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Process for Advanced Management and Technologies of Aircraft EOL

C. Mascle[a] 1, P. Baptiste[b], D. Sainte Beuve[a], A. Camelot[a]*

[a]*Department of Mechanical Engineering, École Polytechnique, Montréal, Canada*
[b] *Department of Mathematics and Industrial Engineering, École Polytechnique, Montréal, Canada*

* Corresponding author. Tel.: +1-514-340-4711 # 4398; fax: +1-514-340-5867. *E-mail address:* christian.mascle@polymtl.ca

Abstract

Different possibilities are available to treat aircraft end-of-life (EOL), each with positive and negative impacts on the 3 spheres of sustainable development. EOL processing includes 4 major steps: decontamination, disassembly of reused or remanufactured parts, dismantling of the remaining carcass, materials recovery and valorization and/or landfill. In this paper, we present general methods to dispose of and/or implement profitable rebirthing processes and a dedicated infrastructure for end-of-life aircraft (real Bombardier CRJ100) and helicopters operated in Canada. This work is critical to help aircraft manufacturers design current and next generation aircraft and to facilitate disposal after use. The scope of this project is well rounded and includes all aspects related to dismantling of an aircraft; from legal, to scientific and engineering. These aspects are studied using both modeling and experimental approaches.

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Keywords: Aircraft EOL; Sustainable Dismantling; Spare Parts and Subassemblies; Recycling Remaining Carcass; Materials Revalorization; Logistic Networks

1. Introduction

EOL processing includes 4 major steps: decontamination, disassembly of reused or remanufactured parts, dismantling of the remaining carcass, materials recovery and valorization and/or landfill. This large project is structured with a series of interrelated tasks, which are listed below. Firstly, the study explores current rules governing the disposal of and/or the rebuilding/alteration of previously certified aircraft assemblies and subcomponents. Secondly, the project seeks increased understanding regarding regulatory implications of an end of service declaration of an aircraft and its impact on the recovery of parts, components and materials that form part of the type design. We study the best ways to dismantle and to dispose of components in an environmentally friendly manner or to recycle components in an economically viable manner within the framework of regulatory compliance. Thirdly, an experimental platform to test and validate the dismantling models is selected and built. The resulting experimental facility combined with the developed know-how is unique to Canada. Fourthly, the project investigates alternative processes to maximize recyclability of the recovered materials (mainly Al alloys) to either target primary grade quality aluminum that meets all requirements for second use in the aerospace industry or to target other high-value products. Other recycling routes will also be studied to find niche applications for these high-value low tonnage aluminum alloys. This fourth segment will highlight possible strategies to provide economically and socially acceptable methods for re-utilization of dismantled metal. It will also provide in-depth scientific knowledge underlying the recyclability of Al alloys and the obtainable properties and characteristics of second-hand products. Finally, the project also deals with the design of logistics networks, the LCA and a redesign approach draft for aircraft future development.

2. Background

2.1. Dismantling and Disassembly/Process planning

Emerging demands for recycling, reusing, remanufacturing or refurbishing explain the growing interest in dismantling and disassembly. References [1-3] present an overview of different disassembly sequence modeling strategies and distinct levels of detail are used in dismantling planning. The strategic level focuses on reverse logistics. The tactical level is the field of

