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END-OF-LIFE EFFICIENT DISASSEMBLY OF COMPLEX STRUCTURES USING PRODUCT AND PROCESS FOCUSED APPROACH

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DEDICATION

This thesis is gratefully dedicated to my parents Zahra and Asghar, beloved wife Audrey and wonderful sister Sima, for all your support along the way.

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RÉSUMÉ

Le démantèlement durable des avions, contenant un nombre élevé de composants métalliques et non métalliques, devient, de nos jours, un problème de plus en plus urgent dans l’industrie aéronautique. Le désassemblage de la structure, en tant que principale tâche de cette procédure, a toujours été un défi considérable que ce soit en matière d’efforts requis qu’en termes de valeur économique apportée. Ce processus est, depuis toujours, apparu comme un service couteux et pas forcément écologique. La revue de la littérature indique que le désassemblage semi-destructif a des bénéfices significatifs contrairement à la destruction totale voir la non-destruction des appareils. Malgré un grand champ d’applications, à l’heure actuelle, il n’existe aucun moyen d’évaluer, indépendamment d’estimations subjectives, quantitativement l’effort nécessaire pour appliquer une telle méthode sur des structures métalliques complexes telles que celles d’un avion.

Le but de cette thèse est donc, de développer une échelle d’évaluation à multiples variables afin de déterminer la performance de chaque opération avant de commencer le travail matériel. Ce modèle serait capable d’évaluer la facilité de désassembler la structure, et ce de manière quantitative, incorporant les aspects relatifs au produit ainsi qu’au procédé. Dans chacune de ces deux catégories (c’est à dire produit et procédé), différents facteurs déterminants, peuvent amener à un résultat économique, environnemental et /ou social décevant, s’ils ne sont pas pris en considération. C’est pourquoi cette méthode explore divers facteurs tels que le temps, la difficulté, la compatibilité des matériaux utilisés dans les pièces/modules de la structure afin que la stratégie choisie corresponde aux objectifs techniques, économiques, et environnementaux.

Dans cette étude de cas, un stabilisateur horizontal provenant d’un appareil Bombardier CRJ series a été sélectionné afin d’évaluer la pertinence et l’efficacité de l’approche proposée. La partie expérimentale s’est appuyée sur des travaux pratiques de désassemblage établis sur une période de plus de deux ans, des analyses des documents de maintenance appartenant à cet avion, ainsi que des entretiens avec des spécialistes de ce domaine. Les résultats ont démontré que l’approche proposée est à la fois facilement réalisable, plus rapide et permet une meilleure récupération des matériaux en comparaison avec d’autres méthodes. Enfin, avec de tels avantages, ce procédé apporte une importante contribution dans le domaine du désassemblage de la structure puisqu’il est aisément exploitable par les sites de désassemblage, pour les fabricants et propriétaires d'avions.

ABSTRACT

Sustainable decommissioning of aircraft with a high content of metallic and non-metallic components is becoming an urgent issue in today’s aviation industry. Airframe disassembly, as a principal step in this procedure, has always been a challenge in terms of the required effort and regained values. This process has historically appeared to be economically costly, socially unviable, and not necessarily environmentally benign. Literature indicates that, unlike entirely destructive and totally non-destructive techniques, semi-destructive disassembly may bring significant benefits. However, despite their use in a wide variety of applications, there are currently no feasible solutions on how to measure the associated physical difficulties and required efforts without any dependencies on expert views or filling out spreadsheet-like forms.

The purpose of this dissertation is then to develop a multiple-variable model in order to determine the performance of each disassembly operation prior to the physical work. The model could accurately evaluate the disassembly easiness of an airframe quantitatively incorporating both product and process features. There are various driving factors in each of these categories (i.e., process and product features) that failing to appropriately address them could result in either significant economic loss, environmental and/or social inconvenience. The methodology used in this study is one of the first investigations in this field, known as a Multivariable Disassembly Evaluator (MDE). It explores 1- time; 2- difficulty; and 3- material compatibility of the airframe parts/modules to ensure that the defined disassembly strategies meet technical, economic and environmental objectives.

A horizontal stabilizer of Bombardier CRJ series was selected as a case study to provide a detailed vision of disassembly evaluating the suitability and effectiveness of the proposed approach. The experimental investigations are based upon the real disassembly works for over two years, aircraft maintenance documentation analysis and discussions with technical domain specialists. The findings demonstrated that the proposed method is easier to fulfil, faster and allows the user to gain more recovery than other current approaches. These advantages should make an important contribution to the field of airframe disassembly since they can be readily used by disassembly sites, aircraft owners and manufacturers.

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LIST OF ABBREVIATIONS AND SYMBOLS

AHP	Analytical Hierarchical Process
AFRA	Aircraft Fleet Recycling Association
AMM	Aircraft Maintenance Manual
BHN	Brinell Hardness Number
CAD	Computer-Aided Design
CRJ	Canadair Regional Jet
DSP	Disassembly Sequence Plan
DDC	Disassembly Difficulty Calculator
EoL	End-of-Life
GHG	Greenhouse Gas
H.S.	Horizontal Stabilizer
HP	Horsepower
LCA	Life-Cycle Assessment
MP	Mathematical Programming
MDE	Multivariable Disassembly Evaluation
MRR	Material Removal Rate
PAMELA	Process for Advanced Management of End of-Life-Aircraft
PMMA	Poly Methyl MethAcrylate
PET	PolyEthylene Terephthalate
PR	Pressure
PMP	Pre-sort Material Prioritization
SMA	Shape Memory Effect

SME	Shape Memory Alloy
SMT	Shape Memory Technology
SRM	Structural Repair Manual
U-Effort	Unfastening Effort
U-Force	Unfastening Force
VE	Virtual Environment
WP	Work-Piece
XRF	X-ray Fluorescence
Cut.	Cutting
D. Dr.	Deep Drilling
Min. dr.	Minor Drilling
u or e_c	Specific Cutting Energy
e_{ch}	Plastic Deformation
e_p	Ploughing Energy
e_s	Sliding or rubbing Energy
d	Depth of cut
v	Grinding feed rate
w	Width of cut
ω	Rotational speed
P	Power
D	Wheel diameter
F_c	Cutting Force
F_n	Normal Force or thrust force
T	Torque

A_c	Chip cross-section area
u_d	Specific cutting energy for the drilling operation
S	Drilling feed rate
d	Drill bit diameter
f	Feed rate
d_d	Nominal shank diameter
E	Young’s module
δ	Diametral interference
μ	Friction coefficient
A	Area of contact
MS	Material Scarcity
DP	Post-disassembly Profitability
ATr	Alloying Tolerance
Pr	World Production or aeronautic-sector consumption
Re	Replaceability
Ab	Abundancy
L_{POT}	Metal-cutting operation length in primary operation time
W_{POT}	Workpiece velocity in primary operation time
VR_{POT}	Drilling speed in primary operation time
D_{POT}	Disengaging time
R_{Ver}	Verification redundancy in secondary operation time
D_{Ver}	Downtime in verification phase of secondary operation time
P_{OD}	Human performance in secondary operation time
D_{OD}	Downtime in downtime calculation of secondary operation time

POT	Primary Operation Time
SOT	Secondary Operation Time
T.Ver.	Tool Verification Time
O.D.	Operation Downtime

CHAPTER 1 INTRODUCTION

Background and description

The process of treating an aircraft at the end-of-life (EoL) has emerged as an increasing concern over the last few years. Recent legislative obligations on landfill and incineration in addition to the shortage of natural resources and energy challenges call for the modernized EoL-oriented design guidelines. While an aircraft EoL maintains a considerable amount of value, it suffers from various technical, environmental and economic shortcomings. The difficulties associated with the disassembly process, low quality of the recycled materials (forceful downgrading), high amounts of leftovers and handling of the dangerous materials are the common noteworthy issues in this field. Meanwhile, with the increasing number of the in-service and retired aircrafts each year, there is a need for a disassembly-based EoL framework.

Product traditional EoL treatments, as a generic approach to deal with a wide range of products, face technical and economic difficulties. Although there might be few similarities between EoL procedures in different domains (e.g., aerospace, automotive, construction, etc.), as suggested by Feldhusen et al. [Feldhusen et al., 2011], the differences are still significant making it essential to initiate separate researches in each field. Nevertheless, regardless of the industry sector, the disassembly process, as a key element in EoL treatment, has been increasingly stressed both in academia and industry over the few last years. The experiences gained form the real disassembly works and the literature also confirm that the disassembly operation has a decisive role on the product EoL ecological competitiveness and economic profitability. In the meantime, it is reported that the product EoL treatment is often governed by the economic consideration [Chen et al., 1993]. The full disassembly, which was once known as a feasible approach, also appeared to be disadvantageous. It was revealed in a research where a complete disassembly of a given case study resulted in only 30% of material recovery [Kondo et al., 2001]. The totally constructive methods do not offer better results either. Along with such importance, our experiments throughout the real disassembly works proved that an efficient disassembly process may turn the EoL treatment into an environmentally sustainable and economically viable alternative.

In this research, this has been looked at from a practical point of view with an initiative aim to increase the added-value associated with the disassembly process together with promoting the environmentally friendly design. A key utility of the proposed approach is that it is a readily-applicable-model (based on the real disassembly works) to evaluate the disassembly performance.

This research should be helpful in determination of the airframe disassembly operation selection and analysis, which can be used both at EoL or design phases. Each operation has to be individually studied with respect to product and process related features. The guidelines and knowledge development about the semi-destructive disassembly behavior can be beneficial to proceed with closed-loop product and materials along with providing high profit operations.

Research motivation

The motivation for this research comes from a need for design and analysis of the semi-destructive disassembly operation, which is a widely-used method in complex structure (particularly aircraft) EoL operations. There is a lack of knowledge when it comes to the understanding of the semi-destructive disassembly fundamentals. The number of decommissioned aircrafts are significantly increasing around the globe. There is a need for a disassembly model that can help improving the disassembly performance. This can provide significant costs reduction and time required for disassembly of the aircraft structure. The airframe disassembly is a relatively complex operation due to the presence of various driving factors. These factors have to be identified and the relationship amongst them must be analyzed in order to attain an efficient disassembly process.

Problem statement

End-of-Life treatment of a product is a relatively complex multi-disciplinary challenge. In other words, the interdependencies between driving factors in the technical, economic and environmental criteria have to be explicitly analyzed. The disassembly process, as a core topic, needs to be explored and its role in product life cycle has to be assessed. The high degree of uncertainties, product unknown geometry, and profitability issues are amongst the most challenging concerns to be principally dealt with.

The literature indicates that most of the disassembly time and effort is driven by disjoining and unfastening operations relating the major problems to the separation of the joints. This is particularly important since there are thousands of elements in complex structures such as the aircrafts, ships and trains. The semi-destructive disassembly method can bring significant advantages to the EoL disassembly process of these particular structures. Nevertheless, to date, it has received only scant attention in the research literature, and no empirical study has been done to deepen our understanding of its principles.

On the other hand, there is a general lack of well-grounded practical considerations on addressing the EoL process evaluation, strategy and planning related to complex structures, as opposed to the small electronic devices, home appliances or automotives. In this thesis, strategies and technics are proposed to answer the following main research questions:

- What is an efficient disassembly operation in the case of a complex structure?
- What are the principles of the semi-destructive disassembly?
- What are the essential metrics to proceed with a disassembly performance assessment process?
- How to define an effective disassembly strategy without compromising profitability, facility and environmental sustainability?
- How to evaluate a semi-destructive disassembly quantitatively prior to the disassembly physical work?

Project objective (goals)

The overall objective of this thesis is to raise the understanding of the semi-destructive disassembly method, as a widely used technic in the complex product EoL disassembly, particularly in aviation industry. This will build the necessary knowledge through determination of the key operation technics and systematically setting them into relationship with influencing factors. To reach these goals, a number of general and specific objectives have been aimed at as follows.

General objectives

- Enhancing the recyclability of the aircraft structures (maximizing the recycling and minimizing the landfill);

This encompasses a more sighted sorting operations of the detached/unfastened components, sub-assemblies and/or modules with the objective of decreasing the chance of forceful material downgrade in the post-disassembly operation stages.

- Increasing the profitability of the EoL treatment of an airframe (benefit-cost);

A higher profitability rate could be attained through minimization of unnecessary disassembly operations together with increasing the chance of obtaining high-end materials (aerospace grade).

- Facilitating the airframe EoL evaluation and planning at the very early stage of decommissioning and/or design process;

The envisioned model would make the disassembly strategy makers and practitioners able to have an explicit view on the disassembly operation performance before the physical works start.

- Establishment of a simple, practical and customized approach for a multiple-variable issue.

The model is based upon two years of direct on-site experiments related to the detailed airframe disassembly. That being said, it is tried to include the current body of industry technics, tools and specialists' feedbacks to enhance the practicality and applicability of the proposed approach.

