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Procedia CIRP 26 (2015) 311 – 316

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12th Global Conference on Sustainable Manufacturing

Proposed framework for End-Of-Life aircraft recycling

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Abstract

The recycling of aircraft materials has come into greater focus in recent years, due in large part to the increase in the number of aircraft which are reaching the end of their working life. Aircraft manufacturers estimate that up to 44 percent of the global fleet will reach end-of- life in the next two decades, amounting to more than 13,000 commercial, military and private aircraft. One of the factors that is impeding sustainable end-of-life is the deficiency of knowledge and lack of total management for the aircraft life cycle from cradle to grave. Therefore, developing a conceptual framework for managing the end-of-life aircraft process is essential to achieving true sustainability and then closing the loop. Our review gives an overview of related research and positions end-of-life aircraft as a key strategy for the future. By merging sustainable thinking into traditional end-of-life aircraft process, this review provides a framework for ongoing research, as well as encourages research collaborations among the various communities interested in end-of-life aircraft.

Peer-review under responsibility of Assembly Technology and Factory Management/Technische Universität Berlin.

Keywords: Recycling; aircraft end-of-life; framework.

1. Introduction

Worldwide air transportation will continuously grow. Current forecasts predict that the worldwide passenger traffic will grow by an average of 5.1 % and the cargo traffic will grow by an average 5.6 % per year until 2030. To meet this increasing demand for air transportation, there will be in total about 33 500 aircraft deliveries worldwide over the next 20 years [1]. The worldwide aircraft fleet will almost double [2-1-3].

An aircraft's life cycle consists of the seven phases materials, design, supply chain, manufacturing, transport, aircraft operations and end-of-life as shown in Fig. 1. Usually, an aircraft is designed, developed and produced to be in operations for about 30-40 years.

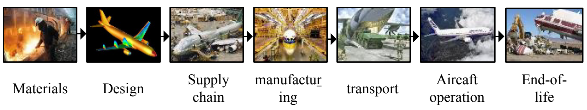

Fig. 1. The aircraft life cycle [4].

At the end of this time span and after millions of flight miles, the aircraft is no longer worthwhile for the operators and is set to retire from service, because it becomes uneconomical to operate the aircraft, e.g. due to high maintenance and overhaul or fuel consumption costs.

As consequence of the predicted development for the next 20 years and the limited aircraft operations time span, about 10 000 passenger aircraft around the world must be replaced and are set to retire from service [2-3]. Fig. 2 illustrates the predicted worldwide passenger aircraft fleet evolution for the next 20 years, subdivided into the aircraft segment of 30-120 seats and the narrow and wide body aircraft segment of more than 120 seats.

The significant growth of the aviation sector will bring considerable economic benefits. It will lead to great adverse social and environmental impacts, too. There is increasing public concern about the impacts of aviation growth on local communities and the environment [5].

Especially, there is growing concern about the aircraft end-of-life by all participants in the aviation industry and society [6]. The end-of-life stage of the aircraft's life cycle was neglected for a long time. The common practice for the final disposal of aircraft was to store them besides airports or in

Peer-review under responsibility of Assembly Technology and Factory Management/Technische Universität Berlin.
doi:10.1016/j.procir.2014.07.048

deserts around the globe until a few years ago. The number of stored aircraft on landfill sites has even more exacerbated since developing countries such as Indonesia, China and Russia have introduced import restrictions for used aircraft with 10-20 years of age in the recent years [7]. For decades, thousands of retired aircraft have been stored in so-called aircraft graveyards. At the same time, the worldwide demand for raw and secondary materials continues to increase. This seems contradictory, because the discarded aircraft provide a large source of valuable material. Landfilling does not seem to be a suitable long-term solution of handling aircraft at their end-of-life stage any more.