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disassembly planning and scheduling. Finally, the operational level is related to the detailed dismantling scheduling. Disassembly sequences are network representations of admissible subsequent disassembly operations. Feasible sequences depend on the type of product to be dismantled, applicable techniques, the objective of the dismantling effort [2] and knowledge of connection types and precedence relations among disassembly actions. In many cases, incomplete disassembly can provide a most cost-effective option than complete disassembly. Bourjault [4] introduced the generation of all assembly/disassembly sequences using a connection diagram. According to precedence relations among disassembly actions, disassembly choice diagrams can be generated. This approach has been used by Zhang to generate a graph-based disassembly sequence planning for end-of-life (EOL) product recycling [5]. However, in the case of complex assemblies the number of disassembly choice diagrams becomes very difficult to manage and the model is not applicable when more than one component or subassembly can be disassembled simultaneously. De Fazio and Whitney elaborated a single disassembly graph based on connectivity state and a graph based on corresponding subassembly states also called a diamond diagram [6]. AND/OR graph representations have been introduced by Homen de Mello and Sanderson [7], offering a compact representation of all feasible assembly sequences and they adapted this strategy for the generation and selection of disassembly sequences. Here again, the number of possibilities can complicate implementation of the proposed strategy particularly if incomplete dismantling sequences must be included. To avoid this disadvantage, a component-oriented approach integrating assembly and disassembly in a computer aided system which includes direction, physical properties, connections and fasteners analysis has been elaborated by Mascle and Balasoiu [8]. A product-oriented approach has also been proposed for automatic analysis of detachability of subassemblies from CAD-files or drawings, but the size of the problem grows exponentially with the number of components, which requires the addition of geometric and technical constraints. Disassembly sequences can be of two different natures: selective or partial. Selective disassembly (service-oriented disassembly) places emphasis on a particular component and optimizes a disassembly sequence for this specific component as mentioned by Wang et al. [9]. Instead of focusing on a particular component, partial disassembly (recovery-oriented disassembly) determines the best disassembly sequence within feasibility limits. Tripathi et al. have implemented this approach [10]. Willems et al. have presented a LP model based on costs and revenues related to a particular network [11]. Artificial intelligence methods have also been implemented as a genetic algorithm, neural networks and fuzzy logic but the generated solutions are often sub-optimum.

2.2. Logistics network

Many models are proposed for supply chains [12]. More and more consider reverse logistics. Reverse logistic refers to recovery of unused products and materials, their retransformation and their redistribution for other use. Many retransformation alternatives can be considered: direct reuse, valorization (remanufacture, repair, refurbishing, disassembling/ dismantling for part and material recovery, recycling) and clean disposal [13]. Logistics network design models integrating reverse logistics usually deal with one or two alternatives [14-16]. Value recovery possibilities are however better when considering many alternatives. These possibilities depend on network capacities, defined with design decisions that may include capacity adjustment, through site configuration and technology selection as proposed for supply chains [17,18]. They are also affected by sales [19] and after-sales policies, which can be referred to as lifecycle product management policies (sale/leasing, maintenance). Although a high uncertainty level is recognized for reverse logistics, still few models are considered in a stochastic context. Some rest on a small number of discrete scenarios [20]. Others deal with a finite but large number of scenarios [19,21], using Sample Average Approximation, defined through Monte Carlo methods [22].

2.3. Materials recycling

Traditional routes for recycling Al: Depending on the disassembly process selected, some contaminants such as paints, coatings and adhesives should be removed by burning or solvent cleaning (organic or chemical) before or after the shredding operation. It is suitable to sort the aluminum into its main families (2xxx and 7xxx), and it will therefore have to be determined if it is more advantageous to do this manually before shredding or automatically after shredding. The traditional route for clean and sorted parts or shredded chips is remelting in foundries [23]. An alternate route for value-added applications: Shredding is currently one of the main processing routes used to break-up components into practical sizes. During this destructive operation severe plastic deformation of the microstructure of the component occurs. The deformation process includes an increase in dislocation density, formation of sub-grains and high angle grain boundaries. If adequate shredding/machining parameters are employed, grain refinement down to the nano-level can be obtained. A limited amount of literature is available describing this approach, but it confirms its viability [24,25]. Because the shredding/machining operation is used in dismantling, the nanostructured chips potentially become a direct by-product of this dismantling. It is worth mentioning that the shredded pieces shown in literature of dismantling airframes have geometrical characteristics that are similar to the residues of machining described by Cai et al [25].

2.4. Ecodesign and Life-cycle Assessment (LCA)

Life-cycle Assessment (LCA) is a systematic scientific approach to assess the environmental impacts of a product, service or process throughout its entire life cycle for a given functional unit [26]. The LCA methodology is defined by ISO standards 14040 and 14044 [27-28]. LCA applied to end-of-life management options faces many challenges because of the multifunctional nature of the processes involved, the lack of inventory data related to dismantling processes and the lack of knowledge concerning the emissions of these processes. So far, no LCA has been published in this sector. Allocating the correct impacts to each function of such processes requires definition of relevant allocation rules, which depend on the option considered, the type and quality of material recovered [29-31]. The LCA of different end-of-life management options as well as an understanding of the primary and secondary markets for recycled parts will allow the industry to better design their supply chains. Ecodesign has already shown to be not only effective in reducing the environmental burden of products, but also economically profitable in most cases.

