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Towards a sustainable disassembly/dismantling in aerospace industry

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Abstract

The quality of recycled material in a recycling process is actively influenced by an appropriate disassembly/dismantling strategy. In recycling the carcass of the aircraft, it is suitable to separate and classify different aluminum grades into their main alloys family before sending them to recycling center. However, due to complexity in the aircraft structure, fully disassembly/dismantling or fully shredding the aircraft is not economically or environmentally viable, respectively. For this reason, this work discusses eight different disassembly/dismantling strategies that have been done on a real Bombardier Regional Jet aircraft. The study proposes an approach to assess the sustainability influence of these strategies, as an important parameter that should be considered to select the most suitable strategy. This concept can be improved in order to be used in aerospace industry as an accurate method that allows to take the best decision depending on the concurrent situation.

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1. Introduction

Several design methodologies have been proposed to be applied to products at end-of-life such as: design for disassembly (DFD), design for environment (DFE), design for rebirth (DFRe), design for recycling (DFR), etc [1-4]. These methodologies are focused on approaches to develop the new generation products more sustainable. However, products that currently are at end-of-life were designed decades ago; consequently these concepts were not taken into account during the product development process. Meanwhile, these retired products have value and should be recovered in an appropriate way. It is the task of expertise to determine efficient strategies that allow preserving the intrinsic properties of materials after the recovery process.

It has been stated that there are 2000 civil aircrafts (excluding military aircrafts) grounded currently and are waiting for an appropriate end-of-life treatment. Even worse, it has been estimated that 250 aircrafts are going to be retired every year for the next two decades. Although this amount is small in compare of the one in automotive sector, the assets value of the materials and components in retired aircrafts is highly considerable [5, 6]. Fig. 1 represents the dramatically increasing amount of civil aircrafts getting to end-of-life over the next decades.

The average weight of a civil aircraft is about 106 tons [6]. according to Airbus's report [7], "Process for Advanced Management of End-of-Life of Aircraft (PAMELA)", around 85% of the weight of a civil aircraft can be recovered (15% for reuse, and 70% through recycling). Recycling includes collecting and sorting recyclable materials that would otherwise be considered as waste and then processing them into raw materials for future aircrafts or other industrial

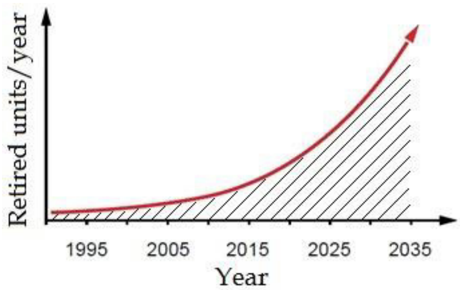

Fig. 1. Increasing amount of aircrafts getting to end-of-life in next years

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applications. Excellent environmental benefits come out from recycling high-tech aerospace alloys rather than production from virgin materials [8].

One of the major problems in recycling aircrafts is aluminum recycling. Shredding has been extensively used as a pre-recycling method that allows transforming huge components of the aircraft into smaller and more practical dimensions. Fully shredding an aircraft as a whole piece, results in a mixture of different aluminum alloys with different grades and leads to a very low alloy quality. This low quality aluminum requires additional treatments to recuperate the mechanical properties that make it suitable for appropriate applications. The lower is the quality of the aluminum alloy retrieved, more additional treatments are required and more costs associated. In this situation, it is preferable to disassemble/dismantle the components with different grades of aluminum alloys into their main alloy families prior to shredding [9]. However, due to complexity in structure of the carcass a complete disassembly is not economically viable.

In this study, eight different disassembly/dismantling strategies before shredding were developed under the project "*CRIAQ ENV-412: Process for advanced management and technologies of aircraft end-of-life*" [10]. These strategies were applied to a real Bombardier Regional Jet aircraft. The main focus of this paper is to describe these strategies; also discuss the contribution of the strategies from a sustainability perspective.

Including this introduction, Section 2 explains the cost-benefit associated to a recovery process; Section 3 presents the extreme disassembly/dismantling strategies; in Section 4, intermediate strategies are introduced; the importance for sustainability assessment of the strategies is discussed in Section 5; and finally, Section 6 presents the conclusion and future works.

