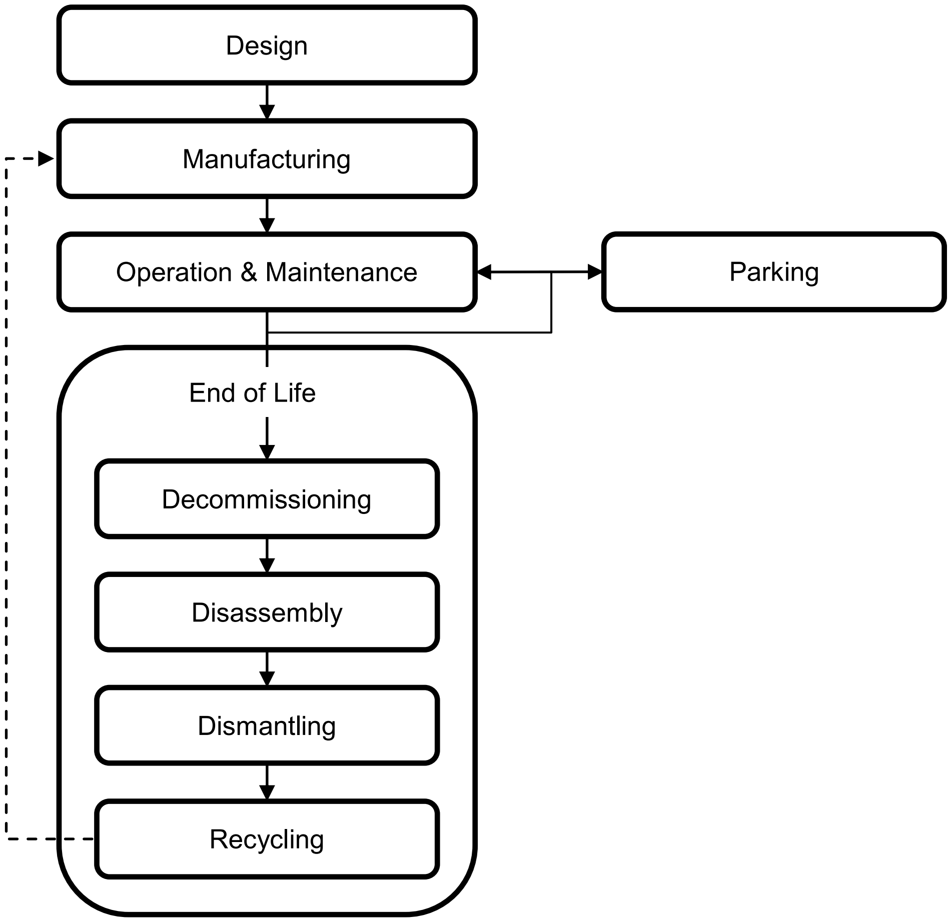

Figure 3.1 Idealized Aircraft Life Cycle (adapted from Soumalainen 2014)

Still, Soumalainen 2014 mentions a missing stage in the idealized cycle: the stage of landfill, disposal or incineration of materials that cannot be recycled.

In addition to the above-mentioned specificities, the aviation industry is driven by regulations and a common process of aircraft manufacturers to largely interview costumers, airlines in this context, before developing a new aircraft. Szabo 2015 therefore takes one more step and divides the lifecycle into the following ten stages:

- Design
- Definition
- Development
- Production
- Testing
- Operation
- Support
- Modernization
- Decommissioning and if necessary
- extension of technical life.

Unfortunately, the basic knowledge of the aircraft lifecycle does not necessarily lead to any improvements. Hence, aircraft lifecycle management is arising nowadays to enable airlines to solidify their competitive advantage by maximizing the fleets performance (Aersale.com 2019). Moreover, knowing the aircraft lifecycle gives airlines the chance to gain more insight on how their fleet will change during the coming years and which countermeasures are to introduce, for example operating older aircraft when the fuel price is low to save flight hours on newer, more fuel-efficient aircraft. Aircraft manufacturers like Boeing and Airbus joined this trend and investigated the whole lifecycle of their airplanes. Recently, Airbus for example stated to take the aircraft operation and end-of-life into account when designing new aircraft (Airbus.com 2020).

3.2 Aircraft Storage

So, what does usually happen to an aircraft when the owner decides to not operate it anymore?

For a long time, the common practice of handling such an aircraft was to store it on so called airplane scrap yards until further decisions were made. These scrap yards offered enough space at favorable conditions such as the storage price as well as airplane conserving climate conditions (hot and dry) (Towle 2004). The stored airplanes were kept functional by authorized personnel if the airworthy aircraft was worth more than its parts. The owner would have then either brought it back into service when operating conditions, e.g. the fuel price, were convenient, or sold it, often to countries with laxer regulations. If these methods were economically unprofitable the aircraft was stored unmaintained for an undefined time.

Usually valuable parts such as engines, landing gears, avionics and electronic motors were removed carefully to be sold afterwards (Keivanpour 2010). The remaining parts of the airplane that could not be removed and sold were disposed by landfill, which meant to simply store them in places where enough space was available. This landfilling led to thousands of aircraft stored, more than four thousand solely at the Aerospace Maintenance and Regeneration Center in Tucson, Arizona, as shown in Figure 3.2 (Saleh 2003).

Figure 3.2 The east side of the AMARC facility (AMARCExperience.com 2020)

The process of landfilling combined with poor traceability and disposal conditions of end-of-life aircraft incurred the interest on the end-of-life phase of aircraft. According to Towle 2004 there even have been incidents of nonserious disposal of aircraft parts into the sea which caused social outrage. To in turn improve the image of aviation, airlines and manufacturers felt the urge to replace common practices by sustainable methods.

4 Aircraft Manufacturer’s Efforts

The first notable approaches to initially understand and furthermore improve the aircraft end-of-life originates from aircraft manufacturers. The largest civil aircraft original equipment manufacturer (OEMs) are Airbus from Europe and Boeing from the United States. Their efforts had big impact on industry and research and hence, led to a number of other research, projects and launches of recycling test plants, covered in Chapter 5. Both manufacturer benefit from the results of their efforts by being able to integrate these into the development of their next generation aircraft.

4.1 Airbus’ Strategy

Airbus began to develop different approaches to avoid aircraft storage and aircraft sales out of the European Union in 2005. The ‘Process for Advanced Management of End of Life of Aircraft’ called PAMELA was launched in cooperation with Suez-Sita – a French recycling company – and the working group LIFE (l’Instrument Financier pours l’Environnement). Moreover, the European Union supported the project which on the one hand aimed to prove that 85-95 % of an aircraft can be easily recycled, reused or recovered. On the other hand, a new standard for safe and environmentally friendly management of “End of Life Aircraft” (ELA) was supposed to be created. Lastly, the third goal was the launch of a European network to enable further dissemination of the resulting dismantling process. (Academy 2020 and Ribeiro 2015a)

In the early 2006 an Airbus A300-B2 which reached the end-of-life phase arrived at Tarbes airport, marking the beginning of the experimental phase of the dismantling project (Airbus.com 2006). The A300 served as the world’s first full-scale demonstration and was completely dismantled, while results and effectiveness of the methods used were recorded. According to Airbus.com 2006 the project was meant to run until the year 2015 but was already completed in 2007 (Ribeiro 2015a).

Nevertheless, a three-step approach, the so-called 3D approach, was successfully developed by PAMELA. Figure 4.1 shows an overview on the process.