Specific objectives

- Definition of the semi-destructive disassembly relevant parameters;

A comprehensive nomenclature is introduced, for the first time, englobing the airframe disassembly parameters and variables related both to the product or process features. It is of great importance to know how these disassembly elements and terminologies are defined and influence each other prior to the performance analysis.

- Development of a quantitative model in order to determine the disassembly difficulty;

The evaluation of the disassembly operation is a highly qualitative problem. This considerably exacerbates the issues related to ambiguity of the analysis and the decision-making process. It is significant to develop a model that can measure the disassembly difficulty quantitatively. This makes it relatively easier to proceed with an efficient disassembly operation and facilitates the decision-making process.

- Development of the airframe Multivariable Disassembly Evaluator (MDE);

The MDE method attempts to perform a quantitative assessment of disassembly performance with respect to three fundamental criteria: 1- technical (reunited as disassembly difficulty); 2- economic and 3- environmental. Although it is tried to gather these three criteria under a unified term, the stress is put upon the technical aspect which forms the main body of this study.

- Definition of the appropriate airframe EoL strategy(ies).

It is essential to define a set of well-rounded EoL strategies allowing for selecting the most beneficial scenario to meet the defined objectives. In the MDE approach, these strategies are included in the evaluation phase offering further assistance to EoL disassembly decision-makers to proceed with a more efficient EoL disassembly operation.

Scope and limitations of research

The advanced aircraft EoL process, in a broad sense, encircles various fields of science including mechanical, electrical, material and environmental engineering. Many researches have been conducted within the fields of Design for Environment, Design for Sustainability and Design for End-of-Life attempting to find sustainable solutions. The airframe EoL treatments could be divided into three separate key steps including pre-disassembly, in-process-disassembly and post-disassembly operations. This research particularly concentrates on the disassembly stage, as a fundamental phase, which can lead to a prosperous EoL treatment.

Disassembly, as a non-destructive or destructive process, may be placed under the remanufacturing or demanufacturing fields, which are covered by multi-lifecycle engineering. Design for disassembly, as a more recent term, could be used for maintenance and/or EoL purposes. Nonetheless, this study focuses on the semi-destructive component of the disassembly with the purpose of improving the overall EoL performance. The approach principally concentrates on technical aspects (i.e., operation difficulty analysis and time) englobing variables from a wide variety of criteria within the disassembly operation. The economic and environmental criteria are also marginally covered. The model is established to principally help processing the current body of obsolete airliners fleet. Nevertheless, the findings could be found helpful in the case of business jets and/or military airframes or also other non-aerospace complex structures (e.g., ships and trains) EoL treatments.

Originality of the research and values

The experimental work presented here provides one of the first investigations into how to measure the difficulty of an airframe disassembly quantitatively. The importance and originality of this study is that it explores the impacts of the relevant parameters and variables on disassembly performance based upon the real experiments conducted on a Bombardier Canadair Regional Jet (CRJ100ER) series aircraft.

The study offers some important insights into the sustainable decommissioning and design of the complex metallic structures, as seen in the airframes. Both academia and industry could benefit from the findings in attempt to improve the EoL overall disassembly performance through:

- Reducing the disassembly difficulty and time;
- Reducing machine downtime and labor cost in maintenance services;
- Enhancing the automation potential of the process;
- Encouraging the production of the disassembly-oriented products.

CHAPTER 2 THESIS ORGANIZATION

This thesis shows how a quantitative disassembly evaluation process can help achieving an efficient disassembly of a complex metallic structure. It would be beneficial to the technical domain specialists and structure designers to understand the performance analysis of the disassembly operation. The organization of this thesis is as follows.

1- Chapter three presents a state-of-the-art review of the literature and relevant body of research associated with the technical aspects of the disassembly evaluation process, as addressed in introduction. The fields of remanufacturing and demanufacturing are explained explicitly. The fundamental researches, latest finding and knowledge gaps in disassembly is highlighted through three different channels: 1-evaluation; 2- planning; and 3- innovative concepts. Moreover, the current challenges associated with the complex structures (i.e., airframe) are noted. The experimental work presented in this study provides one of the first investigations into how to evaluate the complex metallic structure disassembly using the semi-destructive method.

2- Chapter four introduces a conceptual framework proposing a new disassembly roadmap when dealing with a complex structure. A new classification of the disassembly factors is proposed dividing the essential metrics into the process and product related features in order to improve the overall performance of the disassembly. This tends to increase the flexibility of the evaluation system by gaining an understanding of what factors could be managed at the EoL phase. The geometrical positioning, material compatibility, fastening analysis, process depth and process selection are amongst the most significant metrics in these categories.

3- Chapter five provides a systematic methodology of the airframe disassembly to improve the quality of the recovery materials. The pre-sort and pre-shred operations are stressed and incorporated into the disassembly process to reach high-end materials. A list of the feasible disassembly alternatives is proposed and the performance associated with each method is discussed in detail. This includes the operation speed, accuracy and damage risks with the objective of performing a cost effective disassembly process.

4- Chapter six introduces a quantitative evaluation model to measure the disassembly difficulty. A standard nomenclature for defining the disassembly related parameters and variables are presented with respect to the previously noted process and product related features. The cutting and thrust force vectors are singled out for the semi-destructive evaluation process. This further includes the effort-related key variables such as “the number of materials in a component”, “Brinell Hardness Number (BHN)”, “tool speed (in both rotational and linear forms)” and “depth of cut”, to better reflect the real disassembly conditions. The proposed approach can measure the difficulty without any dependencies to the feedbacks obtained from questioners (i.e., scoring/ranking approaches) allowing for a more robust analysis.

5- Chapter seven presents a multiple variable disassembly evaluation approach incorporating the disassembly key factors from several criteria (i.e., technical, economic and environmental) simultaneously. This is a significant study since a difficulty-oriented analysis per se may not be able to appropriately assess the disassembly performance. The factors such as the time, material compatibility, economic profitability and environmental sustainability are gathered systematically in this research approach. This methodology tends to perform a comprehensive study of the disassembly evaluation process presenting a real Bombardier CRJ (CRJ100ER) horizontal stabilizer case study in order to verify the suitability of the model.

6- The general discussion is presented in chapter eight explaining the problem details, topic development and methodology definitions.

7- Chapter nine gives a summary of the thesis highlighting the key findings. A set of recommendations for the future researches is also listed to provide directions for the future works with significant impacts in the related fields.

8- In order to gain insights on the developed methodology and the objective of each step, the research outline is summarized in **Error! Reference source not found.**.

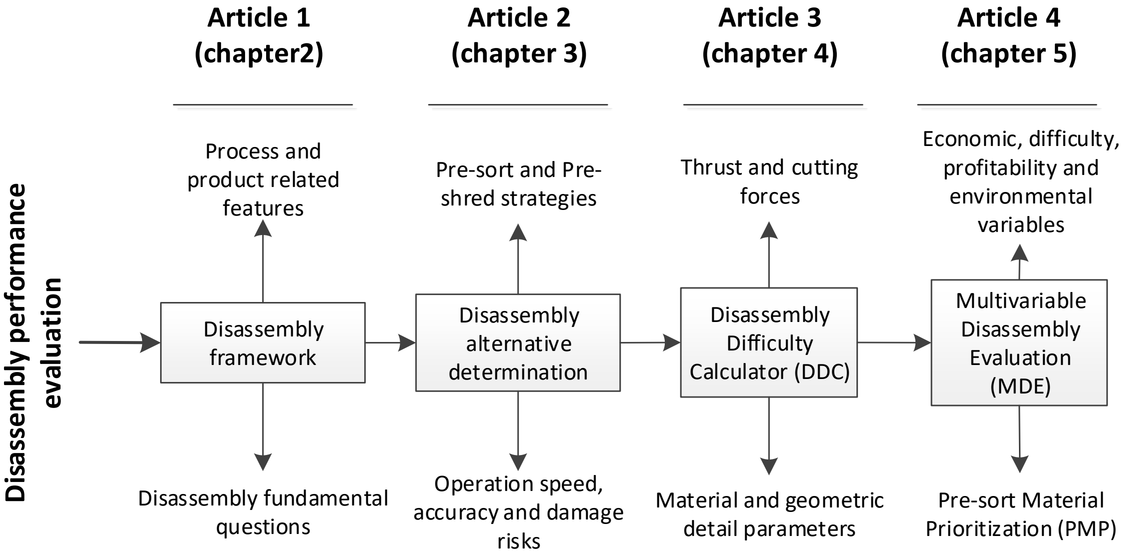

Figure 2-1 Research outline

CHAPTER 3 LITERATURE REVIEW

The literature here gives a survey of the knowledge in the fields of product EoL and disassembly through highlighting the associated works and key findings. The review of the literature has to be relatively broad since the field of disassembly (particularly the airframe disassembly) relates directly and indirectly to several main topics. This is essentially important in order to develop a better understanding of the semi-destructive disassembly evaluation process, as a method with increasing applications. Nevertheless, this is a relatively new and unexplored research field. Consequently, the author provides some of his own insights into the topic.

3.1 Scope of the literature review

The EoL phase of an aircraft consists of various aspects each having their relative importance. As described by Mascle et al. [Mascle et al., 2015] the essential operation steps include: 1- decontamination; 2- removing the valuable parts; 3- dismantling of the remaining carcass and 4- recovery and valorization and/or landfill. Following these fundamental steps, almost all of the valuable and relatively easy-to-disassemble parts are removed at the second stage. The challenges begin during the dismantling of the remaining structure (the third stage), which has significantly less value (as compared to the parts such as the engines and/or landing gears) and is also more difficult to process. A comprehensive literature review can go farther enough to cover each process step (i.e., decontamination, removing the valuable parts, disassembly, etc.) separately which would become exhaustive and cannot help discussing the main topic. Although some subjects have captured more attentions than others, the overall body of literature in aircraft EoL is seen fairly limited when it comes to the study of principal problems. Meanwhile, to establish an understanding of the topic and assemble the current body of the literature, the explored topics fall under one of the following categories:

- demanufacturing and remanufacturing;
- disassembly;
- EoL strategy definition;
- the aviation EoL potentials and methodologies (domain specific);
- aerospace material recycling (domain specific).

3.2 Demanufacturing and remanufacturing

The concepts of remanufacturing and demanufacturing have to be explicitly clarified due to their broad EoL applications. Since there is a confusion in defining correctly what stands behind each concept, they are often referred to interchangeably. Demanufacturing and remanufacturing are two different criteria with regard to the product post-use procedure. Literally, remanufacturing is a product recovery operation bringing a used product to a “like-new state” where its functionalities are guaranteed [Ijomah, 2002]. It is a process of recapturing the value added to the material when a product was first manufactured [Gray and Charter, 2007]. However, despite its significant potentials, the literature shows that the uptake by the academic community has been relatively low on this topic. As reported by Hatcher et al. [Hatcher et al., 2011] only 37 articles specifically addressed the product design for increased remanufacturability from 1995 up to 2001.

Demanufacturing, however, is a process of decomposing a product into its parts/sub-assemblies through an unfastening process and destructive disassembly at the end-of-life with the objective of reusing parts, remanufacturing and recycling of the remainder of the components [Sonnenberg, 2001, Duflou et al., 2008]. According to this definition, one may consider the demanufacturing field more inclusive than remanufacturing per se incorporating several processes such as reuse, recycling, disassembly, refurbishment, cleaning, inspection, etc. The semi-destructive method is also placed in demanufacturing field. This equally means that a part/module might be recoverable only through performing some semi-destructive operations (i.e., demanufacturing) rather than unfastening (i.e., remanufacturing). This is due to the parts’ geometrical location, hazards, difficulties, etc. Therefore, it was of great importance to know where the EoL semi-destructive disassembly is placed in EoL field before discussing the disassembly in its general meaning.

3.3 Disassembly

Product disassembly addresses issues related to the facility of the components/subassemblies to be disjoined and/or unfastened for different purposes (e.g., servicing/maintenance, recycling, remanufacturing, etc.). In a similar definition, researchers defined the disassembly as a systematic approach of recovery and separation of the product’s desired parts, sub-assemblies (or even a group of components) from the recyclables for a specific purpose [Lambert and Gupta, 2004, Gungor and Gupta, 1997, Gungor and Gupta, 1998].

Desai and Mital [Desai and Mital, 2003] have classified the process of product disassembly into two different categories: 1- destructive or brute force approach; and 2- non-destructive disassembly or reverse-assembly [Sodhi et al., 2004]. Nevertheless, it would be even more comprehensive to add the semi-destructive method, as a third category, to this traditional classification.