2. Cost-benefit associated to a recovery process

Disassembly is the act of separation, and separation is acquired when the joints for the two components are clearly removed. A rigorous disassembly can be tedious and time-consuming, but is the best way to avoid cross contamination of different materials for recycling purposes. On the other hand, the action of cutting is to make an opening or incision in (something) with a sharp-edged tool or object. In terms of dismantling operations, cutting has been commonly used. However, cutting parts usually implicates that a certain portion of material X will be mixed with a higher concentrated material Y.

Two main parameters are involved into a recovery process: Recycling and Disassembly/dismantling. The cost-benefit curves were plotted in function of material homogeneity to represent the behavior of these two parameters (Fig. 2). The function curve of recovery process (in red) was obtained by summation of the curve functions for recycling and disassembly/dismantling. Increasing the homogeneity of the materials, the cost-benefit ratio for recycling decreases while, the one for disassembly/dismantling increases. To have a higher material homogeneity more disassembly/dismantling efforts will be imposed into the recovery process.

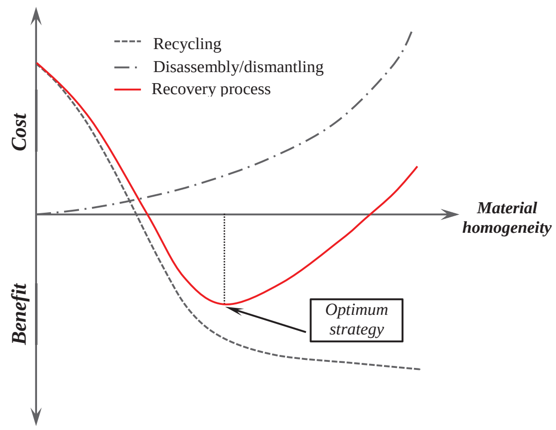

Fig. 2. Schematic representation of the cost-benefit associated to a recovery process

The goal of implementing different strategies in this project was to find the optimum strategy with the lowest cost-benefit ratio for the recovery process.

3. Extreme strategies

Strategy A: *Systematic disassembly*

The purpose of this strategy is to separate and sort all the components based on material composition. The attachments are also removed and sorted. The material composition and serial number are usually printed on the components. Due to the effect of time and corrosion this information is sometimes unreadable. In this case, the identification of the material is performed using Niton, portable X-Ray fluorescence analyzer. Before Niton detection, the layer of paint should be partially removed.

Typically, the removal of one aluminum rivet takes 15 to 20 seconds; while that of for titanium rivet is more than 2 minutes. Pneumatic drills have been used to separate the rivets. The drill bits for aluminum rivets should be often changed after every 20-30 rivets removed, while for titanium rivets after every 7-10. Disassembling the top-skin of the Regional Jet left horizontal stabilizer takes an entire work day.

The time involved in disassembly depends on the different parameters such as accessibility and number of attachments (titanium rivets particularly). Horizontal, vertical stabilizers and wings are considered as compact zones with less accessibility and high number of attachments. A small and compact part does not allow the collaboration of many workers at the same time.

Although *Systematic disassembly* is labor intensive, it is the best strategy in terms of segregation of different type of materials. In other words, this strategy is concentrated on quality rather than quantity.

Strategy B: *Shredding*

The aircraft is cut into small pieces for transportation to recycling center. Each piece is compound of different types of materials: aluminum, titanium, steel, plastics, composite, glasses, rubber, etc. Unlike *Strategy A*, *Shredding* is concentrated on quantity rather than quality.

A and *B* strategies are considered the extremes in cost-benefit ratio. *Strategy A* has the highest potential cost and highest quality of retrieved materials; on the contrary, *Strategy B* has the lowest for both. *A* and *B* are not fully desired to be practiced in industries because of the excessive costs and poor material quality associated to *A* and *B*, respectively. Intermediate strategies can be defined using the available mapping of the aircraft. The mapping contains information for material composition of each component. The following strategies are based on the use of this aircraft mapping.

4. Intermediate strategies

Strategy C: *Smart shredding*

Instead to cut the carcass randomly in pieces, *Smart shredding* selects zones on the carcass based on the mapping. The selection takes regions with higher frequency in similar type of materials. This fact may result in more homogeneous pieces before shredding. However a very limited number of cuts are established in this strategy.

Additionally, it is remarkable to mention that when the selected piece is removed a mass balancing analysis is required to estimate the type of alloy that will be retrieved. This information helps stakeholders to save the intrinsic properties of the materials.