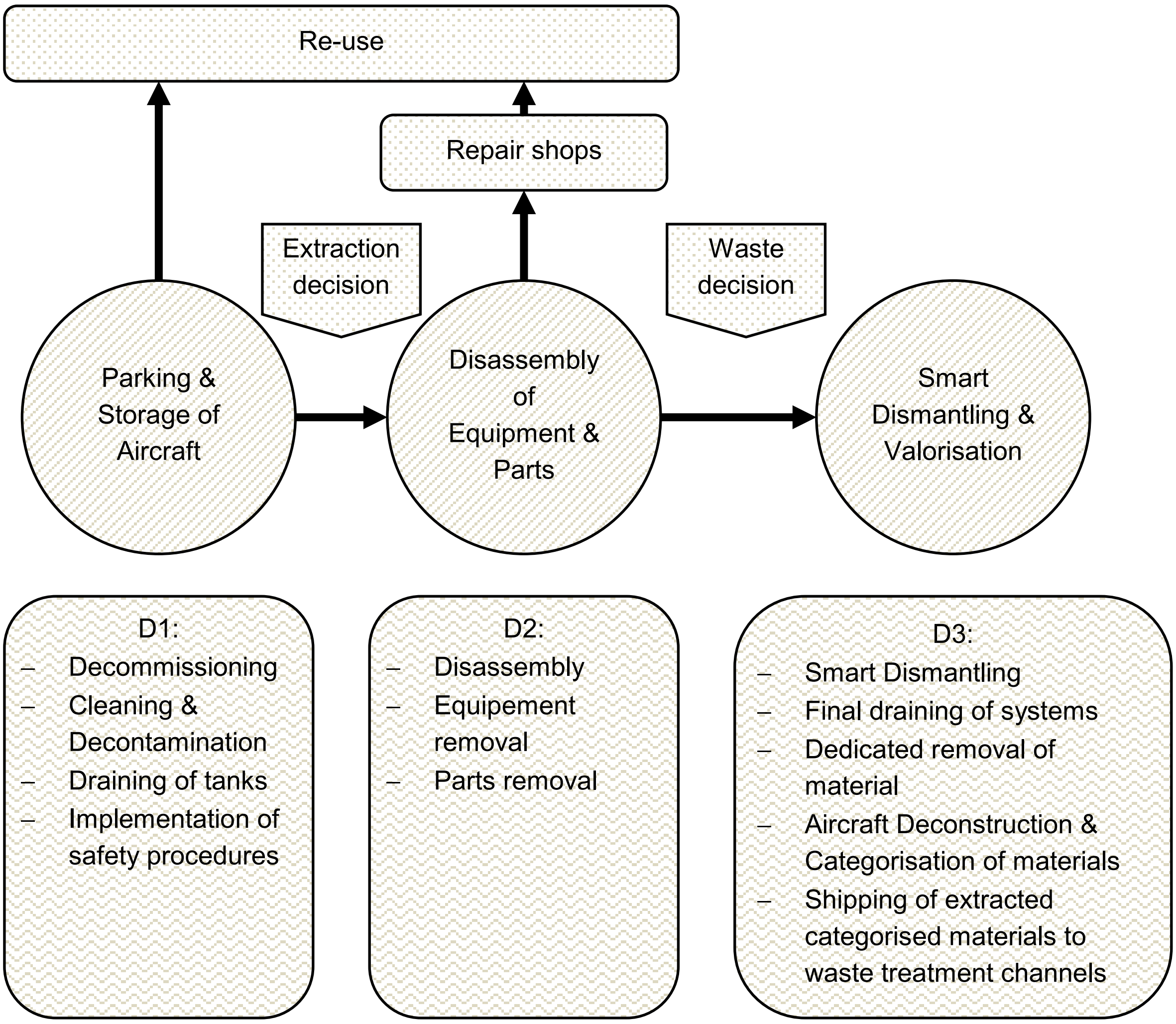

Figure 4.1 PAMELA's 3D approach (adopted from Ribeiro 2015a)

During the decommissioning the aircraft is parked, inspected, decontaminated and cleaned. All liquid material and hazardous substances are drained and either orderly disposed or stored for reuse. The second step starts by planning the disassembly process. All possible spare parts, such as the APU (auxiliary power unit), avionics and landing gears, are dismantled, checked and cleaned. If necessary, repair takes place before completing the part documentation and selling these spare parts. Not airworthy parts are destroyed immediately after disassembly. If the owner then decides to move on to the third step, the dismantling, the aircraft does no longer require aviation legislation but must be handled according to all applicable waste regulations. PAMELA tested different approaches on the dismantling order and techniques in order to improve this step. After dismantling, the resulting materials are grouped, sorted and sent to recovery channels. Eventually the recycled metal can be returned into appropriate. (Ribeiro 2015a, Feldhusen 2011 and European Commission 2011).

As a result, the project demonstrated that it is possible to reach a valorization ratio of up to 85 % in weight and save up to 90 % in energy and mining resources of metallic material (Academy 2020). The A300-B2 those days arrived with a total weight of 106 tonnes, which was reduced to 88 tonnes during the decommissioning. The weight of the disassembled parts in the second step yield to 13.5 tonnes. After the step of dismantling only 13.5 tonnes of material, mainly insulation material and casings, remained unrecycled and had to be disposed. Besides the proof of a high recycling proportion, PAMELA managed to create a generic plan of methods enabling the industry to dispose and recycle any given airplane in an environmentally friendly way with high respect to safety measures and economic benefits (Ribeiro 2015a and Feldhusen 2011).

In May 2007 a new PAMELA project began using an A380 static test frame. The project was named PAMELA A380 and used the techniques and best practices developed by the previous PAMELA project (Airbus.com 2007). By starting PAMELA A380 month before the first delivery of this aircraft type, Airbus approached to already take the aircraft end-of-life into consideration during the development of the new aircraft type. While addressing recycling issues surrounding larger aircraft, Airbus was able to assess the recovery potential of new alloys and achieved a 98 % recovery rate for metallic components. Calling it "smart disassembly" Airbus addressed the technical as well as the business aspects of recycling with the PAMELA projects (Perry 2012a).

Following the PAMELA project and applying its results, Airbus founded the Tarbes Advanced Recycling and Maintenance Aircraft Company (Tarmac Aerosave) in cooperation with companies like Snecma Services and Aeroconseil. The first operative launch of a dismantling facility took place in 2009 in Tarbes, France. In 2012 the company achieved the accommodation of the 100th aircraft in Tarbes. A new facility opened in Teruel, Spain in 2013 followed by Toulouse Francazal, France in 2017 (TarmacAerosave.aero 2020b). The company started with a time effort of nearly three months for a full aircraft dismantling (Airbus.com 2010). In January 2020 Tarmac Aerosave has recycled an overall number of 170 aircraft and 135 engines since their creation in 2007 (TarmacAerosave.aero 2020c). The two shareholders of Tarmac Aerosave besides Airbus nowadays are the Safran Group and Suez, each owning about one third of the company. The organization is moreover accredited by ISO 14001, ISO 9001, EN 9110, EN 9120 and holds EASA / FAA Part 145 and EASA Part 147 approvals (TarmacAerosave.aero 2020a).

Tarmac Aerosave started their business by applying the recognitions of the PAMELA Project and has widened their capabilities to environmentally and socially friendly storage, maintenance and recycling of aircraft and engines. After all, the company was also able to increase the recycling rate to more than 90 % (TarmacAerosave.aero 2020a).

4.2 Boeing’s Strategy

Compared to Airbus’ fleet, the Boeing fleet is relatively old. While Airbus delivered their first commercial aircraft in 1974, Boeings 707 had its debut in 1957 (TheAtlantic.com 2019). Hence, the bigger part of the stored airplanes and nowadays retiring aircraft belongs to Boeing, putting pressure on the company to join the ‘green’ movement. Boeing followed a different approach of handling the increasing thread of retiring aircraft than Airbus. In partnership with ten European and American companies Boeing founded the Aircraft Fleet Recycling Association (AFRA) in April 2006. Originating from industries like waste management, commodity production, aircraft maintenance and manufacturing, part suppliers and service providers, the founding members committed to apply their combined expertise to aircraft scrapping with best technical standards. AFRA is a self-financing non-profit organization whose members work in the aircraft end-of-life sector under a certificate with defined processes. (Feldhusen 2011 and Carberry 2008)

The associations mission includes forming a global network of members from all steps of the supply chain, from manufacturer to material recyclers. With the collective experience of its members a series of “Best Management Practice for Management of Used Aircraft Parts and Assemblies and for Recycling of Aircraft Materials” (BMP) guides have been elaborated of which version 4.0 took effect on April 18, 2019 (AFRA E-Newsletter 2020). The guide outlines the management of parts that are removed from an aircraft or engine during the disassembly of the retired asset, and the recycling of recovered parts and materials through a set of recommendations. For members or companies applying for membership, the document constitutes auditable standards (AFRAAssociation.org 2020c).