3. Objectives and Methodology

3.1. Main objectives

This project discusses many challenges, primarily the fact that end of life of aircraft usually occurs with operators distributed all over the globe in countries with varying degrees of enforcement of environmental legislations and with difficult economics of recovery or recycling of components. For disassembling the main components, EOL shares some similarities with maintenance; mechanical, chemical, logistic, ageing, economic and environmental difficulties can be encountered. At this stage some re-use, remanufacturing or upgrading is expected. This step consists first in decommissioning the aircraft. This includes the legal aspects related to ownership and air worthiness certificates, etc. Then it deals with draining the plane and removal of the main equipments (engines, landing gear, electronic, interior etc.) to deliver a partially empty air frame for the next step. For disassembling and dismantling the remainder of the aircraft it was necessary to conceive a rational organization for disassembly and dismantling. There are no suitable models, methods and data for such large and expensive components. Challenges are faced in the areas of automation, separation of materials and identification of materials. To resolve these, our approach consisted in identifying the best technologies and techniques to separate the main parts of the air frame in different sections. Then each section was further divided into smaller parts which can be sorted by material types (alloys) or recycling processes. For each family of material, shredding and sorting technologies were also analysed. During these two first steps decisions must also be made related to site location, site mission definition (activity and product assignment to sites), capacity adjustment, marketing and after-sales policy selection (sale or leasing, and after-sales service), and recovered product revalorization, according to their state and to network conditions. The major problem in recycling Al is the level of residual impurities found in the recycled metal. The impurities can come directly from alloy chemistries themselves or they may originate from secondary treatments used to improve component performance (coatings, paints, adhesives). During recycling, each cleaning and alloy sorting operation reduces the value of the recycled metal. This part of the project studies advanced routes (direct fabrication of components from recycled by-products) into other applications. During the first steps many data and knowledge are collected related to the aircraft design. This last step is fed by the results of dismantling and recycling experiments and provides feedback to the whole process. Some methodologies such as Design for Disassembly, for Recycling, and for End-of-Life were improved during this work. The goal is to determine the best way to eliminate impediments to disassembly, recycling and reducing the environmental footprint while at the same time making this activity economical. For this last point, a methodological approach has been developed allowing consideration of the particularities of the end of life of airplanes using an LCA study. Behind the above objectives, theoretical frameworks (graph theory, product and liaison models, value loop model, shredding and sorting methods for metal in order to identify limits of materials liberation, design for disassembly and recycling, and life cycle analysis scenarios, etc.) have been used to define, develop and validate the models, methods and tools. An experimental platform was built to support the best ways to recover, revalorize and redistribute reusable and disposable parts and materials at the end of life of aircraft. The project experimental platform is located in the Montreal area.

3.2. Methodology

Figure 1 schematically describes the work plan and it is detailed in the following sections. For comparative analysis of dismantling and recycling in a context of Aircraft End of Life, the methodology contains the following stages:

- Current projects in airplane disassembly (Pamela, AFRA, etc.), existing data bases and BOM for old airplane were studied. Maintenance procedures have been carefully studied.
- Identification of systemic parameters that influences a dismantling strategy and of the criteria to be considered.
- Find approaches to sort recycled grade aluminum alloys and technologies to reuse these alloys in future parts. New construction procedures that facilitate materials recuperation were developed from our research.
- A case based analysis of several dismantling strategies (what is to be disassembled, what to grind) and an evaluation of each strategy on each criteria.
- Development of a decision support system to help choose the best strategy.
- Development of a method to find the best dismantling sequence for a given strategy.
- Evaluation of both methods with the platform.