Many researches have been dedicated to the applications of semi-destructive technic in various domains particularly in cognitive robotics [Umeda et al., 2015, Shiraishi et al., 2015, Vongbunyong et al., 2013a]. A disassembly process, depending on a series of influencing factors (including the selected strategy, available infrastructure, budget, expertise, etc.) incorporates one (or a combination) of the disassembly methods mentioned earlier in the presented classification. However, regardless of the type of physical operations, a disassembly process includes unfastening, cutting, handling, control tasks and other operations, as stated by Sonnenberg [Sonnenberg, 2001].

The disassembly, as a precursor operation towards recycling, is of great importance, since it has a significant impact on the efficiency of the recycling procedure. Several subtopics have been proposed to explore the disassembly field to date. Zuo et al. [Zuo et al., 2002] divided the disassembly process into: 1- Disassembly Leveling (DP) and 2- Disassembly Process Planning (DPP). However, Mok et al. [Mok et al., 1997] have a different perspective through proposing the following division: 1- the definition stage of disassembly concept, and the establishment stage for disassembly.

In this study, the principal topics are divided into three groups of major sectors: 1- disassembly evaluation (cost/benefit); 2- disassembly new concepts and automation; and 3- DPP. Many researches have also centered on the disassembly driving factors/metrics determination process, which is in fact seen as evaluative tools in order to assess the product disassembly [Fan et al., 2013, Das et al., 2000, Güngör, 2006, Desai and Mital, 2003, Kondo et al., 2003, Kroll and Carver, 1999]. Therefore, these methods are regrouped under the first category (i.e., disassembly evaluation).

The maximization of net benefit is a key subject in product disassembly. There are various factors with considerable impacts on the determination of the disassembly profitability. The time required for parts disassembly, quality of recovered materials (which is itself a function of the disassembly and post-disassembly performance), the facilities in which the disassembly works are carried out and the expertise may be the most important elements. The evaluation of the time required for parts separation is amongst the top priorities in the product disassembly assessment. Due to its fundamental importance (based upon the impacts that it has on other variables), many researches have been initiated in this field, and yet there are still many avenues to be explored [Mital et al., 2014, Kondo et al., 2003, Kroll and Carver, 1999, Yi et al., 2003, Suga et al., 1996].

In the meantime, the social and environmental responsibilities of manufacturers have also gained importance due to the several statuary legislations and the overall public awareness. These social and environmental constraints have posed challenges to the profitability of the operations while maintaining sustainable. The maximization of net return, minimization of emission and risks are the major topics where the researches are currently concentrated on. This has been discussed in several studies. Many believe that incorporation of the environmental and social constraints to the design criteria would reduce profitability and then put the stress on the production cost [Achillas et al., 2010], while on the other hand, many consider the social performance as a value for the business and society [Cruz, 2009, Carter and Jennings, 2004]. Nevertheless, in order to have an environmentally/socially benign and economically viable product, disassembly plays an important role either from the design perspective or EoL viewpoint.

To the fulfillment of the objectives certain intrinsic features of the disassembly in analogy to assembly should be pointed out. First of all, disassembly unlike assembly rarely involves part positioning and placement actions besides having a much less net value added [Das and Naik, 2002]. In other words, the required energy, labor costs, time, skills and other related resources must be minimized in order for the whole process to be economically viable. Since in most cases the revenues from reusable/recyclable parts are not sufficient to cover all disassembly expenses, the whole process becomes economically unprofitable. On the other side, having the higher flexibility rate, the design phase is where the products can be shaped to increase the EoL performance and to offer an improved sustainability. This obviously highlights the importance of the evaluation process in terms of the EoL friendliness at the design stage.

3.3.1 Disassembly evaluation

Disassemblability of a product addresses the issues related to the facility of its components/subassemblies to be disjoined or unfastened for different purposes (e.g., servicing/maintenance, recycling, remanufacturing etc.). Often referred to as “ease-of-disassembly”, this process depends upon several parameters such as the required force exertion, accessibility, weight, size of the parts, etc. The literature here gives a survey of the knowledge in this field by highlighting the fundamental researches, latest findings and knowledge gaps.

Zussman et al. presented a product design evaluation in terms of the disassembly and recycling easiness using the formalized quantitative methods to help designers with an improved design procedure [Zussman et al., 1994]. In this process, the ultimate goal is to minimize the disassembly and recycling cost and maximize the profit through disassembly process assessment. The difficulty rating process includes parameters such as force, positioning, and accessibility. Kroll and Haft also proposed a quantitative approach by defining task difficulty scores, printed on a spreadsheet-like chart to assign to different parts [Kroll and Hanft, 1998]. The reference values have been generated according to the real working conditions. However, small-sized products (i.e., electrical devices) may be processed using this method. The gigantic products such as airframes, ships and trains may not fit into the framework of the proposed method, although they form a considerable share of the obsolete products. Moreover, the limited number of difficulty factors such as “accessibility”, “positioning” and “force” might be too general to reflect the real disassembly difficulties.

A similar design assessment research has been conducted by Desai and Mital based on time measurements through assigning different indices to the various design factors [Desai and Mital, 2003]. They found the design anomalies resulting in a series of design modifications which can significantly increase the disassemblability of the products. Their results principally stress the following design anomalies:

1- need for excessive force; 2- component shape, size and weight; and 3- accuracy of tool positioning.

The incorporation of several factors such as “use of force”, “mechanism of disassembly”, “use of tools”, “recognizability of disassembly points” and “toxic materials” are new, comparing to the previous works. Nonetheless, they do not consider the expertise of disassembly worker/technician as it is addressed by [Suga et al., 1996]. Besides, there is a lack of clarity on what component might be selected for reuse, remanufacture or other EoL options from the beginning of the disassembly process.

Suga et al. have proposed an innovative approach based upon “energy of disassembly” and “entropy for disassembly” to measure the product disassemblability [Suga et al., 1996]. Energy, as appears, relates directly to the elastic deformation and frictional energy of the connections influenced by the size and nature of connections. While entropy, here, basically refers to a measure of disconnecting difficulties (e.g., number of interconnections and different disassembly directions). These evaluation parameters are used to finally calculate disassembly time. Despite the innovative approach that this study presents, the entropy is defined vaguely and it may become unusable particularly when the product complexity is high.

As indicated in the literature, the disassembly time required is a fundamental variable to measure the efficiency of the disassembly process. Thus, it is fairly clear that any evaluation process has to incorporate the time analysis in order to provide an efficient solution. Meanwhile, it is revealed that the evaluation of the time and difficulty may include other critical analysis as follows.

3.3.1.1 Product Geometric/Structural Analysis

The geometric features of a product play an overriding role in the disassembly performance/efficiency analysis. Attempting to analyze the impacts of geometric features on disassemblability of a subassembly, researches may explore the following factors: 1- part positioning; 2- geometric tolerance; 3- geometric dimensioning and 4-orientational errors.

It is observed that the literature has very little to say about the effect of these features on disassemblability of a product. Consequently, the author will present and discuss some of his own research to facilitate understanding of the subject. During the design process of a product, the geometrical configuration, tolerance, functional performance details, etc., are determined. However, when these features are optimized for maximum assembly, manufacturing or durability performance, they may cause considerable disassembly related issues at the retirement phase. The real disassembly works on CRJ100ER proved that the issues such as fasteners release trajectory, tightening, sealing, mating surfaces, etc. could impose extra difficulties to the disassembly process.

According to the literature, these geometric aspects are addressed in the context of product assembly (e.g., CAD analysis, geometric constraints for complex assemblies etc.), but has rarely been stressed systematically from the EoL perspective. Despite this, its related impacts on product disassembly performance such as accessibility, fitting and operation facility are pronounced in various researches, as stated by Sonnenberg [Sonnenberg, 2001].

Two researches by Takeuchi and Saitou are worth mentioning in this field where the spatial configuration are highlighted particularly [Takeuchi, 2006, Takeuchi and Saitou, 2008]. They introduced a built-in disassembly system named “product-embedded disassembly” concept. It consists of a set of spatially-configured components assembled together in a way that can be disassembled simply by removing a unique trigger (e.g., pin, screw, bolt, etc.) or pushing a disassembly button. This is achieved by constraining the relative motions of components by locator features (catches, lugs, tracks, bosses, etc.) integral to the components. In other words, once the trigger is removed (one or more fastener removal), the components can be self-disintegrated one after another in a desired sequence, as illustrated in Figure 3-1 (b).

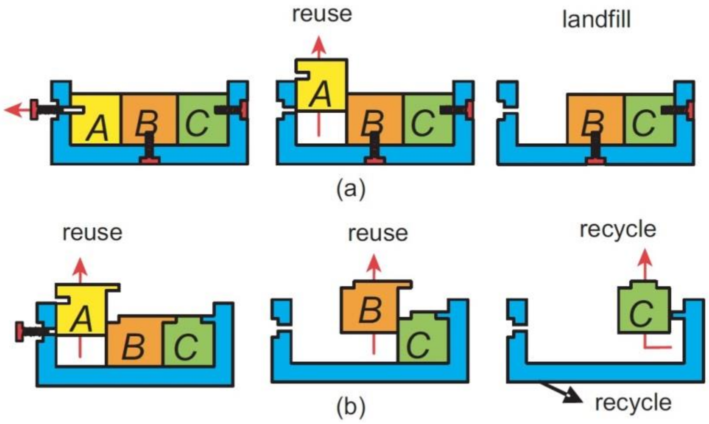

Figure 3-1 Self-disassembly concept proposed by Takeuchi [Takeuchi, 2006] (a) conventional assembly; (b) assembly design for product-embedded disassembly

The topic related to the disassembly facilitating fastener design including the active disassembly will be discussed in details later in “new concepts and automated disassembly” chapter.

3.3.1.2 Material Analysis

The material properties analyses of the fasteners and mating components is a challenging topic in the product design nomenclature. In this regard, one of the most research demanding field is the compatibility of the fastener/connector and mating parts material(s). This may be determined from both recycling compatibility and functioning perspectives. The literature indicates that research on the recycling compatibility of the product materials is still at the stage of infancy. This becomes more severe when dealing with complex products integrating a considerable number of elements. Due to this lack of knowledge, the author would clarify some of his own findings in this field through highlighting the most significant design attributes as listed below.

- *Material compatibility (in-service features)*: depending on the application domain, a given material may commit into reaction (e.g., galvanic corrosion) with the mating material;
- *Material properties*: the quantitative mechanical factors explaining the materials' specific response to the different triggers;
- *Material availability*: meticulous looking at material extraction, demands and recycling rates in addition to considering the resource depletion;
- *Economic factors*: economic value of a specific material and its different alloys;
- *EoL compatibility (EoL features)*: the recyclability issues of the material(s) and the difficulties related to the recovery of high-end materials (due to the safety/hazards and/or technological/economic limitations);
- *Number of materials*: many researchers reported that the number of materials being used in a product is one of the most influential factors determining the material recovery efficiency [Rose et al., 1998, Lee et al., 1997, Lee and Ishii, 1997] (this may also relates to the EoL compatibility).

As long as the material compatibility concerned, parts/joints with the same material(s) are not supposed to be separated while undergoing the recycling process, as stated by Shu and Flowers [Shu and Flowers, 1995]. However, this might not be always easy to perform due to the lack of information at disassembly phase (limited access to the design documentations, lack of analytical equipment, etc.). Nonetheless, these documented guidelines can be quite useful to consider as an informative source at design stage. An example of the material compatibility guidelines is presented in Table 3-1.

Table 3-1 Fastener Material Compatibility [Campbell Jr, 2011]

Structural Materials Being Joined	**Fastener material**		
	Preferred	Acceptable	Prohibited
Aluminum to Aluminum	Anodized-Aluminum	Titanium- Stainless steel A286	Cadmium Plated Steel
Titanium to Titanium	Titanium	Stainless steel A286	Alloy Steel
Austenitic Stainless Steel	No data	Inconel 718	Aluminum
Nickel Base Alloys	No data	No data	Aluminum Coated Fasteners
Titanium To Aluminum	Titanium	Stainless steel A286 Inconel 718	Aluminum Aluminum Coated Fasteners
Carbon/Epoxy	Titanium	Inconel 718	Aluminum Aluminum Coated Fasteners

Mok et al., analyzed the automotive mechanical parts from the material and geometrical standpoint [Mok et al., 1997]. A design guide was proposed to improve the disassemblability of the parts. After establishment of the alternatives, several disassembly factors have been systematically classified into pre-, in- and after-process. The geometrical category with respect to the disassembly friendliness includes: the ease of fixing, approaching and handling. The presented attributes are some key elements in disassembly assessment. Kroll and Carver also raised two decisive questions regarding the material issues in product disassembly at the design phase (as a fundamental disassembly-oriented design guide) : 1- how to use fewer materials in a product; and 2- what would be the application opportunities for the recycled materials [Kroll and Carver, 1999]. The answers may explain how to define the EoL strategies, which is covered very little in the literature. Das et al., have conducted interesting researchers on the issues related to the material composition and recycling which explains further details related to the EoL material recovery [Das et al., 2010].