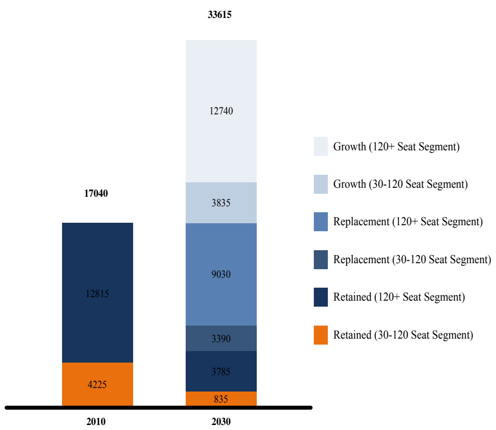

Fig. 2. Worldwide passenger aircraft fleet evolution 2010-2030.

With growing numbers of retired aircraft, growing environmental awareness and growing interest of societies and authorities, the handling of end-of-life aircraft is becoming increasingly important. Primarily the two market leaders Airbus and Boeing carried out first research about the handling of end-of-life aircraft in the recent years beginning in 2005. The handling of end-of-life aircraft has not been legally regulated yet. Facing a prospective legislative regulation, Airbus and Boeing showed general possibilities and limitations of the aircraft end-of-life processes considering the alternatives re-use, recycling and landfilling. Besides the efforts of Airbus and Boeing, the last few years have witnessed a growing realization that applying recycling techniques to aircraft disposal can bring both environmental and economic benefits [8].

1.1 Goal and scope definition

The amount of retired aircraft each year is increasing and landfilling does not seem to be a sustainable end-of-life alternative. Therefore, alternative options to landfill should be taken into account, e.g. re-use, material recycling and thermal recycling. The handling of end-of-life aircraft is a relatively young research topic and little knowledge about the aircraft end-of-life process is available. There is a lack of quantitative, transparent models about handling aircraft at the end of their lives.

Each aircraft end-of-life alternative has its own consequences on the criteria of sustainability, namely economic, environmental and social criteria. One alternative can be better than another with respect to one criterion, but worse regarding another criterion. Furthermore, handling aircraft at the end of their lives affects many participants from the aviation and salvaging industry, and also affects legislators and society. Each participant has his own goals and preferences regarding these criteria.

Research on the decision between the different end-of-life alternatives is little represented in the literature review. Existing research has its origin mostly in the electronics and automotive industry, where regulations forced the manufacturers to improve their treatment of end-of-life products in the last years. The majority of existing recommendations regarding the end-of-life decision for aircraft is based on suggestions which lack a quantitative foundation. There is no model to support concerning the aircraft end-of-life process considering all criteria of sustainability. A systematic, complete and qualitative framework to assist a process in taking a proper aircraft end-of-life is urgently needed.

2. Existing approaches handling end-of-life aircraft

Until a few years ago, end-of-life aircraft were abandoned to landfills around the globe. Beginning in the 2000s, the two largest aircraft manufacturers Airbus and Boeing began to develop alternative approaches of how to handle aircraft at their life's end. Airbus started the so-called PAMELA project (Process for Advanced Management of End-of-Life Aircraft), while Boeing founded the industry association AFRA (Aircraft Fleet Recycling Association) together with several aviation and salvaging companies. Also, an aircraft dismantling industry emerged. In this section, the PAMELA project will be described in detail.

2.1 Process for Advanced Management of End-of-Life of Aircraft (PAMELA) and technology recycling

Parallel to the efforts of Boeing to deal with end-of-life aircraft, Europe's leading aircraft manufacturer Airbus launched the project "Process for Advanced Management of End-of-Life of Aircraft" (PAMELA) in 2005. The project was initiated by Airbus, EADS, the French recycling company Suez-Sita, and the working group LIFE, France (French: l'Instrument Financier pours l'Environnement). The project was also supported by the European Commission. The main goal of the PAMELA project, which was completed after 32 months in 2007, was to demonstrate during a full-scale experiment on an Airbus A300 that 85% of an aircraft's weight can be recycled, re-used or recovered. In addition to this primary goal, a further goal was to set up a new standard for a safe and environmentally responsible management of end-of-life aircraft. To run the project according to the local environmental legislation and current technical recycling knowledge, Airbus needed to found an complementary partnership with the recycling company Suez-Sita [9].