Strategy D: *Gross cutting*

This strategy is conceptually similar to *Strategy C*, but more cuttings are allowed. Consequently, powerful and moveable cutting tools are required. These tools are often bulky and fuel-based permitting to cut fast but noticeably imprecise.

Strategy E: *Semi-gross cutting*

Unlike *Strategy D* this strategy requires more precise cuts in order to increase the homogeneity of the packages. More precision demands for lighter and powerful cutting tools. Most of these tools are electrical.

Strategy F: *Detail cutting*

As the name suggests, this strategy implies a high amount of precise cuttings. It obliges to have more precise tools, which are usually smaller and handy pneumatic tools. Unlimited cuts are allowed which implies that this strategy be laborious and time-consuming.

Strategy G: *Smart disassembly*

The main concern about *Systematic disassembly* is the time and effort spent to remove the attachments. The question is: “Do we really need to remove all the attachment?” The goal of this strategy is to alleviate the excessive time needed to remove the attachments in *Strategy A* by NOT removing rivets that are shared between components with similar material composition. Though, the quality of recovered material is compromised due to inclusion of these attachments.

Strategy H: *Disassembly combined with cutting*

In this strategy, *Systematic disassembly* and *Detail cutting* are combined. First, a meticulous analysis of the whole carcass or the pieces to be recycled needs to be accomplished. The areas to be cut are the ones with higher density of the same or similar materials; on the contrary disassembly should be done in heterogeneous regions where each component has a different material.

5. Sustainable disassembly/dismantling

Sustainability and sustainable development are more and more becoming the center of attention for different industries. Ideally, in sustainable development should be considered the entire supply chain including end-of-life [11]. Frosch and Gallopoulos [12] pointed out: “Wastes (end-of-life materials) from one industrial process can serve as the raw materials for another, thereby reducing the impact of industry on the environment”. Acting as supplier for bigger industries, aircraft dismantler/recycler businesses should focus on strategies that allow to ameliorate their current position in the market. One of the key factors is to practice sustainability and sustainable development in all the dismantling and recycling processes.

In Section 2 was discussed an approach to determine the optimum strategy based on cost-benefit. However, economic aspect is not the only factor that should be considered. For example in aerospace industry, *shredding* the carcass might provide the least cost. Though, the quality of retrieved alloys will be very low causing high environmental impact because of the need to extract new raw material. On the contrary, *Systematic disassembly* involves higher operation cost due to the required tools, number of operators, place, etc.

The eight strategies were evaluated in terms of the three sustainability elements (environment, economic, and social). For each sustainability element, sub-element(s) are identified (Table 4). Identification of the sub-elements is based on our observations and feedbacks from the experts.

Pairwise comparison or direct method can be used to perform the assessment of the strategies in terms of each sub-element. In this study, pairwise comparison has been selected due to more accuracy that can provide [13]. Three interviewees including one expert and two practitioners as a team have been asked to compare every two strategies in terms of each sub-element; so for the eight strategies, 28 comparisons were required for each sub-element.

Nine-point comparison for intensity of dominance between strategies were used as shown in Table 1. An intensity score indicates how many times one strategy is more dominant in compare with another one in terms of the corresponding sub-element. “1” indicates no specific dominance between the two strategies and “9” indicates the overwhelming dominance of a strategy over the other one.

Based on the scores obtained, reciprocal decision matrices for each sub-element were constructed. To assess the score for each strategy, eigenvector as a standardized, reliable, useful, and logical method was utilized. For each decision matrix consistency ratio (CR) was calculated according to [14]. CR lower than 0.10 indicates the decision matrix is consistent enough. Decision matrices with CR greater than 0.10 are not reliable and should be sent back to the corresponding interviewees for possible revision.

After all, eigenvectors for the decision matrices were calculated. There are two types of sub-element. Sub-elements with negative characteristic: the lower the amount is, the better will be the sustainability contribution ("Amount of waste generation", "Implementation cost", and "Level of safety risk"). On the contrary, "Homogeneity of retrieved material" is considered as positive characteristic. Therefore, the results need to be homogenized before further assessments. As a result, except for positive sub-elements (Table 3), eigenvectors for decision matrices correspond to negative sub-elements were inversed (Table 2). Then, to avoid redundancy of the results, values were normalized via division to the maximum value in the group. Consequently, a score between 0 and 1 was assigned as the **positive** contribution of each strategy in every sub-element (Table 4).