It is fairly apparent from the presented literature, that the incorporation of material compatibility into the disassembly evaluation process could significantly improve the assessment quality resulting in a more pragmatic EoL analysis.

3.3.1.3 Impact of fasteners on EoL disassembly

Disassembly performance of a product can be remarkably influenced by the joining and fastening technics. The real disassembly of airframe proved that, the unfastening and disjoining operations forms the most time-consuming part of the airframe post-life disassembly. That is why many researchers stated that the development of the efficient fastening and joining methods can significantly contribute to the improvement of overall disassembly efficiency [Mok et al., 1997, Duflou et al., 2008, Willems and Duflou, 2006, Desai and Mital, 2003]. This becomes even more important when hybrid-joining* is widely applied to products [Grote and Antonsson, 2009]. Particularly, in case of the products with higher degree of complexities (e.g., commercial airliners' structure, fighter jets, helicopters, etc.), it becomes considerably difficult to perform the disassembly operations in an environmentally benign and economically profitable condition. The research efforts contributing to this field will be under scrutiny in this section.

The literature indicates that there is a common interests and linkage between the researches highlighting the need for a breakthrough in joining/fastenings and the disassembly technics [Willems et al., 2006, Willems and Duflou, 2006, Duflou et al., 2008]. A number of different classifications have been proposed for fastening/joining technics with respect to the disassembly process [Sonnenberg, 2001, Lesko, 2008, Grote and Antonsson, 2009]. In this regard, Sonnenberg's classification is based upon the joining types, whereas Grote and Antonsson propose a process-based categorization [Grote and Antonsson, 2009, Sonnenberg, 2001]. Table 3-2 demonstrates this classification (i.e., fastening/joining types) according to the latest findings.

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[*] It refers to the combination of two technics (fastening and joining) in the same zone in order to join/fasten two parts/sub-assemblies resulting in synergistic effects. This can complicate the disassembly planning of a given part with such a design feature due to the different difficulty and impurity levels.

Table 3-2 Fastening/joining technics classification, primarily presented by [Sonnenberg, 2001] with some modifications

Discrete fasteners	**Integral attachments**	**Adhesive bonding**	**Energy bonding**	**Others**
-Threaded Fasteners	-Locators	-Acrylics	-Soldering	-Seaming
-Non-threaded Fasteners	-Locks	-Cyanoacrylates	-Brazing	-Crimping
	-Compliant	-Epoxies	-Welding	-Zippers
		-Anaerobics	-Folding	-Velcro
		-Silicons	-Clinching	-Etc.
		-Polyester Hot Melt		
		-Polyurethane		

As it appears in Table 3-2, the first two columns contain two types of fasteners called mechanical fasteners. Fasteners are mechanical objects used to attach two or more parts together within a defined tolerance in order to reach functionality in a system. They have significant influence on the functionality, efficiency, reliability and safety of a design. The importance of fastening/joining study becomes more significant as the product complexity increases. A common jet airframe, F-18, is composed of 18,000 fasteners, being equal to 1/3 the cost of an airplane and the same as the engines [Cloud, 2013]. During the past decades, fasteners have been profoundly studied to meet the requirements of assembly and production. However, the study of their importance in EoL disassembly analysis is a relatively new research interest. This can be understood from the number of researches dedicated to the topic.

Most of these fasteners are designed in a way to last as long as possible making the EoL process considerably difficult. Nonetheless, the appropriate selection of the fasteners with respect to the EoL may facilitate the recovery process at EoL phase. The interests of the subjects for the researchers, to-date, have remain on two channels: 1- fastener selection according to the different design criteria based on a decision support approach/tool; and 2- disassembly models and analysis of the unfastening/disjoining phenomenon. To the knowledge of the author, the first category has been spurred by numerous researchers during years. However, the second channel gained only a slow uptake of academic interest until this recently. This delay is seen due to the reasons that follow.

- Late appearance of the resource depletion arguments;
- Inclination toward solely economically-benign and lucrative products rather than considering environmental and social responsibilities;
- Lower sensitivity towards EoL measures and analysis.

The German standard, VDI 2243, shows that a major problem area in the disassembly of all products appeared to be in the separation of joints [Beitz, 1993]. The disassembly of a four-cylinder engine has been taken as a case study. It indicates that about 32.5% of all activities in the disassembly process consist of the loosening screws which forms 54% of the entire disassembly process time.

VerGow and Bras proposed an interesting approach through performing the selection process in a Decision Support Problem (DSP) based on VDI 2243 standard allowing a fast and rigorous evaluation of connection types [VerGow and Bras, 1994]. The presented method includes a system of determination of principal attributes classified in a set of feasible alternatives. Eventually, three scenarios have been defined by assigning different priorities to the attributes explaining the 1- technical goal; 2- material recycling; and 3- product recycling. However, despite this facilitated selection process, no matter what type of connection is suggested in this method, it may be technically unfeasible to use one fastener in another specific domain (e.g., application of one aerospace rivet as compared to home appliances' rivets). Moreover, a static strength without any further implications or value, as an example, might not adequately reflect the expected mechanical behavior of the product, and should be stressed more in details. However, the results indicate a meaningful difference between the fasteners which only meet technical requirements and those which satisfy the recycling and environmental requirements.

An appropriate selection of the joining and fastening methods can reduce the disassembly time. In this field, Ghazilla et al. proposed a multiple-criteria decision making model to encourage the product recovery oriented design [Ghazilla et al., 2014]. Their approach includes the qualitative attributes based on fasteners related factors such as structural, in-process and the pre-disassembly operations. They have also substantially stressed the disassembly, assembly, cost and functionality. Furthermore, each of these categories are subdivided into the relevant driving factors such as “fastener reusability”, “fastener commonality” and “automated unfastening” for disassembly; and “axial load”, “shear load” and “damping” pertaining to the functionality categories.

Kondo et al, have experimentally examined some industrial products in a separate research on the disassembly evaluation process [Kondo et al., 2003]. A set of parameters such as the joining direction, length of product life, chemical degradation, physical deformation, and joining methods have been reviewed. Finally, the strongest relationship was observed between the joining methods and the disassembly time. Moreover, reversibility has also been taken into consideration. It was shown that the permanent joining (e.g., soldering and welding) have poor reversibility, whereas the threaded fasteners such as bolts, nuts, screws etc. show better reversibility.

The unfastening phenomena, as a fundamental topic, has been touched on by Sonnenberg and Sodhi [Sonnenberg, 2001, Sodhi et al., 2004]. Sonnenberg’s thesis has focused on the raising of the unfastening knowledge, and highlighting the importance of the unfastening process for designers. In other words, the objective of his works has been fixed to: 1-estimating the unfastening effort of frequently used fasteners; and 2- develop a guideline for the disassembly planning and for the design for disassembly/unfastening. Sonnenberg and Sodhi have developed two concepts, the so-called “U-Effort” and “U-Force” models. The U-Effort aims at the evaluation of the unfastening effort. The common design attributes of the fasteners and integral attachments are analyzed based upon a scoring approach. It seeks to incorporate the unfastening related parameters to assess the difficulties associated with the unfastening process. The geometry and condition of their use are included in their approach. The fasteners/attachments have been classified into two major categories: 1- discrete fasteners aiming to connect two or more separate parts together; and 2- integral attachments (with the same functionality) but they are known to be a part of the component itself. During their research it has been revealed that the shape of the fasteners’ head has a leading effect on the unfastening effort. The following relation, presented in Equation 3-1, is developed to describe the unfastening effort by Sonnenberg [Sonnenberg, 2001, Sodhi et al., 2004].

$$f = B_{min} + W_1.C_1 + W_2.C_2 + W_3.C_3 + W_4.C_4 = B_{min} + \sum W_i.C_i \qquad (3-1)$$

Where, W is the weight of the corresponding factors (pre-defined in each unfastening equation with respect to the selected fastener) and C is the corresponding constant (given in their associated tables). By assigning the “a”, “m”, “i” and “t” to the accessibility, material, environment, and tool effect respectively, the equation takes the following form:

$$f = B_{min} + W_m.C_m + W_e.C_e + W_t.C_t + W_a.C_a + \sum W_i.C_i \qquad (3-2)$$

The presented work is large and concentrated enough to give a clear vision of the fastener selection process to designers with the intention to increase the EoL performance. It is a useful and informative guideline whether it is the matter of product reuse, remanufacturing or even recycling. Nonetheless, the U-Effort model addresses only the non-destructive disassembly methods. Despite the ever-increasing importance of the destructive and/or semi-destructive technics, they are not covered in their approach. The “U-Force” tends to calculate the cantilever and cylindrical snap fits unfastening forces. Meanwhile, the presented model is of less interest in this study since the snap fit applications in complex product structures are quite limited.

A detailed study of the connection types and tool analysis is done by Güngör to develop an evaluative decision-making support framework [Güngör, 2006]. The main objective of his research was fixed to ensure an effective disassembly process through selecting the most fitting type of fasteners. Figure 3-2 shows what type of fasteners are mostly used in a structure of a fighter jet (as a complex structure). As seen in this figure, the use of “washers”, “Hi-Lok” and “Solid Rivet” are significantly more than the rest of the fasteners. The “Nut”, “Collar”, “Screw”, “Collar, Hi-Lok”, “Lockbolts”, “Bolts”, “Blind rivets” are also presented in Figure 3-2. During the real airframe disassembly in Centre Technologieque en Aérospatial (CTA) it is revealed that a business airliner has more “Solid Rivets” than “Hi-Loks”. However, as it is fairly clear in the literature, there is no solid study on the aircraft fasteners analysis with respect to the disassembly process to date. That being said, there are various fields in which pragmatic researches should be channeled in attempt to find an efficient airframe EoL solution. This may include: study of the fastening and joining, material compositions (i.e., different material substances in a single part); semi-destructive disassembly models and optimal tool selection process.

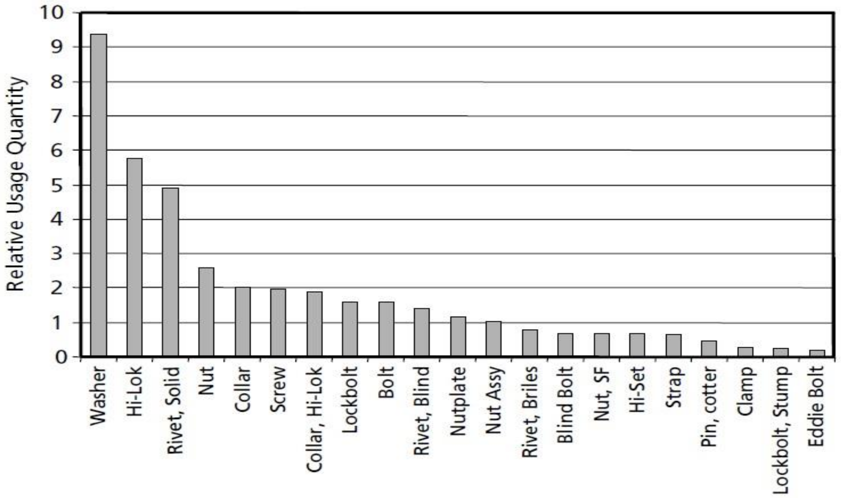
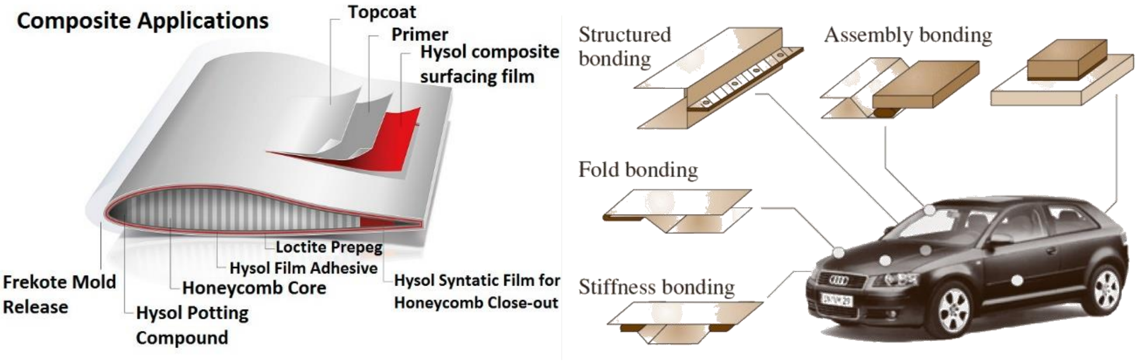


Figure 3-2 Typical Fighter Aircraft Fastener Usage [Campbell Jr, 2011]

The adhesive bonding and sealants are other types of joining technics with broad applications. Having been introduced as structural integrator almost 50 years ago, they have been used as “high performance adhesives” in certain industries (e.g., aerospace, automotive, construction and home appliances), as shown in Figure 3-3. These structural integrator (referred to as composite bonding) are also widely used in the airframe assemblies. Depending on the type and manufacturers, the composite bonding may be found in the: undercarriage doors, wing skin, passenger door, wing skin, central wing box, slats, rear fuselage, rear pressure bulkhead, etc.