Furthermore, in the project Airbus wanted to support a fully integrated lifecycle approach to aircraft design and manufacturing through sharing the experience with Airbus' design teams and suppliers [10].

During the PAMELA project, the consortium created a three step process approach of handling end-of-life aircraft, the so-called 3D approach. The process was realized on an Airbus A300 with a total initial weight of 106 tonnes. The process is shown in Fig. 3 and described in detail in the next section below.

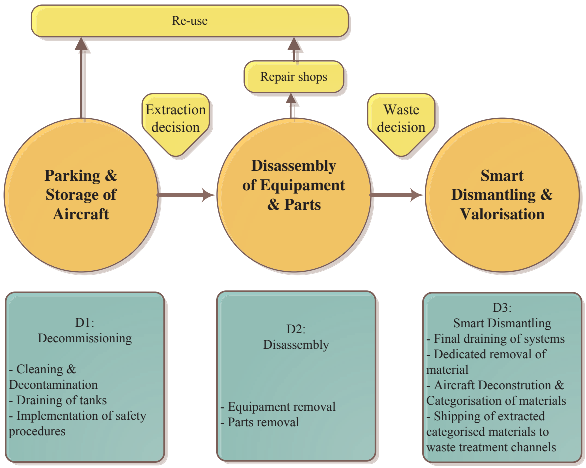

Fig. 3. PAMELA's 3D approach of handling end-of-life aircraft [9].

2.2 *Decommissioning – D1:*

During the decommissioning process, the aircraft finally is taken out of service. The aircraft is inspected, cleaned and decontaminated. Furthermore, all operating liquids are removed and either re-sold for direct re-use or disposed in specific recovery channels. Fig. 4 illustrates the process steps of decommissioning.

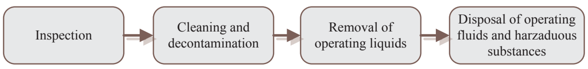

Fig. 4. Decommissioning process chain.

Firstly, the aircraft is inspected and, within this step, a detailed list of aircraft parts which could be disassembled and re-used is prepared. This ensures that the aircraft parts can be tracked through the complete end-of-life phase.

Next, the aircraft is cleaned and decontaminated. In this step, tanks, systems and pipings are drained. For example, waste water from the galleys and kitchen are taken out of the aircraft. Also, all operating fluids such as fuel, oil and hydraulic fluids are removed. Some operating fluids can directly be re-sold and generate benefit, e.g. fuel. If operating fluids cannot be reused any more, they have to be disposed in specific recovery channels according to existing regulation. Besides operating fluids, hazardous substances also need to be removed and disposed, e.g. depleted uranium [9].

2.3 *Disassembly – D2:*

If the aircraft owner does not decide to re-enter the aircraft into service again after the reverse logistics and decommissioning process, the end-of-life aircraft enters the disassembly process. For this paper, it is assumed that the aircraft will not re-enter into service.

Disassembly is defined as a systematic physical separation of a product into its constituent parts, components or other groupings. An efficient disassembly requires a disassembly planning. After the planning, re-usable parts are disassembled and re-sold or stored. Fig. 5 illustrates the disassembly process.

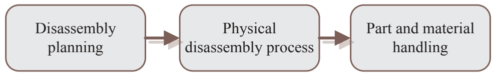

Fig. 5. Disassembly process chain.

During the disassembly planning, knowledge about the specific aircraft type, such as structure, material and part composition needs to be gained. Re-usable and re-sellable parts and equipment on the basis of demands in the spare parts market are selected [11].

Re-usable and disassembled parts are usually engines, landing gears, avionics, auxiliary power unit (APU), ram air turbine (RAT), as well as parts of the cabin equipment. For the selected parts, the geometry, the exact position in the aircraft as well as technical information, materials and connections to other parts should be gathered. With this information a disassembly sequence plan should be created. During the disassembly sequence planning, the selected parts should be sorted into disassembly families and an order for the disassembly of parts and component groups should be determined [12]. Disassembly sequence planning includes a detailed scheduling of the disassembly tasks and the shop floor control. Possible disassembly sequences are determined by the type of the part, its location in the aircraft and its access, applicable techniques, disassembly effort, the connection types and relations among disassembly tasks. A long-term dimension of disassembly planning is the capacity planning, e.g. for the case that several aircraft are disassembled at the same time [13].