Application to AFRA is open to every business and organization having relations to airplanes. An applicant will be approved by the board of the founding members and agrees to ensure that:

- aircraft and parts recovered from them are safe for future use in aerospace applications,
- unserviceable parts and components are disposed of in a responsible manner,
- best practice is spread across the AFRA membership and to all interested parties involved in the storage, maintenance and disposal of aircraft irrespective of the manufacturer of that aircraft and
- at disassembly the airframe and its components are disposed of in accordance with current legislation and best environmental practice. (Towle 2004)

AFRA by now has 90 members (AFRAAssociation.org 2020a), which relish benefits like

- Participate in shaping the future of aircraft end-of-life component and material sustainability, and in development of best practice standards,
- Regulatory and media representation,
- Opportunities to participate in AFRA committee projects,
- Industry engagement through newsletters and updates,
- AFRA eNewsletter, featuring updates from the Association's committees, member news, and upcoming events listings,
- Education about the value chain and emerging technologies for disassembly and recycling,
- Recognition for commitment to environmental responsibility and
- Networking & sponsorship opportunities at AFRA meetings.
  (AFRAAssociation.org 2020b)

In addition, owning the AFRA accreditation results in more valuable refurbished parts, since higher levels of security as well as quality in terms environmental impact and labor safety are ensured. Members currently include Boeing as well as Tarmac Aerosave, Embraer, AELS, American Airlines, Delft University of Technology, Frauenhofer Institute for Chemical Technology, Lufthansa Technik AG, Pratt & Whitney and Magellan Aviation Group, just to pick a few examples (AFRAAssociation.org 2020a and Perry 2012a). Perry 2012a stated that around one third of the yearly scrapped aircraft around the world are disassembled and parted out by AFRA members, which illustrates the impact of the association on the aviation recycling culture.

AFRA also in contacted the official aviation authorities FAA and EASA in order to get their BMP guide accredited and make the first step into a legislatively controlled aircraft end-of-life management. According to missing news, these efforts have not been rewarded yet.

5 Further Advances

Besides the advances pushed by the two big airplane OEMs Boeing and Airbus, other manufacturers, companies and academic institutes also tried their best to gain insight into the aircraft end-of-life phase. Consequently, the industry was enabled to start creating a new aircraft recycling market, implying the efforts of Airbus and Boeing.

5.1 Technological Progress

Apart from Airbus and Boeing further aircraft manufacturer exist, such as Bombardier, Embraer, Comac and others. Most of the other aircraft OEMs joined the 'green' movement in one way or another. Bombardier for example, who is accredited by AFRA, started working on a metals recycling project with the Consortium Research and Innovation in Aerospace in Quebec (CRIAQ), other industry players and academic institutes. The projects first objective was to gain a better understanding of end-of-life requirements and the corresponding commercially practical recycling technologies (Perry 2012a). Furthermore, in the year 2011 Hélène Gagnon, that time vice president of public affairs, communications and corporate social responsibility at Bombardier stated to strive for a fully recyclable aircraft. Therefore, the company must seek for solutions to recycle the last 25 % of their aircraft that had not been recyclable yet (Kaplan 2011). The Bombardier Cseries, renamed to Airbus A220 in 2018, even were awarded an Environmental Product Declaration, a standardized way of quantifying a product's life cycle environmental impact, as the aircraft model was designed for end-of-life (Airlines.IATA.org 2018).

The AiMeRe (Aircraft Metal Recycling) project formed by ENVISA and Bartin Recycling was launched in response to the 11th Call for Proposals JTI-CS-2012-01-ECO-01-050, namely "Metal recycling: Recycling routes screening and Design for Environment", issued by Clean Sky on January 13 in 2012. Clean Sky itself is Europe's largest research program whose objective is to develop innovative technologies aiming to fight global warming. AiMeRe's goals cover the assessment of the dismantling processes of airplanes, the proposal of process improvements and recommendations for the Design for Environment and thus provide valuable input for the Clean Sky program. (AiMeReProject.com 2020 and ICAO 2014)

In 2005 the United Kingdom Engineering and Physical Sciences Research Council (EPSRC) launched the WINGNet (Network for waste reduction in aircraft related groups) project, temporarily limited to two years. The project focused on the development of technologies and infrastructure to meet the challenges of the sustainable use and reuse of aircraft components

and materials. Despite having held a series of events to explore the industrial issues, WINGNet was a cofounder of AFRA. (WINGNet 2020, EPSRC 2005 and Towle 2004)
In the past, a lot of attention has been paid to the so-called development for X, as explained in Zahedi 2015. The X thereby is to replace by attributes like disassembly, remanufacturing, environment, sustainability or recycling. Zahedi 2015 states that these design strategies are more enabling and feasible regarding the attribute given than common strategies. There have been only few research on the application of these strategies in the aviation sector, but the subject was investigated more in other industry branches. Ribeiro 2014b integrates the Design for End-of-Life in a framework. This framework embeds the decision process of end-of-life into aircraft design in order to enable the analysis of a recommended prioritization for each end-of-life alternative (reuse, recycle, remanufacture). The Design for End-of-Life is also included in Ribeiro 2014a's approach for extended producer responsibility where another framework is generated to integrate Life Cycle Assessment (LCA) into the preliminary aircraft design. Wimmer 2015 developed a Design for End-of-Life tool in order to examine aspects like economics, separability and recycling of different material combinations as soon as the design is developed. Shu 1995 evaluates the impact of fastening and joining methods on remanufacturing as an end-of-life option and highlights some of the different Design for X strategies. A detailed Design for Disassembly method is provided by Lee 1996. Besides Shu 1995 and Lee 1996 more research can be found regarding Design for X without special industry integration but with the certain possibility to improve a products end-of-life, such as Zussman 1994.

Moving forward from design strategies to the actual end-of-life phase, the adequate treatment is not the same for every product or part of it. There are different end-of-life alternatives, such as reuse, recycling, remanufacturing and disposal, with differing advantages and disadvantages regarding economy, environment and society. Van Heerden 2010 gives a comprehensive overview on definitions of these alternatives, the respective processes and products, before extracting economic values of the aircraft recycling. A general economic assessment of the end-of-life alternatives is shown by Low 1998. Since perfection only seldomly exists, one alternative can be better regarding one field of interest, but worse regarding another. This complexity is intensified by the fact, that each end-of-life treatment concerns many participants, each having differing objectives and priorities. For these reasons, making the decision of how to handle the end-of-life of complex products such as an aircraft urges for compromises and is a tough challenge without supportive tools. Such tools for selecting an end-of-life alternative can be divided into heuristic approaches, recommendations and analytical models. Gungor 1997 presents an evaluation of different disassembly strategies and a heuristic approach for selecting the best strategy. However, by utilization of fuzzy logic and generic algorithms Keivanpour 2017b proposes a framework to support decision making at both, the strategic as well as the managerial level. In this work lean management, sustainable development and the global business environment are considered regarding the end-of-life treatment. Sabaghi 2015 also uses an efficient fuzzy assessment method to select the best dismantling and disassembly strategy considering the sustainability. In order to build a robust understanding of the sustainability performance factors of each dismantling/disassembly strategy, ten different risk scenarios are examined in that paper. Moreover, Keivanpour 2016 first provides a review of the different end-of-life phase models, followed by a framework integrating sustainability, assessment tools and different modelling approaches. Apart from this, Ribeiro 2014a follows an approach of extended producer responsibility to develop a conceptual framework for the analysis of recommended prioritization of the end-of-life alternatives. Miglorância 2010 proposes the concept of producer responsibility as a chance to implement the end-of-life management of an aircraft as part of the customer service of aircraft manufacturers. A new maintenance program called "Life-Monitoring" was developed, integrated in the aircraft end-of-life management framework. Despite these research Goggin 2010 describes a software model supporting the decision-making to recover either the product, part or only the material without specialization on airplanes.

If in some cases a disassembly plan is already specified and corresponding scale values can be estimated, DAS 2000 introduces a tool to support and facilitate the economic analysis of the disassembly activity, enabling estimations of disassembly costs and efforts before starting the process. This tool either might be used to choose between a selection of end-of-life alternatives, giving insight on resulting costs, or can be used as part of the disassembly management.

Another investigated part of the end-of-life phase of the aircraft is the planning and scheduling of the disassembly to choose the most time- and cost-saving sequence. Research on this topic has been done by Dayi 2016, using a lean approach, by Yi 2008 using algorithms and a disassembly wave concept and by Camelot 2013, in which a tool was developed using heuristic methods and models obtained by the AMM (Aircraft Maintenance Manual). Zahedi 2015 takes a closer look on the disassembly process, gaining insight on issues, fundamental elements and another approach to ease the end-of-life handling.