(a) (b)

Figure 3-3 (a) Aircraft bonding/sealing application [Henkel, 2014]; (b) car adhesive applications locations [Grote and Antonsson, 2009]

3.3.2 New concepts and automated disassembly

As stated earlier in the previous chapters, there is a need for a change in the current fastening/joining available technics as well as in their selection process (during the design procedure). In fact, this is an essential step to provide a proportionate response to the current and future needs for sustainable EoL trends. This momentum gives place to the innovative concepts with objective of improving the disassembly efficiency.

The active disassembly, often referred to as “self-disassembling”, “auto-disassembly” or “One-to-Many disassembly”, as a non-destructive approach, is one of these ideas. It sparked a wave of academic research due to the variety of advantages it can offer. A group of researchers used heat as a trigger in this technic to change the shape of the parts [Chiodo et al., 2002, Chiodo et al., 1999, Chiodo et al., 2001]. Yang et al., reviewed the recent progress in the Advanced Shape Memory Technology (ASMT) with the applications in product life cycle including the recycling stage. The overviewed technics comprise the wrinkling and stress-enhanced swelling effect helping the designers to reshape the life cycle of products [Yang et al., 2014]. The Shape Memory Effect (SME)-based disassembly is also an enabling approach since it allows for programmed active disassembly in product EoL applications. According to a research by Zhang et al., a commercial hydrogel (poly acrylamide) revealed to show outstanding stimulus-responsiveness while providing reasonable strength making it a valuable choice for active disassembly [Zhang et al., 2014]. The hydrogel can take shapes and disassemble into original pieces depending on the nature of stimulus (water/moisture and heating or a combination of both) [Yang et al., 2014]. The following figure shows the disassembly process triggered by wetting process (hot water) where, (a) is the assembled shape, (b, c) the disassembly process and (d) are the after drying phases.

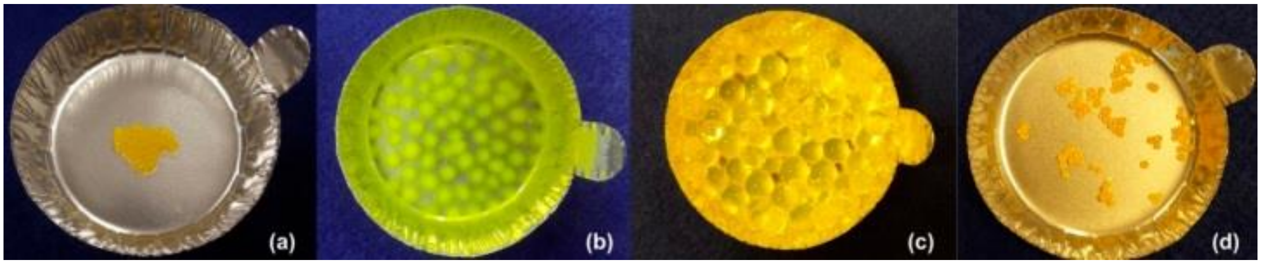


Figure 3-4 Disassembly of hydrogels by wetting process (hot water) [Yang et al., 2014]

A comprehensive review on active assembly-disassembly is also conducted by Sun et al., exploring the applications of SMT in active assembly/disassembly [Sun et al., 2014]. The SMAs and polymers are discussed in details highlighting their advantages and disadvantages in active disassembly. It is indicated that the recoverable strain, an important criterion in disassembly process, for many polymers, is far superior than SMAs. This can significantly help the designers to proceed with the material selection process in case of using the materials with shape memory effect. Nevertheless, more pragmatic researches are still needed to optimize the programming parameters in order to reach the defined deformation. Figure 3-5 illustrates the disappearance of threads in active disassembly process using poly (methyl methacrylate) (PMMA), as an engineering polymer [Purnawali et al., 2012].

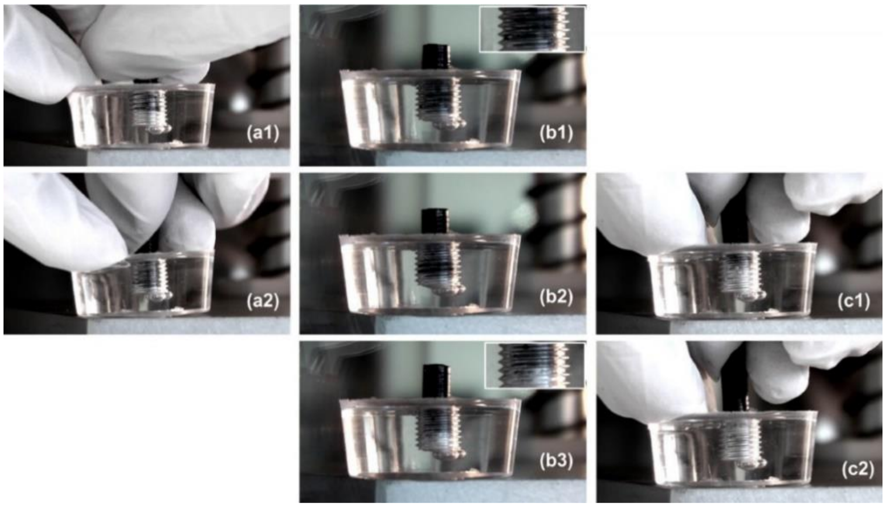


Figure 3-5 Application of PMMA screw. (a) Tightening phase; (b) heating (threads disengagement); and (c) threads disappearance [Purnawali et al., 2012]

Peeters et al., have proposed a new methodology incorporating the Rate of Return (RoR) calculation on investing in active disassembly [Peeters et al., 2015a]. The study included the ecological and economic parameters of the EoL treatment alternatives to determine the RoR. The results indicated the RoR on investment in active fasteners (pressure sensitive snap-fit) to approximate 27%, proving the profitability superiority of investing in active disassembly in an electronic payment terminal. Similarly, a low-cost elastomer-based fastener is developed by Peeters et al. allowing for fast and profitable product disassembly operations [Peeters et al., 2015b]. The air pressure and the external force are used to trigger the disassembly operation. To analyse the disassembly efficiency, 8 recent LCD LED TVs were tested using the active disassembly technic. The results indicated an approximate 70% decrease in the disassembly time.

The active disassembly technics offer new perspectives in product design and life cycle engineering. Nevertheless, their applications are limited to the small electronic devices (e.g., telephones), small fasteners, and polymer and/or plastic materials. In fact, they are still costly and there are much to know about their mechanical performance especially when used in products with high number of connections/joints and fracture-critical applications (e.g., commercial airliners, fighters, rockets, etc.). Moreover, they could not be applicable to the current body of the obsolete products and remain only a solution for future products.

Umeda et al., proposed a semi-destructive disassembly technic using split-lines. This computer-aided design method aims at material extraction in a more efficient way as compared to manual disassembly [Umeda et al., 2015]. The suggested approach uses a selective disassembly pattern to destruct the product into a desired shape. An example of product disassembly using split-lines is presented in Figure 3-6. An overall 58% reduction of the disassembly number of steps (as compared to total disassembly) is reported by the authors.

A similar study is also conducted by Shiraishi et al., where the split-lines are used for partial product dismantling [Shiraishi et al., 2015]. In their work, they used products' geometric model to find the feasible disassembly regions using this technic. The presented concept is of great value due its unique hands-on approach. It can be immediately implemented in product design with the least amount of design changes. Nevertheless, maintenance concerns may be raised and interrupted if the product is intended to be only repaired rather than being destructed (even partially) since the destruction is not reversible.

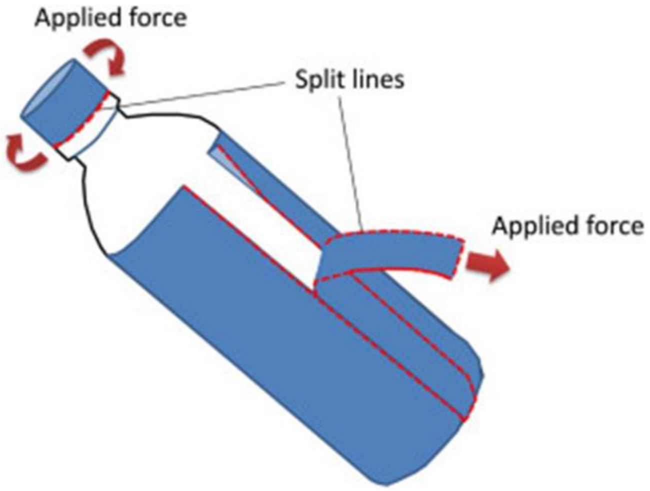


Figure 3-6 Example of the split lines (PET bottle) using the split-lines technic [Umeda et al., 2015]

New concepts like modular disassembly would also be significantly helpful to increase the efficiency of the disassembly process when it is reported that over 30% of disassembly time is dedicated to the searching and positioning of tools [Duflou et al., 2008]. This concept has been proposed in order to securely make use of a large number of tools at disassembly phase for both manual and automated operations. Further details of modular disassembly procedure could be found in researches by Seliger et al. and Duflou et al. in which the relevant technics and available devices are specified [Seliger et al., 2002, Duflou et al., 2008]. The composition of the presented system is illustrated in Figure 3-7.

While automation in several researches have been proposed as a viable solution, the manual disassembly has proved to be the most efficient method to date, according to Opalić et al., [Opalić et al., 2010]. This is due to the following principal reasons: 1- variety of the products and the collected parts to process; and 2- unfavorable design with respect to the disassembly easiness (design-related issues) [Fugger and Schwarz, 1998].

One of the biggest issues in product disassembly is the profitability of the EoL processes. That is why many researches have been initiated in automated product disassembly. Disassembly operations (unlike assembly where the product's added-value and functionalities come together to attain one or several objective(s)), traditionally suffers from the lack of economic interests and/or technological progress, especially at EoL phase. However, despite the grate variation of products with high degree of uncertainties, the process automation may boost the overall operation performance in terms of the cost-effectiveness, time spent, and physical efforts.

Various research attempts have been made in this field some of which trying to propose a fully automated process [Reap and Bras, 2002, Seliger et al., 2002, Kuren, 2006, Torres et al., 2009, Vongbunyong et al., 2013b, Vongbunyong et al., 2012, Merdan et al., 2010, Shuvaev et al., 2012]. The automated disassembly unscrewer is a worth mentioning concept presented by Seliger et al., (see Figure 3-7) in which a new acting surface is generated at the beginning of the disassembly (loosening, handling or fixing process) [Seliger et al., 2001]. This provides an increased flexibility for wide variety of tools. Meanwhile, the remaining difficulties such as: non-uniformity of returned products, significant technical complexities, and laboriousness of the current technics necessitate further studies to be conducted in this domain before being commercially available and productive.