Systemic parameters are environmental parameters that can influence the choice of a dismantling policy. They are related to logistic structures, resource costs, legal constraints, etc. Criteria can concern costs, environmental issues, human resources management, etc. Five dismantling strategies were studied: the 2 extremes (1- to disassemble all components of the carcass and 2- to grind the carcass) and 3 intermediates. The definition of intermediate strategies must be done to maximize the production of information. Each strategy has to be studied in term of technical constraints, technical and logistic costs, environmental impacts, etc. From obtained data, a method is developed to choose the best dismantling strategy according to local values of systemic parameters, and according to relative weights attributed to each criteria. Finally, for a given strategy, a method was defined to find the best sequence. The results of this task (method to choose the best dismantling strategy and the best sequence for this strategy were validated with the platform. Last steps included: developing new strategies including global logistics of dismantling and proposition of a dismantling strategy, developing of fundamental concepts, methods and models to support decisions related to the design and management of value loops, proposing an approach to evaluate the impact of a changing and uncertain business environment on value loop performance, validating concepts, methods and models for the aircraft end-of-life management context prevailing in Canada and in other countries if deemed necessary. It is important to study whether aircraft deemed "dead" should be sent to specific locations, or whether the process should be so simple that dismantling can be carried out locally. Economics of scale must be considered as a factor in disassembly & recycling of discarded materials or environmentally friendly disposal of materials. The distribution of locations adds an independent variable in the mathematical model. Two approaches for recycling routes for the recuperation of Al from the structures were developed in parallel. The first is remelting of the parts in foundries after they have been disassembled, cleaned and sorted by alloy families. The best applications for remelting were determined in collaboration with Al industry. The objective was to select applications where the alloying elements were considered useful rather than applications where they are considered as contaminants. This step involved mechanical testing and characterization of R2XXX and R7XXX grades for aircraft and new generation materials and alloys including titanium for Helicopter grade Al. Ideally, these grades should offer properties comparable to the existing primary aeronautical alloys from smelters. The second proposed route was performed in collaboration with industry that performs metal shredding to evaluate their methodologies and study how the process can be adapted to obtain value added products after the structure is destroyed. The particular objective targeted during shredding is to create by-products that are a suitable size for consolidation with a refined microstructure. A secondary shredding operation was also studied to measure the extent of blending of the impurities within the nanostructured metal. A processing route including deformation parameters was developed. The data and results for both routes were fed back to the dismantling team to see if the engineered process can be implemented economically within the recycling plan. The LCA methodology is carried out in parallel with the work of the other teams and contains the following stages: 1) In depth analysis of the primary and secondary markets of the dismantled aircraft 2) Inventory of the different end-of-life data 3) Development of A-LCA and/or C-LCA models and evaluation of their respective potential environmental impact, 3) Data collection and integration within the CIRAIG LCI database 4) Impact assessment using Impact 2002+ and/0r ReCiPe LCIA methods and, 5) Sensitivity plus uncertainty analysis. Further to this, a framework of an algorithm was developed to help engineers design a product for dismantling, disassembly and recycling.

4. Results

4.1. Disassembly Process planning and logistic

The Aircraft Maintenance Manual (AMM) gathers procedures and technical interventions that may need to be performed on an aircraft: maintenance tasks. The maintenance tasks and associated standard numberings (ATA-2200 and AMTOSS Index) are available data sources. Realization orders between maintenance tasks are disassembly constraints. A propagation of achievement from task to task can be considered; which approaches the wave propagation concept. To minimize displacements, technical operations waves (task waves) have to be built by work zone; and the number of realized tasks per transit must be maximized. The best disassembly organization is established with a minimum number of displacements. The model must be consistent with good practices in EOL aircraft processing. First, the model must represent all necessary tasks and all connections between them (disassembly constraints). Secondly it must support all information towards the tasks zoning and work progress. A task i (t_i) is composed of a sequence of 4 or less subparts: Job Set-Up Information (JSUI), Job Set-Up (JSU), Procedure (P) and Close Out (CO). The subparts of t_i are themselves subtasks sequences: $(JSUI)_i$, $(JSU)_i$, $(P)_i$ and $(CO)_i$. In addition, each task t_i is associated with a work zone z_i. To move to the next subtask, the entire work request has to be realized: the subtask effective work and related tasks. Figure 2 presents an example of a tasks graph G_{tc}, where t_1, t_4, t_6, t_{11}, t_{12}, t_{13}, t_{17} are independent tasks, and t_8, t_{15}, t_{17}, t_{18}, t_{19} are terminal tasks. Numerous research works focusing on order relations have been developed for the sequence alignment problem, particularly in the genomics field. Solving this kind of problem is NP-complete even in simple cases. Here, we choose a heuristic to solve a disassembly problem using a graph G_{tc} provided by the model. As evoked before, each maintenance task is associated to a zone, and consequently a set of tasks is associated to each zone: $z_l=\{t_k\}$ $(l,k \in N^*)$. We define the 'zone availability' (Disp) to define the quantity of work able to be achieved in a zone in terms of "activable" subtasks. The entire work to be achieved in a zone corresponds to the total subtasks number, and is defined as Tr.