End-of-life management of complex products includes a high number of factors. Despite the work of Miglorância 2010 concerning this topic, Keivanpour 2017a presents strategies for modelling the end-of-life phase of complex products, addressing operational, tactical, strategic and sustainability aspect. The approach is then applied on the aircraft end-of-life.

Mascle 2014 approaches general methods to implement a profitable rebirthing process exemplary on a real Bombardier CRJ100 using heuristic and experimental approaches. In addition, a large project was carried out in Mascle 2015, where the optimal ways to dismantle, dispose or recycle aircraft components in an environmentally friendly manner and with respect to regulatory compliance have been studied. An experimental platform was built for testing the studied models and lastly logistic networks, life cycle analysis and a redesign approach have been considered.

The possible treatments of getting rid of an aircraft are dividable into destructive methods, which have been used for a long time by simply crushing the structure unorganized, and non-destructive methods, which completely disassemble the aircraft party by part but are not economically viable. As both methods are not optimal, Zahedi 2016 performs a research on semi-destructive operations, which combine disassembly with down scrapping. An evaluative model is presented to assess the process before it is physically started and give quantitative insight.

Research on recycling technologies themselves, such as metal alloy recycling or the separation of coatings and metals, has been carried out in high number. General insight on recycling technologies can be found in Martens 2016. The reference book also discusses aspects like steps in the recycling chain, general recycling technologies (mechanical, thermal, chemical, etc.) and the recycling of special materials and parts. Technological researches applicable to aircraft recycling are not further discussed here but offer scope for further literature research.

5.2 Market Progress

For a long time, the industry was inhibited to build an aircraft recycling market due to an only small amount of retired aircraft supplying an insufficient amount of scrap for a new type of industry to rise. But with the increasing amount of aircraft at their end-of-life simply being parked, a recycling industry for aircraft end-of-life is arising. AELS (Aircraft End-of-Life Solutions) for example is a Dutch company buying, selling and recycling airplanes. The company was launched in 2006 and has three main competences: support in end-of-life decision-making, disassembly and dismantling of aircraft and component management. AELS claims to have disassembled and dismantled 75 aircraft in their history while currently having clients such as KLM, Lufthansa and TNT (AELS.nl 2020 and Perry 2012a). Another example for the new industry branch is Air Salvage International (ASI), a United Kingdom based aviation services company, having experience in dismantling of over 750 projects. The company also contributes knowledge to AFRA and its Best Management Practices (AirSalvage.co.uk 2020 and Ros 2018). At the Air Center of Châteauroux Airport in France, Bartin Aero Recycling is located, a subsidiary of Veolia and the Vallière Aviation Group. Bartin owns the ISO 14000 certification and their 20 employees dismantle between three to 10 airplanes each year (Chateauroux-Airport.com 2019 and Perry 2012a). In this context, Perry 2012a mentions the sequence of dissection of Bartin, starting with the wings and then going from tail to front or rear landing gears. All resaleable parts were removed previously. The left-over aircraft structure is then cut into manageable pieces and transported to recycling plants. Yet another big player in the aircraft recycling industry is called eCube Solutions, who is also accredited by AFRA. The business was formed in 2011 initially specialized in aircraft end-of-life project around the globe. The company with main site in St. Athan, Wales soon became an expert in all phases of the aircraft end-of-life, starting from aircraft parking and storage to disassembly and disposal, comprising also parts storage and costumer management. In 2019 the company launched a facility in Castellon, Spain (eCube.aero 2020). Figure 5.1 shows an airplane at the recycling site of eCube Solutions.

Figure 5.1 Decommissioned aircraft at a recycling plant. Photo taken at eCube Solutions

The AFRA accreditation achieved big influence in the aircraft recycling industry. Accordingly, airlines with social acknowledgement rather choose recycling companies owning the AFRA accreditation than those companies offering lower price but higher insecurities. Further companies dedicated to the aircraft end-of-life thus can be found at AFRAAssociation.org 2020a. Beyond those companies' objective to manage and execute aircraft recycling, two different business models are observable. On the one hand those companies only perform the aircraft recycling process and handle parts and materials gained from an aircraft. In this case, these parts and materials still belong to the prior aircraft owner. The recycling company will not earn money on sales of parts and material. In contrast to this the second business model includes a change of the ownership of the aircraft. The recycling company will buy the aircraft from the previous owner for a scrap price. The recycler will than perform all processes like decontamination, disassembly, part and material management and will finally sell parts and materials to in return earn money.

On the contrary to this common end-of-life handling strategies special reuse approaches exist. Such an approach on giving a component a second life is examined in Morquillas 1990, discussing the usage of old aircraft engines in other industry fields, either as pure industrial engine or as the gas side of a combined cycle power plant. This procedure is cost and time saving for involved companies compared with the purchase of new equipment, but the research does only cover engines. However, it might be applicable to other aircraft components. According to Asmatulu 2013b P3 Aviation, a UK-based supplier of rotating parts follows such an approach of reuse by selling all kinds of aircraft parts as furniture or decorations. More Information on P3 Aviation is released by Reals 2011.

6 Legal Classification

Even today, where research is ongoing and where the future number of airplanes retiring from service is well studied, there is no regulation directly concerning the handling of end-of-life aircraft. Feldhusen 2011 and Ribeiro 2015a state that the comparatively small number of currently retiring aircraft is used as justification for this missing regulation.

Though a proper regulation would be the best way to clarify the legislative situation of aircraft recycling, two approaches exist for a better classification.

The first approach uses regulation with indirect impact on aircraft recycling. The fact that there is no regulation concerning the aircraft end-of-life directly does not mean recycling of those is not affected by any governmental regulation at all. The processes are indirectly affected by different existing regulations due to the characteristics of some of the used materials. Exemplary regulations adopted by the European Parliament and the corresponding council include Directive 2002/96/EC on “Waste Electrical and Electronic Equipment (WEEE) , the Directive 1994/62/EG on “Packaging and Packaging Waste” (Richtlinie 94/62/EG), Regulation (EC) No 1907/2006 concerning the “Registration, Evaluation, Authorization and Restriction of Chemicals (REACH)” and the European Directive 2002/95/EC from 2012 on the “Restriction of the Use of Certain Hazardous Substances in Electrical and Electronic Equipment” (Richtlinie 2002/95/EG). Those regulations apply the principle of extended producer responsibility. The trend of industrial legislations clearly goes to this principle, as for example European Directive 2008/98/EC on “Waste and repealing certain Directives” clearly states to introduce “the concept of ‘extended producer responsibility’”, which “may include an onus on manufacturers to accept and dispose of products returned after use”. The directive also confirms a principle, where the original waste producer must pay for the costs of the waste management, called “polluter pays principle”. A waste hierarchy is as well established, choosing prevention to be the best waste handling, followed by reuse, recycling, recovery and finally disposal. Council Directive 1999/31/EC on the “landfill of waste” addresses a reduction of organic material disposed by landfill. This directive therefore again has an indirect impact in aircraft recycling. Organic materials include composite material and some liquids. By analyzing existing regulations aircraft recycling companies are able to adjust their processes to requirements given by governments which can possibly one day also impose on the aircraft end-of-life.

The second approach attempts to find similarities to other transport industries such as the train, shipping or automotive industry. Feldhusen 2011 acquires analogies to all three of those transport means, finding similarities and differences in the initial incidents, legislative and other requirements and the realization of end-of-life handling. Recycling processes of the railway industry offers only few information. Similar to the aviation, there is no special regulation defining the treatment of decommissioned trains, giving no urge for a change in the end-of-life handling. Railway wagons are usually classified as waste. The main difference between aviation and railway industry therefore is the idea of an environmentally friendly lifecycle strategy where the waste declaration should be done when all reusable parts are removed (Feldhusen 2011). The shipping industry, however, is regulated since the adoptions of "The Hong Kong International Convention for the Safe and Environmentally Sound Recycling of Ships" in 2009. The convention contains, inter alia, the obligation of carrying an inventory of hazardous materials when a ship is being send for recycling, and guidelines to assist the implementation of the convention covering the whole lifecycle of ships from design to recycling (Hong Kong International Convention 2009 and Ribeiro 2015a). The main problem in the naval industry is a huge amount of violation of regulations, as ships are commonly broken down in shipyards, where regulations are far less strict, for instance India or Bangladesh. Those ships, consisting mostly of steel covered in coatings, are then recycled in the most simple way, disregarding safety and environmental issues (Feldhusen 2011).