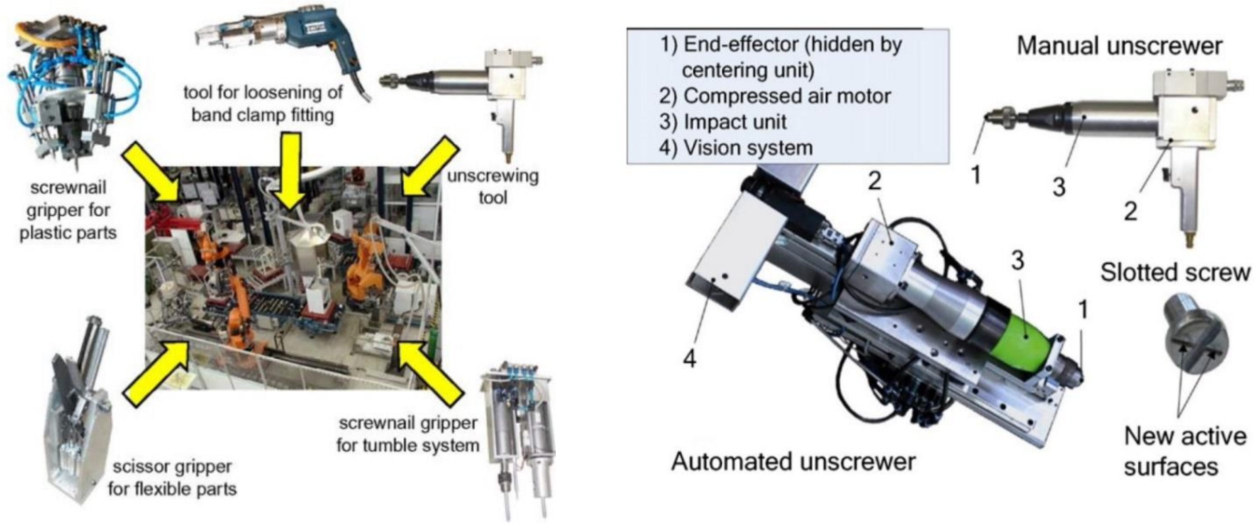
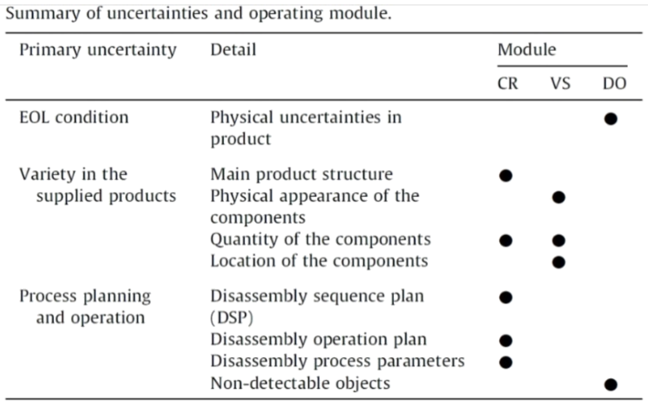


Figure 3-7 Disassembly innovative approaches. Left: Modular disassembly concept [Seliger et al., 2002]; Right: Automated unscrewing system generating new acting surface [Seliger et al., 2001]

Non-destructive automated disassembly, however, remained as an academic topic rather than a practical solution since the expected economic benefits from such operation is easily outbalanced [Duflou et al., 2008]. Nonetheless, according to Vongbungyong et al., by using the semi-destructive technics, high rates of success can be attained without needing complex sensors, multiple tools or complicated calculations to be made [Vongbunyong et al., 2015a]. The automation efforts in this section could be evaluated in terms of: 1- disassembly time; 2- task completion; and 3- the need for human assistance.

Recently, extensive researches have been initiated in cognitive robotics. This is to smooth the issues related to the disassembly inherent problems. These difficulties are namely the unknown geometry, data accessibility issues, large variety of products and material types. In this regard, the vision based and cognitive robotics approaches in EoL disassembly could have considerable potentials due to their abilities of learning and revision process [Vongbunyong et al., 2013a]. This allows for better treatments of unknown geometries, fasteners, and accessibility complications. Vongbungyong et al. proposed an approach in which a combination of model-specific knowledge and learning processes is used to proceed with a fully autonomous disassembly operation. Although a minor human intervention is also observed during the knowledge creation and corrections steps, the operation time is reduced significantly and the process increasingly becomes autonomous through successive learning procedure [Vongbunyong et al., 2015b]. Torres et al. also proposed a cooperative control technique for the robotic-assisted disassembly process resulting in overall disassembly time reduction [Torres et al., 2009]. The Main advantages of this newly presented method are: 1- Autonomy and self-improving capabilities; 2- Tool changing capacities (tool change usually time takes 30% of disassembly total time in manual disassembly, as noted earlier); and 3- The cognitive system is not necessarily dependent on the input data.

A series of LCD screens made by different producers has been subject to disassembly tests using cognitive semi-destructive approach by Vongbungyong et al. [Vongbunyong et al., 2013a]. The results state that the system is able to recognize accurately all cases except one which has been misclassified due to an unsuccessful operation. The system architecture is drawn in Figure 3-8 where CR, VS and DO stand for cognitive robotics, vision system and disassembly operation modules respectively.



Summary of uncertainties and operating module.

Primary uncertainty	Detail	Module		
		CR	VS	DO
EOL condition	Physical uncertainties in product			●
Variety in the supplied products	Main product structure	●		
	Physical appearance of the components		●	
	Quantity of the components	●	●	
	Location of the components		●	
Process planning and operation	Disassembly sequence plan (DSP)	●		
	Disassembly operation plan	●		
	Disassembly process parameters	●		
	Non-detectable objects			●

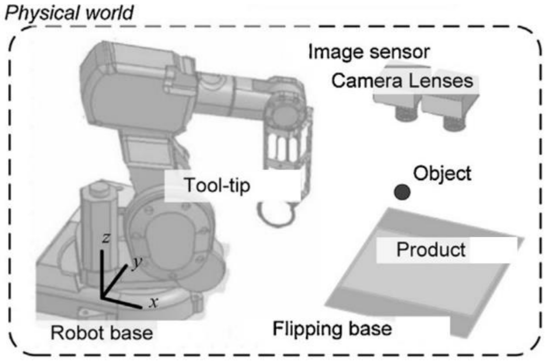


Figure 3-8 Cognitive robotics and disassembly of LCDs proposed by [Vongbunyong et al., 2013a]; Left: summary of uncertainties and operating modules; Right: system architecture

It can be understood from the presented approach that the efficiency of the system relies on the complexity of the part to disassemble. In other words, the more the given part is complex the more the need for human assistance would be. However, it is clearly shown that the semi-destructive approach can offer significant advantages when it comes to the overall disassembly time required (as a driving factor) and the simplicity of operations.

3.3.3 Disassembly planning

Disassembly planning is a key step in EoL treatment and has a crucial linking function between the product EoL and the recycling alterative in product recovery [Duflou et al., 2008]. The literature review indicates that a large number of researches in this field have been dedicated to the study of the disassembly cost, revenue and component clustering. A product can be usually disassembled through various ways, known as “sequence of disassembly unit operations” which has to be determined prior to the physical operation [Lambert, 2007, Gungor and Gupta, 1998]. That being said, an extensive body of research has been created in the past by focusing on disassembly sequencing as well as finding optimal or near-optimal disassembly sequence plan (DSP) [Gungor and Gupta, 1997, Wan and Krishna Gonnuru, 2013, Smith et al., 2012, Kara et al., 2006, Kaebernick et al., 2000].

A DSP is a sequence of disassembly which starts by processing a given product resulting in subassembly(ies) through different methods (e.g., connection graph, direct graph, AND/OR graph, etc.). In this regard, using CAD data, as seen in researches by Mani et al, and Arai and Iwata, is amongst the most classic research topics to evaluate the disassembly process during the design iteration phase [Mani et al., 2001, Arai and Iwata, 1993]. According to Güngör and Gupta, disassembly sequencing of a product can be either a partial or a complete operation [Güngör and Gupta, 2002]. The disassembly precedence tree has been formed fully or partially using geometrical relationship to optimally prioritize the disassembly process in several researches [Zhang and Kuo, 1997, Kuo, 2000, Kuo, 2006a, Tang et al., 2002]. Later on, attempting to seek the highest net revenue, finding the optimal disassembly depth and sequence have been also stressed particularly. Mathematical Programming (MP), heuristic, metaheuristics and artificial intelligence techniques are amongst the most common approaches in this field of research [Willems et al., 2006, Lambert, 2007, Go et al., 2012, Hui et al., 2008, Kalaycılar et al., 2016].

Achilas et al. proposed a decision support tool to determine the optimal depth of product disassembly [Achillas et al., 2013]. The developed model is a mathematical formulation based on cost benefit analysis concept in order to determine the depth of disassembly considering both environmental and economic concerns. This included the minimum recycling, reuse rate, personnel cost and recovered material prices. Seven discrete scenarios have been considered through altering these parameters in order to examine the effectiveness of the proposed approach. Despite the optimization values that this method may offer, it is still not generic and can face difficulties to be used for other products EoL streams. Furthermore, they have not accommodated the disassembly intrinsic factors such as, type of disassembly actions needed to reclaim parts and tool (used into the methodology channel) which may result in partial effectiveness of this approach.

The heuristic methods are still being used widely by researchers to reach promising solutions in a shorter time as compared to other available methods. However, they do not necessarily result in the most optimal solutions. Consequently, their applications are often limited to collect all the good-enough solutions and then let the Mathematical Programming (MP) take steps. Literature is fairly rich on the heuristic applications [Güngör and Gupta, 2002, Langella, 2007, Inderfurth and Langella, 2006]. Güngör and Gupta implemented this method to modify the disassembly line balancing for an intricate product or for a large quantity of products in order to maximize the productivity by optimizing the line balancing [Güngör and Gupta, 2002].

MP applications are broad due to their capacity to find the optimum value when combined with heuristic or metaheuristics methods. Basically, a model containing connection diagram and a set of precedence relationships are needed. Mainly this information is described using AND/OR representation which contains all of the disassembly sequences in a product. Suzuki et al. conducted a research using binary integer linear programming to model the assembly process [Suzuki et al., 1993]. AND/OR graphs are a set of graphical presentation of the subassembly precedence. It is a useful tool when the number of elements in a product is not relatively high.

Various researches have been dedicated to the Artificial Intelligence (AI) applications in disassembly planning and line balancing problem (DLBP) [Avikal et al., 2014, Kalayci et al., 2015, Luo et al., 2016, Go et al., 2012]. Seo et al. developed a heuristic algorithm based on Genetic Algorithm (GA) to solve the disassembly sequence problem with an emphasis on the environmental and economic criteria [Seo et al., 2001]. The GA dynamically explores the disassembly nodes to find the optimal sequence. Hui et al. also implemented GA tool to solve a disassembly sequence plan through finding the optimal sequence based on a feasibility information graph (DFIG) [Hui et al., 2008]. Nonetheless, running a genetically optimized model may become more difficult and time-consuming when the number of connections and mated parts are high. Moreover, selecting a good fitness function and defining the solution space before genetic search space starts are also amongst the most prevalent issues.

As Smith et al. indicated in a research work, some of the noteworthy shortcomings of these models are: increased search time, low model quality and high complexity [Smith et al., 2012]. Besides, the study of relevant literature indicates that an efficient and feasible disassembly sequence can only be obtained if the disassembly operation itself is optimized, planned properly with aims to address the disassembly economy, coordination with the environment and technical feasibility [Go et al., 2012, Yan et al., 2006]. Nonetheless, the overall volume of literature dedicated to the disassembly physical operation is low and there is still much to learn about the subject. The present work in this thesis is intended to help filling this specific gap.

3.4 EoL strategy definition

Defining an appropriate EoL strategy is a crucial step in EoL process of a product. As stated by Rose et al., only through predicting of EoL strategy of products a designer and recycling technology developer can incorporate the "design for environment" into their design [Rose et al., 1998]. Equally, the EoL strategy in almost every research approach until now, is considered as a selection amongst the following operations (i.e., recovery options [Teunter, 2006]): "Material recovery", "Reuse", "Remanufacture" and "disposal" [Rose et al., 2002, Masui et al., 1999, Rose and Stevels, 2001, Rose et al., 2000, Remery et al., 2012]. Rose et al. explains the strategy as the appropriate proportions of "*reuse, remanufacture, material recycling and disposal*" [Rose et al., 1998]. The literature shows that the strategy and scenario have been interchangeably used in this field. They are assigned to the post-evaluation, post-decomposition (i.e., assigning the recovery options) as well as the evaluation/decomposition operations. As indicated in a research conducted by Feldman et al. one can visibly notice that the author assigns the scenario and strategy for the material recovery by addressing "determining the optimal disassembly path" and "evaluation" [Baldwin et al., 1991, Feldmann et al., 1999]. Meanwhile, VerGow and Bras applied three types of scenarios so as to meet the technical goals, material recovery and product recovery, attempting to select amongst the fastening/attaching technics with respect to those scenarios [VerGow and Bras, 1994].

As this forms an important part of the methodology, a survey of the knowledge in this field is presented to establish an understanding of the topic. A worth-noting point is that there are various perspectives in defining strategies in the literature. Teunter has channeled the planning disassembly and recovery operation in three steps as: 1- determining disassembly sequences; 2- determining recovery options and the associated profits for each assembly; and 3- determine the optimal disassembly and recovery strategy [Teunter, 2006].

A number of researches have centered on the second step [Rose et al., 2000, Rose et al., 1998, Masui et al., 1999, Remery et al., 2012]. Amongst the first studies is a research conducted by Rose et al. where they proposed an End of Life Design Advisor (ELDA) [Rose et al., 2000]. It determines the EoL strategy through the selection between EoL treatment alternatives by associating a set of relative numbers (i.e., scores) resulting in a so-called “prediction of end-of-life”. It strives for integration of various factors including the product technology cycle, the physical wear-out time, the reason for redesign and also the level of integration. Once the scores are associated, the respective values of each factor are calculated through referring to the pre-defined tables. Thus, one can easily assign an EoL treatment label for the product (e.g., remanufacturing, material recovery, etc.).