An average of the scores for sub-elements: "Amount of waste generation", and "Homogeneity of retrieved material" was attributed to environmental sustainability. The final sustainability contribution scores for the eight strategies in terms of environment, social, and economy were tabulated in Table 5.

In Fig. 3 the contribution level of each strategy to environment, economic and social aspects was plotted. Social contribution is represented by the size of the bubbles, and the score associated is shown in the centre.

From the graph, it can be seen that *Strategy A*, although it has the highest contribution to environment, the cost associated to implementation is very high; which compromises its economic contribution. Also low social score indicates the high level of safety risks by applying this strategy. In contrast, *Strategy B* while has good contribution scores in terms of social and economy, it appears to have a very low environment contribution. This is a drawback that might negatively influence for selecting this strategy for end-of-life treatment of the carcass.

In the figure, four zones were established based only on the economic and environmental contributions. These divisions facilitate a better understanding of the graph. *Strategies A*, *G*, and *H* are located in Zone 3 (High environmental-Low economic). These strategies deal with disassembly tasks which results in better separation of the components. Thus, the amount of waste generation and homogeneity of retrieved material are lower and higher, respectively.

On the other hand, cutting based strategies as *Strategy D*, *E*, and *F*, have a similar social and environmental performances. However, *Strategy D* (gross cutting) has better economic contribution. From this result, it can be generalized that cutting techniques have low environmental performance since during this procedure materials are cross contaminated which reduce the material homogeneity. At the same time the impact of these strategies on economic is not significant in compare with shredding techniques (*Strategies B* and *C*) in Zone 2 (Low environmental- High economic).

No strategies were classified in Zone 4 (High environmental-High economic). With the aim to have strategies falling in Zone 4, more innovative technologies might be required.

6. Conclusion and future work

It is a fact that in big industries (aerospace, naval, construction, etc.) the major profit is generated during the use phase. Hence, most efforts are put for manufacturing and use phases in products life-cycle, while less attention are being paid to disassembly and end-of-life. So, stakeholders and researchers should deal with this problem that these products are not completely suitably designed for disassembly and end-of-life. Thus, the efforts should be focused on developing more innovative and intelligent strategies to compensate these existent deficiencies in the design and recover as much as possible in a sustainable way.

Table 1. Nine-point comparisons between strategies for every sub-element

Definition	Intensity of dominance	Reciprocal intensity
Just equal	1	1
Weakly more than	3	$\frac{1}{3}$
Moderately more than	5	$\frac{1}{5}$
Strongly more than	7	$\frac{1}{7}$
Absolutely more than	9	$\frac{1}{9}$
Intermediates	2, 4, 6, 8	$\frac{1}{2}, \frac{1}{4}, \frac{1}{6}, \frac{1}{8}$

Table 2. Pairwise comparison matrix for "Amount of waste generation"

	A	B	C	D	E	F	G	H	Eigenvector	Eigenvector^{-1}	Normalized
A	1	$\frac{1}{9}$	$\frac{1}{7}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{4}$	1	1	0.2928	3.4158	0.8822
B	9	1	2	5	4	2	8	7	2.6248	0.3810	0.0984
C	7	$\frac{1}{2}$	1	3	3	2	7	5	1.8362	0.5446	0.1407
D	2	$\frac{1}{5}$	$\frac{1}{3}$	1	$\frac{1}{2}$	$\frac{1}{4}$	3	4	0.6199	1.6131	0.4166
E	2	$\frac{1}{4}$	$\frac{1}{3}$	2	1	$\frac{1}{2}$	4	2	0.7344	1.3616	0.3517
F	4	2	$\frac{1}{2}$	4	2	1	5	4	1.3330	0.7502	0.1938
G	1	$\frac{1}{8}$	$\frac{1}{7}$	$\frac{1}{3}$	$\frac{1}{4}$	$\frac{1}{5}$	1	1	0.2583	3.8719	1.0000
H	1	$\frac{1}{7}$	$\frac{1}{5}$	$\frac{1}{4}$	$\frac{1}{2}$	$\frac{1}{4}$	1	1	0.3007	3.3254	0.8589

Eigenvalue=8.245; Consistency index= 1.40; **Consistency ratio(CR)= 0.025**

Table 3. Pairwise comparison matrix for “Homogeneity of retrieved material”