The end-of-life handling in the automotive industry is by far the most investigated and known among the transportation industries. The most likely reason for this is the high number of cars entering the end-of-life status every year and the close relation to private citizens. Just like recommended aircraft recycling sequences from PAMELA and AFRA, usually the first step of automotive recycling covers the removal of dangerous components or materials and all liquids. Afterwards reusable parts are disassembled while the remaining materials are recycled according to the composition and applicable rules. This recycling chain corresponds to the one given in Martens 2016, a reference book on recycling technologies. The automotive industry is regulated in Europe by the Directive 2000/53/EC on "End-of-Life Vehicles", applying the principle of extended producer responsibility. The regulation covers the obligation for manufacturers to accept end-of-life vehicles back, the recycling rate and some procedure limitations. (Feldhusen 2011 and Ribeiro 2015a)

As the idea of an environmentally friendly aircraft throughout the whole lifecycle can only be achieved, when a retired aircraft is not considered "waste", neither the railway nor the shipping industry offer suitable approaches yet. The automotive industry, however, provides an appropriate model concerning end-of-life vehicle handling. Both industries, automotive and aviation, face challenges like social pressure and the need of bringing recycled materials to a high quality while staying economically beneficial. A big difference constitutes the much higher amount of security and documentation efforts needed in the aviation industry, as reusable parts must have a gapless documented history. Both industries moreover face a growing amount of composite materials used, which will be a future challenge and will require more specific regulations. (Feldhusen 2011)

The aviation has been an international affair for a long time. The social and legislative pressure on emissions in combination with missing global regulations led to national attempts trying to reduce aviation emission, e.g. by applying emission-based landing fees. Aircraft end-of-life certainly is a global issue, just like environmental effects are a global issue. As many countries follow the lead of the European Union and the United States in terms of regulations, adopting a regulation on aircraft end-of-life in either one of those can change a lot on a global level. Extended producer responsibility therefore can be a beneficial approach. Still, the complexity of the aircraft and economic characteristics need to be considered when designing a regulation.

The first step into a legally classified aircraft end-of-life was done by modifying the norm ISO 14001 in 2015, extending its compulsory implementation on the aeronautical industry. The topics covered by ISO 14001 are environmental management systems, requirements, and guidelines for application. (Ribeiro 2014a and DIN EN ISO 14001:2015-11)

7 Situation Aspects

When designing a regulation on the end-of-life handling as well as when examining strategies or processes concerning the same topic, aims and challenges need to be highlighted to close the loop. Keivanpour 2010, Feldhusen 2011, Asmatulu 2013b, Soumalainen 2014 and Martens 2016 discuss different aspects of those, summarized in the following.

Aims and driving forces can be divided into environmental and economic issues. Environmental benefits from improving the aircraft end-of-life include the reduction of emissions produced during the end-of-life stage and savings on energy and natural resources. These benefits lead to a decreasing environmental impact and hence to a minimization of the global warming. The savings on energy and natural resources has despite environmental as well economic benefits, as recycled material of high quality can be sold for a good price while saving money on the energy consumption and on the acquisition of raw materials. Economical driving forces comprise labor costs, documentation costs and the costs for disposal of remaining materials which cannot be recycled. All of these costs increase the more environmentally friendly the aircraft is recycled. Nevertheless, the achievable outcome from selling removed parts and recycled materials also increases. The most used example for benefits of material recycling is aluminum. As for now most aircraft consist mostly of aluminum alloys, 60 to 80 %, the lightweight metal shows one of the biggest potentials of recyclable materials in the aviation. It takes 47 MJ primary energy to produce 1 kg of aluminum from cradle-to-gate for new material production, whereas only 2.4 MJ are needed to produce 1 kg of recycled aluminum. 3.83 kg CO_2 are generated per 1 kg virgin aluminum while recycling only generates 0.29 kg CO_2 per kg. Similar benefits can be found for other metals used in airplanes for instance in Asmatulu 2013a. Woidasky 2017 calculated the “flying stock” of different materials, stating that around 95 000 tonnes of aluminum are flying around the world solely in the active Boeing 747 airplanes. The biggest problem for aluminum recycling, however, stays the use of many different alloys in the aircraft and the separation of metal and coating. Muñiz-Lerma 2017 published a research on the refining and recovery efficiencies of applying fractional crystallization to aircraft aluminum components. The study showed that fractional crystallization can be used on aircraft aluminum alloys to obtain high-grade aluminum alloys with a potential reuse in the aerospace industry. A study on the thermal degradation behavior and characteristics of the coating on aluminum substrates from aircraft components was performed in Muñiz-Lerma 2016. The study presented an isotherm temperature of 480 °C as optimum for thermal decorating, which results in almost clean aluminum surfaces. A thermodynamic analysis of a variety of aluminum alloy recycling technologies was furthermore performed by Cui 2017.

The challenges faced by everyone involved in aircraft recycling comprise the general complexity of the product aircraft on the one hand. On the other hand, as there is no regulation directly addressing aircraft recycling the key driver for proper processes is the market itself. Thus, environmental claims always face high economic claims. The quality of the recycled materials and the marketability of these is another challenge of aircraft end-of-life. The aircraft mostly consist of material combination, increasing the effort to gain “pure” materials. Furthermore, the requirements of aviation legislation are strict in many ways which lead to downcycling of parts and materials. In addition, a comparatively small number of aircraft at end-of-life and the hence small amount of recycled materials and parts makes aircraft recycling a niche market resulting in the urge for recyclers to have at least a second pillar in business. Keivanpour 2015 meanwhile developed a methodology for a reliable estimation of retired fleets and highlighted guidance for occurring challenges. The market for recycled materials is tough and the demand for recycling services is connected to the market price of the scrap materials. If for example the market price of scrap aluminum is low, selling it may not cover the processing costs and hence recycling is not economically profitable (Perry 2012a). Keivanpour 2010 describes the value chain of aircraft recycling treatments with 3 bases: process base, performance base and stakeholder’s base. Added to contradictions between these bases, the levels themselves hold a certain complexity such as implementation effort, human resources, sustainability, effectiveness, size and influence of stakeholders The last two important challenges in aircraft end-of-life are represented by various hazardous materials used in airplanes and high logistical efforts needed due to the internationality of the aviation.

The aircraft recycling field is complex with many different stakeholder, businesses, objectives, and processes. Improving processes saves energy, emissions, money as well as space which would otherwise be used for landfill. The end-of-life stage recently gained a lot social interest which put pressure on a previously solely economic business having to deal with fluctuating metal prices. Soumalainen 2014 clarifies that for an optimum aircraft end-of-life handling legislative help by for example guaranteeing a stable revenue is a must. But another challenge is about to come especially in the field of recycled materials, namely composite materials, covered in Chapter 8.

8 Composites Recycling

The recycling of composite material is as complex as the recycling of a whole product because a chain of processes needs to be executed successfully in order to enable the achievement of reusable recycled materials. The most common industrial composite materials can be sorted into thermoset matrix, thermoplastic matrix and a whole bunch of other composites such as reinforced concrete. These different kinds of materials also require different recycling technologies. A comprehensive overview on composite recycling issues and technologies is presented by Yang 2012. Pimenta 2011 publicized a technology review on recycling of carbon fiber-reinforced polymers for a structural application, including a market outlook. A publication edited by Godship 2010 updates and summarizes many aspects in the field of composite material recycling. Wong 2017 gives a short insight on composite recycling before merging it into aviation industry and Towle 2004 focuses on the aircraft end-of-life but also mentions issues regarding composite materials. These technologies and a short insight on research progress of these are explained shortly in the following before relations to the aviation industry can be investigated. Composite materials covered in this study only include glass and carbon fiber reinforced plastics, as these are mainly used in aircraft.