2.4 *Smart dismantling – D3*

With the waste decision the process proceeds to step D3 *"Smart Dismantling"*. First, different recovery channels and associated requirements were identified. Also, a plan was set up to dismantle the aircraft in a specific order to optimize the material recovery. As a next step, the aircraft was dismantled with several different tools: plasma torch, angle grinder with different types of abrasive grinding discs, high pressure water jet, chainsaw and hydraulic scissors. Next, the materials were grouped: types of aluminium alloy according to the requirements of the recovery channels, titanium, austenic nickel-based superalloys, stainless steel, WEEE, wiring, tires, plastics etc. Finally, the materials are prepared for shredding and sorting and sent to recovery channels [9].

After re-fusion or smelting, the recycled metal was cast into ingots and returned to the appropriate markets (aeronautic, mechanical or automobile). Also, all steps were performed considering the regulatory compliance and the life cycle design to promote and improve the design performance.

Overall, in step D3 a total sum of 61 tonnes of material could directly be provided for recycling. The remaining 13.5 tonnes, mainly insulation material and casings, could not be recycled and had to be disposed conventionally [9]. Table 1 summarizes the recovery channels during.

Table 1. Recovery channels PAMELA project [14].

Recovery materials	Channels
Engines and auxiliary power unit Landing gears, Avionics, System equipment, Movable parts and structural parts	Re-use upon conditions
Fluids (fuel, oils, hydraulic fluid), Security and safety, equipment, Avionics Tyres	Specialized recovery channels (technology oriented and/or regulation based)
Aluminum alloys substrates, Titanium, alloys substrates, Steel alloys substrates, Wiring, harnesses, Thermoplastics, foams, Textiles, carpets, tissues	Specialized recovery channels (material based)

3. Current situation

3.1 Legislation requirement

Currently, there is no legislation which regulates the handling of end-of-life aircraft. Recycling of aircraft is voluntary until today [15]. This could be justified by the comparable small amount of end-of-life aircraft so far. However, the trend in the transportation sector goes to legislation in terms of an extended producer responsibility. Correspondingly, the aviation industry could also face legislation similar to the regulations in the automotive industry. Although the aviation industry has begun to develop first approaches, it still should be proactive in the development of technologies to improve the handling of end-of-life aircraft, e.g. through an increasing of the recycling rate and decreasing the environmental impact [16].

Aviation has always been viewed as an international affair and many regulations especially by the International Civil Aviation Organization (ICAO) ensure smooth aircraft operations between different countries and societies. Environmental perception varies strongly between geographical regions. Environmental concerns have, therefore, for a long time led to different national attempts to regulate. For example, aircraft emissions during operations have led to local emission-based landing fees (e.g. London-Heathrow, Zurich). In 2001, the ICAO Assembly endorsed the development of an open emissions trading scheme for international aviation. Because of those regulations emissions became a decisive criterion for the purchase of aircraft and for its design [17]. Similarly to the legislation in aviation regarding emissions during operations, the environmental impact of end-of-life aircraft is not only a local, but also a global issue. Legislation regarding the handling of end-of-life aircraft could have similar consequences for the actors in the aviation industry on the aircraft design. The aviation industry is only indirectly affected by existing regulations for end-of-life aircraft.