Similarly, Masui et al. gathers a complementary list of analytical parameters (known as product characteristics) with significant influence on the product EoL strategy definition [Masui et al., 1999]. This encompassed several driving factors including the wear-out life, design cycle, replacement life, functional complexity, obsolescence, number of materials, number of parts, number of modules, hazards, size, and recycling factor drivers. The strategy definition phase, in this study, may be more inclusive and can result in a better reflection of real EoL status through determination and incorporation of the broader factors and variables.

Concerning the third step, Modaresi et al. have encouraged two important keynotes for aluminum recycling: 1- enhancing the dismantling as long as the dismantled parts are kept separate from the shredded scrap, as a very useful technic; and 2- fortifying the alloy sorting of mix shredded scrap if the components are too expensive to dismantle [Modaresi et al., 2014]. All presented methods focus on the second step, recovery options and associated profits, while in both academia and industry, there is still a big lack of knowledge in the third step.

3.5 The aviation EoL potentials and methodologies

The disassembly topic, as a whole, is discussed in detail earlier. In this section the potential of the air fleet EoL will be explored highlighting the state-of-the-art academic and industrial uptakes in this field. Processing an aircraft at the end-of-life is a sophisticated issue due to the associated cost, technical difficulties, hazard, national/international burdens, etc. That is why throughout the past few years thousands of aircrafts have been decommissioned and stocked in the desert graveyards. According to the various statistics, almost 12,000 planes will be retired in near-future and an approximate 2,000 are already parked to be disposed [AFRA, 2014a, Towle, 2007]. This even further highlights the importance of finding an appropriate solution to this issue. This has raised significant concerns that are even referred to as an aircraft retirement Tsunami by the rate of 1,000 aircrafts a year within a decade [AFRA, 2014b].

Most of the researches on the EoL processes to date are rather generic approaches. Consequently, they are hardly able to specify the real shortcomings in this sector [Nasr and Thurston, 2006, Hatcher et al., 2011]. Nonetheless, considerable efforts have been made by the aircraft manufacturers (i.e., namely Boeing and Airbus) around the world on boosting the decommissioning and processing of the EoL aircrafts (i.e., AFRA and PAMELA project) [AFRA, 2014a, PAMELA, 2008]. Asmatulu et al. conducted a state of the art research highlighting the AFRA and PAMELA projects [Asmatulu et al., 2013a]. The recent progress in aviation recycling, marketability of the treated aircrafts and the environmental impacts are the key elements covered in this research.

Keivanpour et al. assessed the previous and the current conditions of the aircraft recycling world from a global view [Keivanpour et al., 2013]. The objective of their research was to bring up a strategic conceptual framework in order to discuss the opportunities and barriers within business, market, industry and knowledge sectors. A greater need for the aircraft skeleton disassembly methodologies was clearly highlighted in their research due to its decisive effect on the overall process performance. An analysis of the recycling effort of the local aircraft companies is conducted by Asmatulu et al. where the recycling efficiency and environmental benefits of aircraft EoL process are highlighted [Asmatulu et al., 2013b]. This includes a cradle-to-gate (CTG) life cycle inventory analysis where the current and potential recycling status of EoL aircraft materials (e.g., coated wires, gloves, aluminum, composites, etc.) are discussed in detail. It was shown that the aluminum has the highest actual recycled (kg/yr) and potential recyclable materials (kg/yr) rates, based upon the disassembly of 1765 planes and 1029 major components in Wichita aircraft manufacturing facilities.

Ribeiro and de Oliveira Gomes developed another conceptual framework in which integration of the feedbacks from the different EoL stages are stressed as a decision-support tool [Ribeiro and de

Oliveira Gomes, 2014]. The presented approach is intended to be incorporated directly into the preliminary design phase of the aircrafts. They highlighted the EoL distinct alternatives namely remanufacturing, recycling, reuse and disposal from which the feedbacks would come to facilitate the decision-making process. Nevertheless, no emphasis was put upon the technical evaluation of the disassembly efforts. A more innovative methodology is developed by Camelot et al. where disassembly of the aircraft reusable parts is optimised through arranging the maintenance task [Camelot et al., 2013]. The model consists of non-destructive disassembly works with respect to the manufacturers standard documentations given in the Aircraft Maintenance Manual (AMM).

Feldhusen et al. assessed and presented the analogy between EoL approaches commonly used by the naval, railway and automobile practitioners in comparison with the aeronautic sector [Feldhusen et al., 2011]. An overview of some of the well-known projects in this sector (e.g., Pamela and AFRA) was also presented to analyze the existing research projects. The economic and ecological driving forces are evaluated, and eventually an analogy between automotive EoL practice regime and aeronautics has been bolded. Meanwhile, no further discussions have been made upon the fundamentally different disassembly nature of the airframe and the automotive structure, although some post-process operations such as shredding and separation might resemble.

In attempt to proceed with a more inclusive research, Mascle et al. presented a general method to dispose of and improve profitability of the aircraft rebirth process [Mascle et al., 2015]. It incorporates a step-to-step methodology where generated data from the existing data base (of a decommissioned aircraft or the current aircraft EoL projects) is used to find the best dismantling sequence for a given strategy. The proposed methodology included the identification of the systematic parameters with significant influence on dismantling strategy, finding the best approaches to sort out the recycled grade aluminum and the development of a decision support system to find the best strategies.

The term “rebirth” was suggested by Mascle in a separate study dedicated to the sustainability improvement of products [Mascle, 2013]. In this new terminology, the rebirth, as a new feature, encapsulates the social aspects such as skills and human capacities, continuing education and retaining. One of the most neglected, and of course vital aspects of the disassembly process is the economic dimension. The methodology proposed in his work is more flexible since it allows predefining characteristics based on the defined objectives.

It is quite apparent from the literature that the airframe disassembly has received only scant attention by scholars, particularly when it comes to the technical analysis including the real disassembly works. This obviously reflects a knowledge gap in the field of product disassembly, thus further empirical researches will have direct and practical implications on the whole topic.

3.6 Recycling of aerospace materials

The CRIAQ ENV-412 project (Process for Advanced Management and Technologies of Aircraft End-of-Life) proved that one of the most neglected parts of the airframe EoL is the material recycling. According to the real dismantling works, the disassembly operations has to be customized based on the capabilities and the available technologies of the recycling facilities or the quality of the recovered materials would be incomparable. There are several notable challenges in this fields including hazards, toxic materials and the issues related to the impurities. According to Das et al., the cost-effective recycling of the airframe alloys is complex due the existence of: 1- high levels of alloying elements (e.g., Cu and Zn in 2xxx and 7xxx series respectively); and 2- low levels of minor elements to increase the fracture toughness (i.e., to comply with the aerospace application requirements) [Das et al., 2010]. The complementary information on the current and future trends of aluminum recycling may be found in a separate research by Das [Das, 2006]. Several works have been initiated around the globe within the industry-based projects such as AFRA, PAMELA, and ENV-412 to boost the aircraft EoL processes. Nevertheless, it is fairly clear that the literature has very little to say about the recycling of aircraft materials particularly the aerospace-grade aluminum.

The literature pertaining to this topic is concerned with the study of metallic and non-metallic materials. According to Kundu, the composite materials may be used as secondary and tertiary structures due to the safety reasons [Kundu, 2010]. Nonetheless, as technology evolves, more composite materials are used in the primary structure. That is why, the composite recycling is also gaining momentum specially when, according to Carberry, the recycling of carbon fiber can be done at 70% of the cost while requiring less than five percent of electricity (as compared to the original new carbon fiber) [Carberry, 2008]. An extensive state-of-the-art study in the field can be found in a research by Yang et al. where several topics are covered including: an overview of the composite recycling technologies, sector-based analysis of the composite recycling and the study of the relevant challenges [Yang et al., 2012]. Pimenta and Pinho have also conducted a solid review of the carbon fiber recycling technologies for structural applications [Pimenta and Pinho, 2011]. According to their study, the recycling process of composites is a complicated process due to the complex composition, the linkage of thermoset resins and their combination with different materials in a structure.

As stated by, Kundu, aluminum alloys, forming the main element of the aircraft structure, is still the most dominant material in airframe [Kundu, 2010]. The following table shows the percentage mass of types of materials for Boing 777 and 747 aircrafts, as noted by Kundu, indicating the dominance of aluminum in airframe EoL.

Table 3-3 The percentage mass of the materials in Boeing 747 and 777 aircrafts [Kundu, 2010]

Material	**Boeing 747**	**Boeing 777**
Aluminum alloys	81	70
Steel alloys	13	11
Titanium alloys	4	7
Composites (various types)	1	11
Other	1	1

An environmental assessment tool is presented by Paraskevas et al. aiming at improving the secondary aluminum production through sustainable management of the metal resources [Paraskevas et al., 2015]. This is an innovative study with significant impacts on the output material quality. They have incorporated the Al scrap contaminations (i.e., alloying elements and impurities) in a decision making support system to highlight the essential role of quality degradation and delusion loses in metal recycling process. Das et al. explained the Al recycling challenge through highlighting the difficulties associated with controlling the iron and silicon element levels [Das et al., 2007]. This is especially troublemaking in the aerospace sector demanding exceptionally high ductility and toughness. Their results indicated several problems in Al reuse if significant measures are not taken in disassembly and presorting operations.

Prendeville et al. have stressed the material selection process in their study where the product eco-efficiency is emphasized through highlighting the key role of stakeholders' decision makings and partnerships [Prendeville et al., 2014]. In their approach, a classification is presented to develop a material typology including additional materials to reduce the environmental impacts. This arrangement along with the eco-design strategies and trade-offs help boosting the eco-efficient material selection process. A more specific research on how to separate the waste metal layers of the aircraft wings (i.e., aluminum) have been conducted by [Benyahia and Hausler, 2016]. An improved separation process was achieved through the application of an electrochemical process and hydrochloric acid. The environmental impact analysis of the aerospace alloy recycling was subject of a research by Eckelman et al. [Eckelman et al., 2014]. It is shown that a significant reduction of greenhouse gas GHG could be reached through recycling of aerospace materials, as a substitution for virgin materials. Meanwhile, Lerma et al. has conducted a valuable research striving to boost recycling of aerospace alloys through improving the decoating process [Lerma et al., 2016]. This is particularly important since coating impurities are one of the most fundamental challenges in airframe post-disassembly processes. Their work presented new methods on decoating the aerospace-grade aluminum as a preparation phase for an improved-recycling process. The literature in this field suggests that presorting the alloys would help maximizing the value of recovery elements in aircraft EoL treatment.

3.7 Summary

The results of the systematic literature review suggest that there is a significant knowledge gap and methodological weakness in disassembly of complex metallic structures. It has been equally noticed that there is a huge research potential in various areas particularly in disassembly performance evaluation. The study of relevant literature in this field indicates that:

- Disassembly process is a pivot stage that can determine: the ideal EoL strategies, the competitiveness of ecologically preferred scenarios, and the quality of the recovered materials in EoL process;
- It is shown that the applications of the semi-destructive disassembly have grown significantly due to its advantages over the other methods;
- No known empirical research has focused on exploring the fundamentals and performance analysis of the semi-destructive disassembly;

- The few previous studies ignored the key role of presorting dismantling in defining the convenient disassembly strategies, despite of its significant impact on the out material quality;
- No research effort has been directed to the multiple criteria disassembly analysis (technical, economic and environmental variables).

These topics, as essential steps towards an efficient disassembly process, forms the body of this thesis. The findings should make an important contribution to the field of product disassembly and spark further researches in this field.

CHAPTER 4 ARTICLE 1: A CONCEPTUAL FRAMEWORK TOWARD ADVANCED AIRCRAFT END-OF-LIFE TREATMENT USING PRODUCT AND PROCESS FEATURES

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Abstract

The process of treating an aircraft at the end-of-life (EoL) has caused an increasing concern during the recent years. While an aircraft EoL maintains a considerable amount of value, it suffers from various environmental and economic shortcomings. High amounts of leftovers, difficulties associated with handling of the dangerous materials and low quality of the recycled materials are the common related problems. Meanwhile, with the increasing number of manufactured and retired aircrafts each year, there is a need for a disassembly-based EoL framework. In this research, this has been looked at from a conceptual point of view with an initiative aim to increase the added-value associated with the disassembly process while reducing the environmental footprints.

Keywords: Aircraft disassembling and dismantling, Aircraft structure disassembly assessment, Disassembly-planning, Disassembly performance and efficiency.

4.1 Introduction

Recent legislative obligations on landfill as well as incineration besides growing natural resources depletion and energy challenges call for a modernized design philosophy providing new insights into the end-of-life (EoL) process of products. Product traditional EoL treatments as a generic approach to apply to a broad type of products are no longer environmentally benign or economically viable or even technically feasible. Disassembly of a product, amongst the first steps to proceed with EoL treatment has got an increasing interest during recent years. However, a blind application of such operation would result in an absolute waste of energy, time, and money.