8.1 Mechanical Recycling

Mechanical breakdown is used for almost all types of composites since this technology is also used as initial size reduction of the composite scrap. These technologies are highly investigated and involve only moderate setup costs. Common processes include shredding, crushing, milling and other similar processes. After a gross break down of the scrap, the pieces are again milled into different grades of recyclates without the use of higher temperatures or chemicals. Afterwards the recyclate is sorted by cyclones and sieves into fiber-rich (coarser) and matrix-rich (finer) fractions. This process does not include fiber extraction and obviously also cuts fibers into short pieces with poor mechanical properties. For this reason, the second milling process is usually only used for glass fiber reinforced polymers. Those recyclates are then used as filler or reinforcement for lower grade applications. Carbon fiber composites only experience the first step of mechanical breakdown, after which the pieces still hold fibers with a length possible to extract and realign. (Yang 2012, Pimenta 2011 and Wong 2017)

Industrial progress on mechanical recycling has been achieved for example by a company called ERCOM, established in Germany in the nineties. The company shredded sheet molding compounds and proved the feasibility of the mechanical recycling in an industrial scale, before closing the plant in the year of 2004 (Wong 2017). Shredding fiberglass reinforced composites into recyclates for construction applications has been the task of a company called

Mixt Composites Recyclables launched in France. The company is still active in research and nowadays recycle inter alia automotive composite waste (m-c-r.com 2020). Other composite recycling companies were established in most parts of the world and will not further be named here. Ribeiro 2015b presented a successful study on fiberglass reinforced pultrusion profiles that were shredded and then used as reinforcement in polymer concrete. Another research was given by Palmer 2009a and Palmer 2009b on the potential of recycled glass fiber composite materials used instead of virgin composite materials. These researches however did not deal with the special features of the aviation industry.

8.2 Thermal Recycling

Processes using or producing high temperatures are called thermal processes. Three different types of operations exist for composite waste:
1.) Incineration or combustion for energy recovery only,
2.) Combustion for fiber and filler recycling with energy recovery and
3.) Pyrolysis with both fiber and fuel recovery. (Yang 2012)

As some European directives determine a distinction between ‘recycling’ and ‘recovery’, the first type of thermal recycling resulting solely in energy recovery cannot be considered as a recycling process and is therefore not further explained. The term combustion in this case needs to be separated from common waste incineration, as this type of recycling leaves behind reusable material while waste incineration does not leave any usable material behind.

Oxidation is a type of thermal process that consists of the combustion of the matrix in a hot and oxygen-rich flow. The so called ‘fluidized-bed’ technology is one of those processes and on the one hand recovers fibers, while on the other hand the organic resin matrix and the combustion heat are used for energy recovery. This technology can be used for polyester and epoxy resin composites with both, glass and carbon fiber. First, composite scrap is mechanically broken down into manageable pieces which are then fed into a fluidized-bed reactor. The reactor is operated with a sand-bed that is heated and fluidized by a hot air stream, which enables a rapid and uniform heating condition. Epoxy resin composites require a temperature of up to 550 °C while polyester resin composites only require 450 °C. Though glass fibers suffer from 50 % tensile strength loss at 450 °C, carbon fibers offer a higher thermal stability and suffer from less degradation even at 550 °C. The hot airstream decomposes the matrix and burns off pyrolytic char. The clean fibers are then elutriated away from the fluidized bed by the hot air stream before being separated from the air by a cyclone. Heavier components such as metallic components are not carried up with the air stream and the resin from the matrix is fully oxidized in an afterburner which generates energy. The resulting fibers have a fluffy form and a length of up to 10 mm. A tensile strength degradation can until now not be inhibited, but the Youngs Module and the surface condition of the recycled fibers are comparable to virgin fibers. The combined characteristics of these recycled fibers lead to a limitation in applications. They can only be used in any non-aligned fabrics or materials such as molding compounds. (Yang 2012, Pimenta 2011 and Wong 2017)

Pyrolysis uses a temperature of 300 to 800 °C in the absence of oxygen to decompose polymers. The resin matrix is broken down into lower molecular weight organic compounds, that can be used as feedstock for either composites or other chemical processes afterwards. Through the pyrolysis process and a subsequent ashing or oxidation in air, long fibers and fillers of high module and clean surface can be obtained. The process can be used for polymer-matrix composites with both, glass and carbon fibers. Different types of reactors can be used, though fluidized-bed reactors and rotary kilns are more suitable. The resulting products are a mixture of solid, condensed liquid and gaseous components with varying proportions and material compositions. As said before, the pyrolysis technology is often combined with a combustion process (such as subsequent ashing) to remove leftover materials from the fibers’ surface. (Yang 2012, Pimenta 2011 and Wong 2017)

The university of Nottingham developed a fluidized-bed recycling process using the combustion of resin matrices for energy and fiber recovery (Pickering 2006 and Pickering 2010). A different approach was given by the University of Hamburg, using the fluidized-bed pyrolysis process to recover fibers as well as secondary fuels from the depolymerization process (Kaminsky 2010). These studies are only examples and mark the beginning of progress on thermal composite recycling. Both technologies, but pyrolysis especially, are still in research and improve slowly. They offer a high range of adjustable variables and hence, haven’t found their optimum yet. Despite the technological work on thermal methods for the recycling of waste composites, Pickering 2010 also investigated the commercial viabilities of these processes. Due to a higher market value of carbon fibers, carbon fiber plants can have a smaller scale than glass fiber recycling plants which are said to be economical at a processing capacity of above 10 000 tonnes per anno. The high amount of glass fiber used in wind turbine blades, nevertheless, caused the development of a pyrolysis-gasification process called “ReFibre” by Larsen 2009 in Denmark. The process recycled glass fiber of end-of-life wind turbine blades and recovered the thermal energy and the glass fibers, that later were usable in thermal resistance insulation materials.

8.3 Chemical Recycling

Chemical recycling is also done to recover fibers from composite material and is particularly suitable to carbon fiber composites with a thermoset matrix (CFRP). Carbon fibers offer high thermal and chemical stability and therefore inhibit mechanical and bonding degradation from the recycling process. With this recycling process the matrix is chemically polymerized or removed with the use of chemical dissolution reagents and thereby exposes the fiber. As reactive mediums fluids like catalytic solutions, benzyl alcohol and supercritical fluids (SCFs) can be used. Fluids at temperatures and pressures just above their critical point are called supercritical, combining characteristics of the fluid and gaseous state. The application of SCFs is a comparatively new approach, promising no chemical degradation on carbon fibers and the recovery of useful chemicals from the matrix. Chemical recycling is also called solvolysis. Water and alcohol offer the benefit of being environmentally clean and can be separated from the dissolved solution by using evaporation or distillation. Solvolysis, however, is typically energy intensive leaving the urge for research on more economic approaches. (Yang 2012, Pimenta 2011 and Wong 2017)

Regarding chemical recycling technologies Allred 2001 developed a tertiary recycling process using low-temperature liquid catalysis. A more recent study was given by Nakagawa 2009, developing a carbon fiber epoxy resin composite recycling process with the usage of benzyl-alcohol and a catalyst under a N2 atmosphere. Moreover Piñero-Hernanz 2008a and Piñero-Hernanz 2008b published research on supercritical fluids with varying temperatures and pressures to recycle carbon fibers. An optimization study on chemical recycling of carbon fiber reinforced composites has been done by Keith 2016. According to Wong 2017, a solvolysis pilot plant was about to be established by Vartega Carbon Fibre Recycling LLC in 2017 in the United States with an annual capacity on 100 tonnes of composites. (Yang 2012, Pimenta 2011 and Wong 2017)

8.4 Aviation Relations

Coming from wood to steel and on to aluminum, the composition of the aircraft structure has changed a lot during the decades. In the recent years the next change has already begun: the partial replacement of aluminum alloys with composite materials. Driven by the goal to reduce operational costs and emissions, aircraft OEMs use the lighter and stronger composite material. Figure 8.1 shows the composite weight of larger commercial aircraft on a percentage basis over the past years.