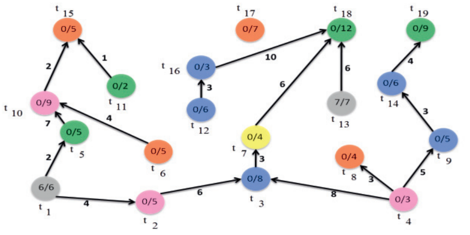

Fig. 2. Task graph.

4.2. Dismantling Process planning

To maximize recyclability of aircraft, we explored ways to create homogeneous areas from the recycling point of view. We had the opportunity to map a majority of the metallic materials present in a CRJ100/200. For example, the wing weighs approximately two tons, if we subtract all internal equipment such as pipes, cables and functional equipment. In spite of a very weak unitary weight, we chose to take rivets into account; they represent about 3.5 % of the characterized mass. The heaviest parts are the skins of the wing and the sub-assemblies positioned near the junction with the fuselage and near the landing gear. We were able to list 48 different combinations of materials and heat treatments. Afterward we had the opportunity to identify the most present alloys, as well as their origin (Figure 3). CAD system allows mapping of aircraft cartography automatically because it contains information on the distribution of materials in 3D. We developed an algorithm capable of automatically generating homogeneous zones. The model was developed taking into account various similarities that exist between the parts. So the first main axis of the study for the wing is the perpendicular axis in the plans of "Rib". The second axis was chosen as parallel to the axis of the fuselage and the third was chosen so that the mark is a direct trihedron.

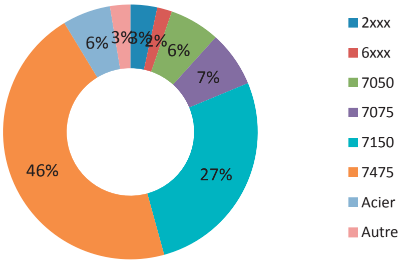

Fig. 3. Mass of the various materials used in the wing.

4.3. Materials recycling

After reviewing current practices and exploring different technology that can enable better recycling, we studied the reactions that take place in a molten aluminum bath. We demonstrated that six alloying elements (Li, Mg, Ni, Ti, V, Zr) common in aluminum alloys of current aircraft can be reduced through reactions with oxygen, chlorine and boron. On-site investigation of the AluGreen Technology (AGT) process was detailed. AGT products were replaced in the context of the powder metallurgy industry. An example of powder produced by AGT was discussed in this context. An approach to the modeling of the shredding process was studied for aeronautic applications (red zone on Figure 4).