	A	B	C	D	E	F	G	H	Eigenvector	Normalized
A	1	9	7	6	5	4	3	2	2.6633	1.0000
B	$\frac{1}{9}$	1	$\frac{1}{2}$	$\frac{1}{3}$	$\frac{1}{4}$	$\frac{1}{5}$	$\frac{1}{7}$	$\frac{1}{4}$	0.1993	0.0748
C	$\frac{1}{7}$	2	1	$\frac{1}{3}$	$\frac{1}{4}$	$\frac{1}{5}$	$\frac{1}{7}$	$\frac{1}{5}$	0.2474	0.0929
D	$\frac{1}{6}$	3	3	1	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{4}$	$\frac{1}{3}$	0.4632	0.1739
E	$\frac{1}{5}$	4	4	2	1	$\frac{1}{2}$	$\frac{1}{4}$	$\frac{1}{3}$	0.6197	0.2327
F	$\frac{1}{4}$	5	5	2	2	1	$\frac{1}{3}$	$\frac{1}{2}$	0.8439	0.3169
G	$\frac{1}{3}$	7	7	4	4	3	1	2	1.7463	0.6557
H	$\frac{1}{2}$	4	5	3	3	2	$\frac{1}{2}$	1	1.2168	0.4569

Eigenvalue=8.392; Consistency index= 1.40; **Consistency ratio(CR)= 0.04**

Table 4. Assessment of strategies in terms of sustainability sub-elements

Strategies	Environment		Economic	Social
	Amount of waste generation	Homogeneity of retrieved material	Implementation cost	Level of safety risk
A	0.8822	1.0000	0.0830	0.4785
B	0.0984	0.0748	1.0000	1.0000
C	0.1407	0.0929	0.9157	0.8707
D	0.4166	0.1739	0.5927	0.2560
E	0.3517	0.2327	0.4176	0.2337
F	0.1938	0.3169	0.2441	0.2215
G	1.0000	0.6557	0.1600	0.8652
H	0.8589	0.4569	0.2660	0.8521

Table 5. Sustainability contribution scores for the eight strategies

Strategies	Sustainability contribution score		
	Environment	Economic	Social
A	0.9411	0.0830	0.4785
B	0.0866	1.0000	1.0000
C	0.1168	0.9157	0.8707
D	0.2953	0.5927	0.2560
E	0.2922	0.4176	0.2337
F	0.2553	0.2441	0.2215
G	0.8278	0.1600	0.8652
H	0.6579	0.2660	0.8521

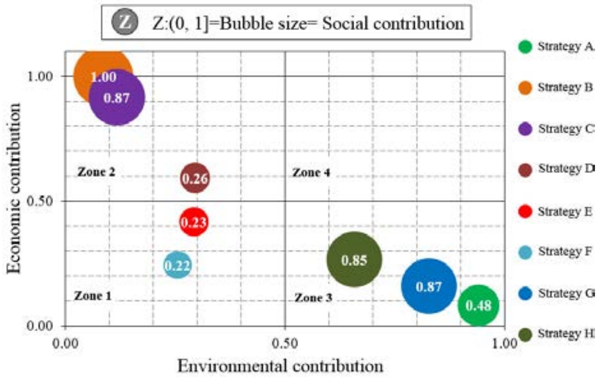

Fig. 3. Contribution of strategies into sustainability elements

In this work eight disassembly/dismantling strategies have been introduced as different alternatives to be appropriately used in recycling of the carcass. A sustainability evaluation need on all the implemented strategies was discussed as an approach to select the optimum strategy.

The strategies have been implemented on a Bombardier Regional Jet aircraft. With the goal to assess the sustainability contribution of each strategy, elements and sub-elements pertinent to sustainability aspects were identified. A pairwise comparison technique was used to numerically measure the identified sub-elements.

In this paper few sub-elements were determined to assess the sustainability contribution and is a preliminary study that shows the necessity to assess sustainability and sustainable development as a crucial aspect to be considered at end-of-life recovery process. However taking into account pros and cons of each strategy based on the qualitative analysis performed in this study, further research need to be done to solidly determine the ideal strategy and improve the strategy of choice in terms of sustainability.

Future works, should be focused on identification of more sub-elements and indicators to increase the reliability of the assessment. Also, application of decision aid techniques such analytic hierarchy process (AHP) can be helpful. Other techniques as fuzzy logic might be useful to control the uncertainty and vagueness derived from assessment of the indicators.

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