4. Proposed framework

The European Commission is very active to bring the principle of extended producer responsibility into legislation. For example, the European Directive 2000/53/EC on end-of-life vehicles in 2000 regarding the automotive industry was inspired by the principle [18]. The directive includes that manufacturers have to accept end-of-life vehicles back without charge starting in 2002. Furthermore, beginning in 2006 85 % of the vehicles' weight has to be recycled, with a minimum of 80 % of actual reuse. In 2015, these values increase to 95 % and accordingly 85 %. From 2003 on, automotive manufacturing has to avoid lead, cadmium, chromium and mercury [18]. In addition to the development in the automotive industry, end-of-life regulation for the shipping industry is being introduced by the International Maritime Organisation (IMO). In 2009, the IMO adopted the International Convention for Safe and Environmentally Sound Recycling of Ships [19]. It is expected that the convention entries into force in 2014. Ships to be sent for recycling will be required to carry an inventory of hazardous materials, and series of guidelines are being developed to secure ship recycling in a safe and environmentally sound manner [19]. Further examples for implementing the principle of extended producer responsibility into legislation by the European Commission are the European Directives on “Waste Electrical and Electronic Equipment” (WEEE) 2002/96/EG [20]. On the “Registration, Evaluation, Authorization and Restriction of Chemicals” (REACH) 1907/2006 [21], as well as on “Packaging and Packaging Waste” 1994/62/EC [22]. The WEEE directive, for example, essentially applies to all equipment that can be plugged into an electrical circuit or that operates on batteries. It includes large and small household appliances, information technology and telecommunications and regulates especially the operations directly involved in the treatment during their disposal [23]. China, South Korea, the USA, Japan and Taiwan have in many kinds of legislation followed the European Union and have also introduced legislation on the basis of the principle of extended producer responsibility [24]. The main reason for this was to ensure that their product exports, e.g. electronic exports, can compete globally [25].

4.1. End-of-life aircraft recycling

Recycling is defined as “any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes”. It does not include energy recovery and does not include the reprocessing into materials that are to be used as fuels or for backfilling operations [26].

Following the definition, recycling can be divided into two levels: the product recycling level and the material recycling level. Product recycling focuses on the direct re-use or remanufacturing of an end-of-life part or assembly [27].

During the analysis of recycling another distinction between closed-loop and open-loop recycling has to be made. Closed-loop recycling occurs when a material is used again in the same product at the same level of material quality. The goal is to optimize the utility of the material throughout multiple product uses. For example, a particular aircraft aluminum alloy could be reclaimed and used to produce new aircraft structures made out of the same aluminum alloy. Also, closed-loop recycling takes place when a material is re-used in another product or material, but when its inherent properties are maintained, because the use of primary materials in the other product is avoided [28]. For example, Nickel is used to produce aircraft turbines. After the operations phase, the scrap turbines can be recycled with carbon steel scrap to produce stainless steel. In that case, closed-loop recycling takes place from the point of view of nickel, because recycling the turbine blades avoids the need to produce primary nickel [29].

End-of-life aircraft contain a lot of materials and parts that can be recycled. Therefore, an aircraft has a rest value which should be recovered. This is the first motivation for recycling.

Secondly, the production of new aircraft parts requires raw materials, capital, energy and labour. Through recycling or re-use, a great amount of material and parts can be recovered and consequently primary and natural resources can be saved. This leads to the second motivation for recycling. Next, the production of secondary raw material requires significantly less energy than the production of primary raw materials. Because of this, recycling leads to a reduction of emissions to air, water and soil, which is the third motivation. The fourth and fifth motivations are that recycling leads to a reduction of waste, and because of this to a reduction of land use in landfill sites [27].

The reprocessing of aircraft parts into secondary material requires several procedures of mechanical processing, chemical process engineering as well as metallurgical processes.

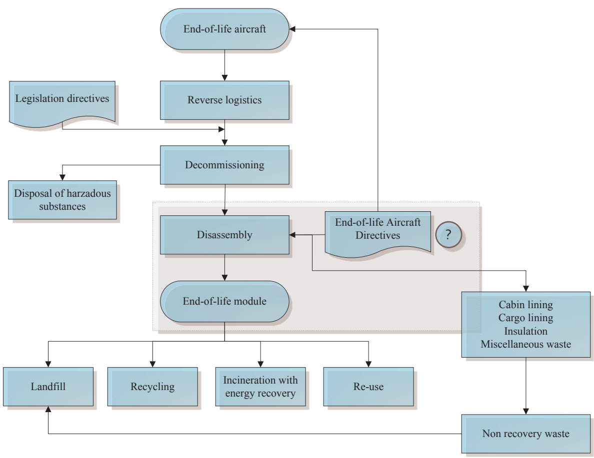

Fig. 6. Proposed framework for end-of-life aircraft process.