4.4. Ecodesign and Life-cycle Assessment (LCA)

The main problems faced during life cycle impact assessment (LCIA) result from the need to connect the right burdens with the right impacts at the correct time and place. It is however necessary to note that the choice of a method (complete dismantling, complete grinding or intelligent cut) also depends on the interest and on the context, for example: re-use of a part from a stored aircraft to replace a defective part in a plane in service. The material and structural characteristics are very different according to the zones of the aircraft. Here we show the results obtained for the empennage of the CRJ100ER and in particular the horizontal and vertical stabilizers. In this study, we consider that the aluminum recovered at the end of the process does not possess the physical characteristics necessary for re-use in aeronautics. We also note that the stage of evaluation of the environmental impact is supported using two valuation methods, TRACI 2 (North America, Figure 5) and IMPACT 2002 + (Europe, Figure 6). These methods are typical among those usually used in life cycle analyses. The data are seized in the software SimaPro by using the database Ecoinvent to model the processes. Figure 5 illustrates the results obtained in the basic configuration. Negative values indicate the impacts avoided for each of the strategies and positive values denote actual impacts. We notice that more impacts are avoided using the method of intelligent cutting (red strategy B) compared to the method of complete grinding (blue method A), and thus fewer impacts are felt during the process of end of life. Presentation of the categories of final impacts allows us to confirm the observation made previously (Figure 6). The method of intelligent cutting (red strategy B) produces lower environmental impact in terms of damage on human health, ecosystems, climate change and use of resources. An analysis of global sensibility allowed identification of the influence of each parameter on the variation of the results.

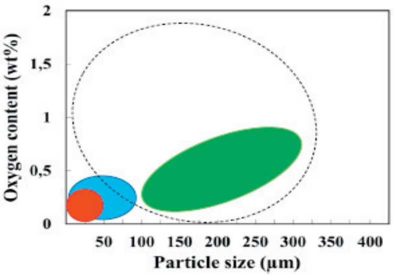

Fig. 4. Aluminum Powder Metallurgy (P/M) industries.

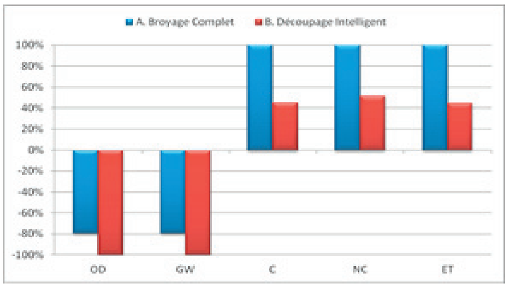

Fig. 5. Results with the method TRACI 2 (OD : Ozone Depletion, GW : Global Warming, C : Carcinogenics, NC : Non Carcinog., ET : Ecotoxicity).

5. Conclusion

Disassembly of aircraft reusable components must follow all solicited maintenance procedures gathered in the AMM. A strategy using a scheduling heuristic is presented. This heuristic uses the model and permits the evolution of the tasks graph step by step until the complete disassembly is achieved. Results are an optimal sequence of aircraft visited zones and a tasks realization sequence. To implement one of the proposed methods, structural mapping of a CRJ100 wing was performed. This allowed us to demonstrate that it is possible to create areas that are more easily recyclable. Finally, we showed that a slight improvement before shredding effectively reduces downgrading of materials.

Acknowledgements

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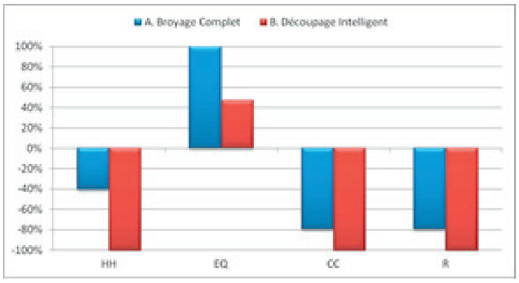

Fig. 6. Results with the method IMPACT2002+ (HH : Human Health, EQ : Ecosystem Quality, CC : Climate Change, R : Resources).

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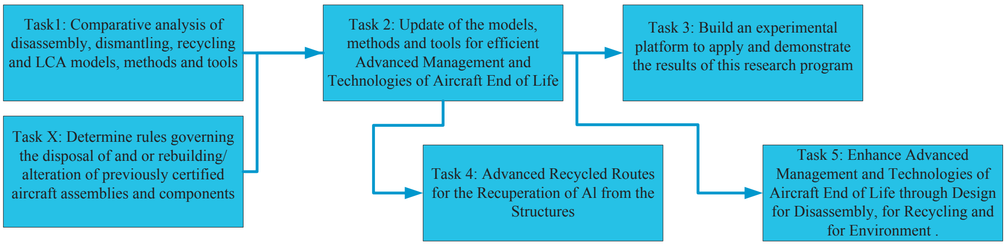

Fig. 1. Work plan