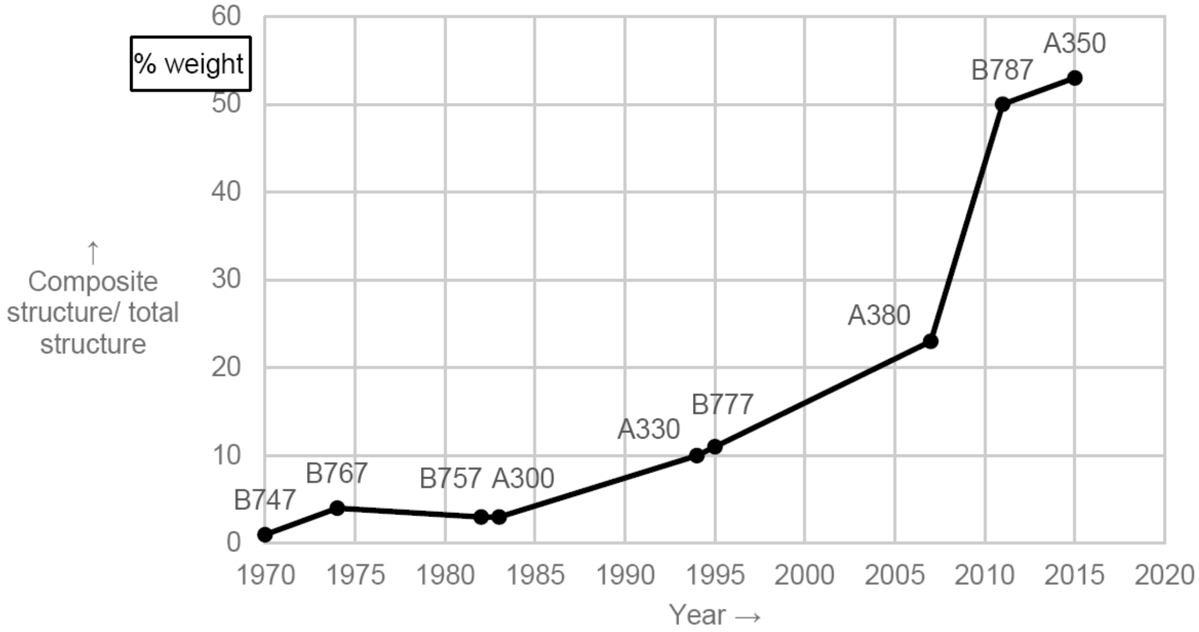

Figure 8.1 Use of composites in aircraft (values from Woidasky 2017, Wong 2017 and Towle 2004)

Starting with almost no composite material at all with the Boeing 747, the last next generation aircraft models Boeing 787 and Airbus 350 hit the 50 % mark. The increasing "green" thinking and the recycling efforts done by aviation industry and academic facilities also pursue the urge to face the challenge of proper environmentally friendly composite recycling now, even though the aircraft with high composite amounts are not retiring during the next 20 years.

The challenges of aircraft composite recycling combine technological, economic, environmental and logistical problems that need to be solved or at least investigated.

The first challenge addresses the existing two types of composite scrap from the aircraft industry. On the hand composite waste is generated during manufacturing itself, on the other hand there are composite parts that have reached their end-of-life. Despite GLARE (a glass fiber and aluminum composite), carbon fiber and epoxy resin are most commonly used in large commercial aircraft. This fiber matrix combination is generally delivered in an uncured prepreg roll for manufacturing. This roll is nowadays cut to size and shape in an automated process, increasing accuracy and consistency and shortening the cutting time. Due to this process, the waste cuttings were reduced compared to prior hand cutting. Added to the waste cuttings of "fresh" composite prepreg, other waste from manufacturing occurs from prepreg that has reached the shelf or freezer date and therefore cannot be used anymore. This adds up to a buy-to-fly ratio of about 1.5 (Wong 2017). As the usage of composites increases, the amount of composite waste from manufacturing will increase equally if no revolutionary technology is developed for the manufacturing process or any other way can be made up to anyhow use these mechanically sound waste materials.

Heading directly from manufacturing to the end-of-life phase, the second type of composite scrap occurs to be the supposedly bigger challenge. This sort of waste consists not only of completely cured carbon fibers and epoxy resin, but also of metallic inserts, honeycombs, foam cores and is most likely contaminated with chemicals such as coatings. Considering the "flying stock" of composites, Woidasky 2017 determined a mass of 13 618 metric tonnes composites to by flying in the year of 2017 solely in Boeing 787 airplanes. The overall mass of flying composites has already increased and is not going to stop.

These two types of composite waste require different recycling technologies, which leads to differing processes, tooling and market conditions. Hence, the waste supply for composite recycling plants is not homogeneous. It ranges from fresh to hardened to cured composites. Thus, a cooperative relationship between waste generator and waste recycler is necessary to ensure a predictable composite waste supply and enable profitable economics. Thomas Hunter, president of Firebird Advanced Materials Inc, suggested in an interview with McConnell 2010 that a network of smaller-scale facilities near a composite waste generator offering sufficient supply would be the best setup. With this approach, the logistical efforts will be kept low, as delivery routes are short, the waste material will not change consistency during transport, and the waste can be separated directly after emergence to ensure a reduction of post work efforts. Furthermore, essential information to increase the quality of the recyclate can be provided more easily with a cooperative relationship. Such information include material chemistry, fiber content and may also imply raw material certification to allow for a higher market price of the recyclate.

By the time that the waste arrived at an appropriate recycling plant, the technological challenge appears. For a long time, composites have gone to landfill not only because it was a cheap option but primary because the industry was not able to recycle this type of material in a beneficial way. Over time the stowage costs, civil awareness for environmentally friendly products and legislative burdens increased and the industry finally felt the urge to deal with the technological challenge of composite recycling. It took a lot of research to solely figure out, how to recycle composites in a way, that results in usable recyclate. Moreover, the recycling process needs to be environmentally friendly, not to mention the indispensable necessity of being economically profitable. Nevertheless, there has been and there is still a performance perception issue, as a big part of the industry still believes, that recycled fibers are of lesser quality than virgin fibers.

One of the biggest challenges is the missing market for composite recyclate. For a long time, the industry was unable to use the individual components resulting of composite recycling and hence did not need a market for those. Now that recycling technologies deliver fibers with properties comparable to virgin fibers and a realization of the market value of composite waste takes place, slowly an unstructured market is building up. Perry 2012b describes a general model including a hierarchical sequence of passing recycled composites from industry to industry, depending on the specific requirements. This sequence starts in the aircraft industry having the highest requirements, moving on to automotive, sporting goods and finally to the civil construction industry. This sequence represents a possible way to create a structured market. Nevertheless, the development of a composite recycling market requires further environmental, economic and technical parameter estimations, e.g. the volume of material to be recycled, the demand for recovered fibers and the leftovers of the matrix and the reliability of the materials. According to Vieira 2017 these requirements can be solved by the obligation of certifying the materials as well as the waste generator and the recycler. Yet, according to McConnell 2010 an evolving composite recycling business is still in the need of certain prerequisites, such as an consistent waste availability, appropriate size reduction technologies, established process parameters, infrastructure like material collection at the waste generator and the standardization of recyclate product properties. Yang 2012 mentions that characteristics and properties of the variety of recycled fibers have to be determined, processing times and costs have to be assessed and the value of the recyclate needs to be established in order to identify the potential recycled composite market. These statements leave scope for further research to help stakeholders in the composite recycling market.

The recyclate properties depend on their future use, which is the last challenge to mention here, while there certainly exist even more problems. Due to size reduction and the recycling process fibers have a certain size and might have a fluffy form, as said before. As a result, they cannot be used for infinite fiber prepregs and therefore find less use cases. Typical applications present milled carbon fiber, nonwoven mats and fiber alignment, which is the most difficult but also the most valuable method regarding mechanical properties. Wong 2017 gives an overview on these applications.

8.5 Miscellaneous Advances

Composites are said to be a future material, but in this case the future is already here. Despite all challenges, the material combination offers huge opportunities in lightweight engineering and other fields of the industry. With high mechanical characteristics and a low weight, composites fit perfectly into the requirements of aircraft manufacturing but also ask for new manufacturing and recycling methods.