5. Different approach for end-of-life aircraft

The growing concern about the product end-of-life in general in many industries has caused considerable research and development activity that tries to solve some of the problems, as it raises more and more interest from all participants in the aviation industry and also from society. A lot of attention has been paid to design for environment (DfE) and design for disassembly (DfD) [6]. Research on the decision between different end-of-life alternatives itself is little represented in the literature review. All research has its origin mostly in the electronics and automotive industry, where regulations forced the manufacturers to improve their treatment of end-of-life products in the last years.

Every end-of-life alternative has its own consequences on the criteria economy, environment and society. These three general criteria are the main pillars of sustainable development. One alternative can be better than another with respect to one criterion, but worse regarding another criterion. Furthermore, selecting an end-of-life scenario concerns many participants in handling the end-of-life of the product especially in the aviation industry. Each participant has own objectives and priorities and it is possible that a good scenario for one participant is not necessarily good for another participant. Even if two participants use the same family of criteria, the relative importance of their criteria might differ [30]. Because of the many participants and their various interests and conflicting criteria, especially in the end-of-life of very complex products like aircraft, the decision for an alternative requires compromises and has always been a multiple goal problem [31]. The decision-maker should seek the best compromise end-of-life alternative, because an optimal solution rarely exists in a decision with multiple conflicting criteria [32].

The existing approaches of selecting an end-of-life alternative can be divided into heuristic approaches or recommendations and analytical models.

The most widespread heuristic recommendation for choosing an end-of-life alternative is to recover as much as economic and ecological value as reasonably possible [24]. During the decision making process the decision maker should seek a win-win situation and create both environmental and economic benefit at the same time. Another heuristic approach is the so-called end-of-life pyramid. The United Kingdom and the European Commission recommend it as a hierarchy of preferred end-of-life treatment alternatives. At the top of the hierarchy is waste prevention, then re-use, followed by recycling, other recovery such as energy recovery, and landfill. However, the end-of-life pyramid and the general recommendations lack a quantitative foundation. Considering the waste hierarchy, several questions arise: which criteria is the hierarchy based on? Is it a compromise solution between environmental, social and economic impacts of waste treatment, or does it only focusing on one of these criteria? If the aim of the hierarchy is to recommend the most favorable end-of-life treatment alternative from an environmental perspective, it, in many situations, does not [6]. It is therefore not clear on which of several possible criteria the hierarchy is based. The European Commission, who implemented the waste hierarchy into their environmental policy, did not add anything to clarify the situation [6].

Regarding the aviation industry, there is almost no method which supports the end-of-life decision of aircraft. Therefore, a simple, systematic, logical and quantitative method to guide the decision maker in taking a proper aircraft end-of-life decision is needed.

6. Conclusion

This paper shows a straightforward approach for evaluating end-of-life aircraft process. The aircraft end-of-life framework illuminates all the process steps in detail.

The state-of-the-art about the aircraft end-of-life shows that there is a lack of complete and qualitative models and decision contributes to filling this gap in the relatively young research topic about handling end-of-life aircraft, since it brings transparency on the potential economic and ecological consequences. This is particularly important in the realm of aircraft end-of-life in which regulatory policies have yet to be fully developed. It is also necessary to include aircraft end-of-life alternatives re-use, recycling, incineration with energy recovery and landfilling regarding their impacts on the criteria of sustainability, namely economy, environment and society supported by appropriate models.

Of course, to realize these high-arching goals, research leaders must develop models approach for sustainable decision making in life cycle aircraft are all linked.

Understanding and controlling, aircraft end-of-life decision support models is essential to facilitating economic growth and improving health and societal well-being.

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