The aircraft industry in cooperation with other industry branches and academic institutes are by now involved in technological research and industrial advances. Stade in Germany is the venue of a whole composite center, including research and innovation centers(CFK-Nord.de 2020), a network called “CFK Valley” (CFK-Valley.com 2020), an academic institute on composites (Composite-Campus.de 2020) and the composite recycling company CFK Valley Stade Recycling GmbH & Co. KG (CFK-Recycling.de 2020). In Japan the Japan Carbon Fiber Manufacturers Association, first established in 1978, is involved in all topics of composite materials and considers a variety of industry branches in relation with this material. The association's goal is to push the application of composite materials and investigate every question regarding the material and products, e.g. the lifecycle, recycling and legal classification (Carbon-fiber.gr.jp 2020). According to Pimenta 2011, the association also launched a pyrolysis re-cycling plant in the mid-2010s. These companies, institutes and associations represent only a small part of an expanding (general) composite recycling industry.

The University of Nottingham is another leader in composite research. Besides several projects on recycling technologies, the university also put much effort on developing a fiber alignment process for finite recycled carbon fibers. Moreover, the university led a project that produced aircraft cabin parts with aligned composite mats to demonstrate their potential (Wong 2017). The Materials Innovation Technologies (MIT) furthermore proved that recycled fibers can be used in the automotive industry by chopping, mixing and molding the fibers (Asmatulu 2013b).

Despite Allred 1997., who investigated a tertiary recycling process of cured composite aircraft parts, technological research on composite recycling has also been pushed by the aircraft industry itself. According to Towle 2004 the pyrolytic process developed by Milled Carbon Ltd is able to recycle all kinds of composite aviation waste. Uncured prepreg scrap can not only be recycled but also upcycled into different forms and potential end-products, as proven by Nilakantan 2015. The Boeing company is involved in research on composite waste, too, for example by supplying recyclers with primary composite scrap from the 777 and 787. Boeing collaborated with a variety of partners, including Adherent Technologies in the USA, Milled Carbon from the UK, the University of Nottingham and the University of North Carolina (Perry 2012a) The potential applications are another focus of Boeing's research. One of these works involved testing recycled carbon fiber in non-structural components of their airplanes. In conjunction with Materials Innovation Technologies (MIT) from Fletcher in North Carolina, US and Recycled Carbon Fibre Ltd (RCF), Boeing developed pyrolytic processes for fiber recovery (Yang 2012). In addition, the American aircraft manufacturer has launched pilot recycling facilities, such as a recycling plant in cooperation with Alenia Aeronautica in Italy and another one in cooperation with Milled Carbon Limited (Asmatulu 2013b). In 2012 the BMW Group announced the cooperation with Boeing in terms of composite manufacturing and recycling (BMWGroup.com 2012). Similar to Boeing, Airbus launched several projects on composite recycling, partly also included in the PAMELA project. According to Yang 2012 PAMELA also used pyrolysis to extract carbon fibers and scale-up the process to define best practices. In cooperation with the Bordeaux University, the France National Centre for Scientific Research (CNRS), EADS Astrium and Snecma, Airbus investigated a solvolysis process for carbon fiber reclamation and methods for fiber alignment (Perry 2012a). Bombardier on the other hand, was involved in a composite recycling project together with Canada's National Research Council and the Université du Québec à Montréal (UQAM), according to Perry 2012a. The goal was to understand the material and apply the gained knowledge to the CSeries aircraft, which was under development at that time of the project and is now called Airbus A220.

The recent work of Zahibi 2020 introduced another recycling technology which completely reclaims carbon fiber composites by using a microwave assisted chemical method. While being fast and cost-efficient, the process promises to be environmentally friendly and efficient, producing carbon fibers with only marginal mechanical degradation and a possible improvement of the surface. With these benefits being proved, this technology offers huge opportunities to be applied in an industrial scale. Nzioka 2019 used a mechanochemical-enhanced recycling method to investigate effects on surface properties. The results showed no cracks but contaminations. Still, this study points out that the quality of recycled fibers is still increasing with technological progresses made.

In contrary to aircraft recycling, composite waste material is currently partially covered in European Regulation (EC) no 1907/2006 (Reach) on chemicals. This results in safer handling of these materials but also in higher requirements and costs from an economic point of view. Hagnell 2019 presents an economic and mechanical potential evaluation of the usage and recycling of fiber-reinforced composite materials. A new recyclate material value model was developed based on the retained mechanical performance of retrieved fibers. It was shown that the recycled fibers possess high value and therefore can reduce the high raw material costs of common composite systems and hence, classify composite recycling as economically viable. Economic benefits nowadays go hand in hand with environmental concerns. Asmatulu 2013a quantifies production and recycling properties of recyclable aircraft material which also comprise composites. The production of new CFRTS (carbon fiber reinforced thermoset) requires 234 MJ/kg energy and generates 12 kg CO_2/kg, while the production of recycled CFRTS only uses 33 MJ/kg energy with a generation of 2 kg CO_2/kg. Thus 201 MJ and 10 kg CO_2 can be saved with every recycled kilogram CFRTS composite. These savings in turn save money, resulting in a better market price while having a good material quality and with a better price, an increasing amount of companies will choose to buy recycled composites and hence preserve natural resources.

A completely different approach to all research mentioned before is given by Vieira 2017., exploring possible models to minimize the use of carbon fiber composites and extend their life. Vieira et al. also describes the state-of-the-art carbon fiber composite recycling by pointing out recycling processes, restrictions and regulations.

9 Summary and Conclusions

The aircraft end-of-life can clearly no longer be ignored due to an increasing pressure on everyone involved. This pressure is a result of rising civil awareness, the increasing amount of annually retiring aircraft and thus an increasing economic value that would be lost if only stored. Recycling aircraft materials has environmental, economic and social benefits. The environment will be relieved due to savings in energy consumption, emissions and natural resources. Recyclers and aircraft owners will gain economic advantages through missing stowage costs and selling parts and recyclable material from end-of-life aircraft.

There has been research carried out through main aircraft OEMs such as Airbus and Boeing, through various other industrial companies and through academic institutions. These researches included recycling technologies for aircraft materials, management processes for the complete aircraft end-of-life and economic analysis. The huge potential of aircraft recycling has been shown, while challenges were identified. These challenges include a missing market for recycled material, high requirements of the aviation industry increasing efforts and costs and a complex environment that is not clarified by regulations.

By now the aircraft recycling industry started to build up by the launch of several recycling plants and guidance material for economic and environmentally friendly recycling processes have been given by associations like AFRA and research programs such as PAMELA. These guidance material and associations support new recycling companies to improve their economics and thus ensure an aircraft recycling market is set up. Yet the field of the aircraft recycling industry is still only indirectly affected by regulations that could define responsibilities, structures and other parameters. Combining the knowledge that has been build up through the diversity of research, and existing regulation concerning other industries, a probable legislative model can be concluded.

The trend of regulations concerning end-of-life products goes to extended producer responsibility as seen in European Directive 2000/53/EC on automotive end-of-life products. Unfortunately, neither the naval nor the railway industry offer an end-of-life situation that could be used to further define the future of aircraft recycling. Aircraft OEMs thus draw parallels to the automotive sector, trying to completely understand the end-of-life phase of their products and bring the recyclability of the future aircraft to the maximum. PAMELA already stated that around 85 % of the weight of an aircraft can be recycled and Bombardier is trying to design future aircrafts with 100 % recyclability.

But as technology advances the aircraft market will change in the same pace. Therefore, the aircraft recycling market that will be further defined in the coming years will experience another change with an increasing amount of next generation aircraft models consisting of a higher composite percentage. The Boeing 777 airplanes that begin to retire nowadays already own a significant percentage of composites with 20 % by weight. Composites face the same challenges as the general recycling industry, just more intense. Technologies have not yet been optimized, new technologies are still investigated, there is no market for individual recycled components and applications of these usually represent downcycling.

There are still questions not answered in the aircraft end-of-life. A regulation is strongly needed to clarify the situation but is not foreseeable by now. Thus, the main driver for aircraft recycling stays the industrial market itself, putting the highest priority to economic benefits. The recycling market is growing nevertheless, and the flow of ongoing research is fortunately kept steady.

The aircraft end-of-life is highly complex. All participants of the industry, associations and academic institutes need to keep working together in order to keep up the commitment for a ‘greener’ aviation from cradle to grave This report cannot cover every aspect, giving the urge for further research on more specific topics. As a final remark there is research going on in the field of how aviation will change in the future**.** Åckerman 2005 mentions three scenarios of sustainable air travel in 2050: a) information technology (IT) replaces travel, b) a slowed but yet globally curious society, c) a slowed and regionally focused society. If any of these scenarios will come true? Only the future will tell.

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