Processing an aircraft at the end-of-life is a sophisticated issue due to the associated cost, hazard, and national/international burdens. That is why during the past few years thousands of aircrafts are decommissioned and stocked massively in the desert graveyards. A brief look at the approximate 2,000 aircrafts parked to be disposed of plus the upcoming roughly 12,000 planes (a considerable number of military aircrafts are also to be added to the previous statistics) that will come to the retirement phase in near-future appears to be an even more urgent issue to be dealt with today [AFRA, 2014a, Towle, 2007]. This has raised significant concerns that are even referred to it as an aircraft retirement Tsunami by the rate of 1,000 aircrafts a year within a decade [AFRA, 2014b].

It is also remarkable that an aircraft having been stocked in a graveyard for a long period has considerably less value than an obsolete, but-still-in-service one. In other words, such an old aircraft still loses its value although having been retired from the service (i.e., the end-of-life period) for each day it is stocked. This can even further complicate the problem representing an urge for a dynamic and flexible approach to be introduced in the domain.

End-of-Life treatment of products is relatively a complex multi-disciplinary challenge. Different spectrum of products along with the various design roots has made this issue even more sophisticated. With this in our mind, deconstruction has been selected during the decades to get rid of the retired aircrafts. Nonetheless, treating an aircraft at this phase using the traditional methods consisting of solely an unorganized crushing and scrapping its structure (i.e., destructive) is neither economically viable nor environmentally sound. On the other hand, total disassembly of a structure (i.e., non-destructive) is not a smart action either since it has recently been revealed that a complete disassembly of a given case study resulted in only 30% of material recovery [Kondo et al., 2001]. That is why many airlines decide to keep their withdrawn aircrafts in storage rather than breaking them up for spare parts [Horwitz, 2007]. This also indicates that the associated processes are often strongly governed by the economic consideration [Chen et al., 1993].

With the products maintaining a higher complexity levels such as airplanes, the ambiguity of the current trends starts glaring even more.

Therefore, it is highly desired to define a convenient method addressing the real issues related to EoL process of the complex aircraft structure. This necessitates a better understanding of the key elements in order to define the appropriate disassembly strategies. By incorporating the environmental, economic and social attributes, the framework picks up a sustainable approach to proceeds with closed-loop aircrafts and materials. This provides considerably higher added value associated with the EoL processes through consideration near-future/future requirements.

4.2 Scope of research

At the core of these subjects lays disassembly, which is known as a key issue in product EoL assessment. High degree of flexibility, product unknown geometry, and profitability are amongst the most challenging concerns to be dealt with.

Literature indicates that design and careful selection of a connection between mating parts in a design is equally as important as a design of the parts. Indeed, most of the disassembly time and effort is driven by the disjoining and unfastening operation which means the major problems maintain in the separation of the joints. On the other hand, a lack of a solid research body on the process evaluation, strategy, and planning cause a significant loss of economic and ecological sources which can consequently make the process a totally low-added-value procedure [Wiendahl et al., 1999]. These shortcomings have made both the manufacturers and stakeholders reluctant to further invest in this field. On the other hand, new legislation such as EU directives makes it without any doubt that new EoL strategies should be defined [Ferrao et al., 2006]. This becomes even more sophisticated when considering end-of-life disparities in Europe, Japan, and United States [Bok et al., 1998].

It has also been revealed that the different EoL treatment scenarios and strategies can have considerable impacts on the EoL performance of a product. The lack of a flexible analytical system, the product design drawbacks and also the ineffective fastener/joining tools make the disassembly process, as an essential step to close loop products, economically, environmentally, and socially unsound. In order to realize the product optimal EoL treatment with such above-mentioned challenges, a new framework serving as a treatment map is proposed to proceed with product comprehensive analysis and determining the efficient EoL pathway.

This framework makes use of the partially destructive process (semi-destructive) processes to proceed with the disassembly operation. It should also be noted that temporary fasteners (usually used to provide clamp-up and hold the parts together temporarily during the product assembly stage) will not be covered due to their application limitations. The post-disassembly operations, also, are considered to be outwith the scope of this research.

This approach tends to contribute to the raise of the EoL procedure efficiency. It is based upon the analysis of an aircraft structure by virtue of the real inspection, disassembly and dismantling operations, as a primary objective, and culminates a set of disassembly operation design improvements as a final objective. The process includes the identification, and formulation of the relevant parameters and arranges them according to the defined strategies.

4.3 Literature review

4.3.1 Aircraft EoL industrial initiatives

The study of the literature indicates that most of the researches on the EoL processes to date are generic approaches, and consequently are unable to specify the real shortcomings in this sector [Nasr and Thurston, 2006, Hatcher et al., 2011]. Nonetheless, the major aircraft manufacturers around the world (i.e., namely Boeing and Airbus) have pushed further investigations on boosting the decommissioning and processing of the EoL aircrafts (i.e., AFRA and PAMELA project) [AFRA, 2014a, PAMELA, 2008].

4.3.2 Current status of the aircraft EoL frameworks

Asmatulu et al., conducted a state of the art research highlighting the above-mentioned projects [Asmatulu et al., 2013a]. Recent progress in aviation recycling, marketability of the treated aircrafts and the environmental impacts are the key elements covered in this research.

As far as the definition of a conceptual framework concerned and with respect to the aeronautic EoL treatment, the body of literature is relatively narrow. Keivanpour et al., evaluated the previous and current states of the aircraft recycling world from a global view [Keivanpour et al., 2013]. They tried to bring up a strategic conceptual framework through which opportunities and barriers within business, market, industry and knowledge sectors are discussed. The authors in this research highlighted a greater need for the aircraft skeleton disassembly methodologies. Although it has a decisive effect on the whole process performance, this topic has been left barely touched in this field.

Ribeiro and de Oliveira Gomes developed another conceptual framework in which integration of the feedbacks from the different EoL stages are stressed as a decision-support tool to be incorporated directly into the preliminary design phase of the aircrafts [Ribeiro and de Oliveira Gomes, 2014]. They highlighted specifically the alternatives such as remanufacturing, recycling, reuse and disposal. The feedbacks coming from these EoL alternatives would then facilitate the decision-making process. Nevertheless, this has far to be seen as a strong conceptual framework if no emphasis is put upon the technical evaluation of the disassembly efforts.

Feldhusen et al. in [Feldhusen et al., 2011] highlighted the analogy between EoL approaches in naval, railway and automobile processes as compared with the aeronautic sector. Pamela and AFRA related works, as some of the well-known projects in this sector, are also discussed in detail. The analogy between automotive and aerospace EoL procedure has explicitly been bolded through the evaluation of the economic and ecological driving forces. Meanwhile, despite some similarities between the post-disassembly operations such as shredding, separation etc., no emphasis was put upon the fundamentally different nature of the airframe and the automotive structure disassembly operations.

It is pretty apparent that the literature dedicated to the technical disassembly of the airframes has very little to say and further solid researches will definitely have direct and practical implications on this topic.

4.4 Methodology

Literature indicates that the efforts concerning EoL treatment are mostly summarized into the universal study of “product analysis” as well as the selections between a set of recovery strategies. However, disassembly per se, as the most prominent process in EoL, is technically untouched. At the core of the disassembly process lays process analysis. The proposed methodology takes an enabling approach through incorporating both process and product features to alleviate the problems related to the evaluation of the disassembly process as an uncertain operation.

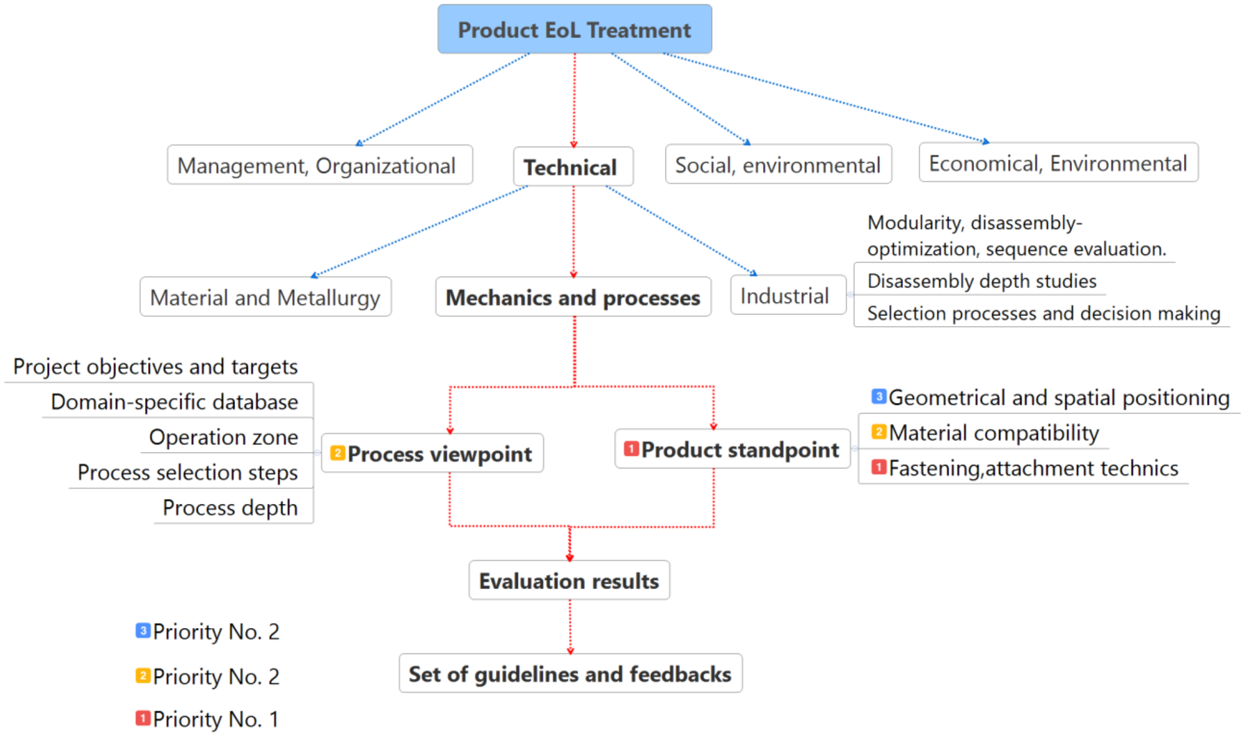

Figure 4-1 Aircraft end-of-life treatment within product and process related frameworks

As it is shown in the Figure 4-1, the product and process related features have been separated. This will help increasing the versatility of the methodology through dividing the problems of different natures, and then dealing with them in separate channels.

Product Analysis: it addresses the product evaluation process with regard to three principal aspects: geometrical, material compatibility and fastening/attachment technics. Product analysis has a key role in the proposed approach since the EoL scenario definition is based on the data coming from the product and process related features.

Process analysis: Once the product is evaluated and the gathered data is analyzed, the process features such as elapsed time associated with each technic is set. Then the scenarios (i.e., process setups) should be generated. The process features have a considerable advantage of being manageable at the EoL stage. These fundamental features will answer the following questions:

- What part/module of the product should be selected to be disassembled first (mainly in case of the complex products where disassembly could be started in different places/modules)?
- Once the place is fixed, what kind of operation should the product undergo explicitly?

- To what depth a part/module should be disassembled (destructive methods or not) to attain the best results?

- Once a part/module is disassembled to a given depth, what sort of post-disassembly operation is the best choice (e.g., shredding, landfill, incineration etc.)?

4.5 Framework

It is of a great importance that the framework be able to incorporate both the process and the product related features in order to process the EoL airframe. In other words, it is to contain a series of actions being prioritized and followed by the practitioners.

The Figure 4-2 presents the EoL treatment procedure integrated into the disassembly framework. The legislative, environmental, and economic metrics are incorporated early in the processing structure influencing the decision making process. This determines whether or not allowing for proceeding with further disassembly operations (depth of disassembly).

The first step in decommissioning process (when the aircraft is parked within the disassembly site) is to remove and carefully handle the dangerous materials. Then, according to a set of legislative, technical, environmental, and economic metrics a premature general strategic disassembly planning is made.

This planning incorporates a set of key decisions (made by the technical domain specialists) followed by the physical disassembly operations. These primary decisions here may define a sketchy frame of the disassembly which highly depends on the aircraft age, airframe size, structure details, manufacturer, production date, after-market values, etc. Legislatives may also apply certain rules depending on the local policies, which could consequently have an impact on the decision making process significantly. The aircraft undergoes an economic evaluation process to bring about certain decisions which, later on, directly affect the scenario proposition procedure (i.e., disassembly place, methods, and depth).

As further disassembly carries out, a scenario and strategy definition phase has to be proceeded with, as accommodated into the process channel. A set of documentation data (which is already prepared) is formulated into a series of process variables (gathered all into the process database). Keeping in mind that the database contains the process variables, four fundamental questions as listed previously would be answered.

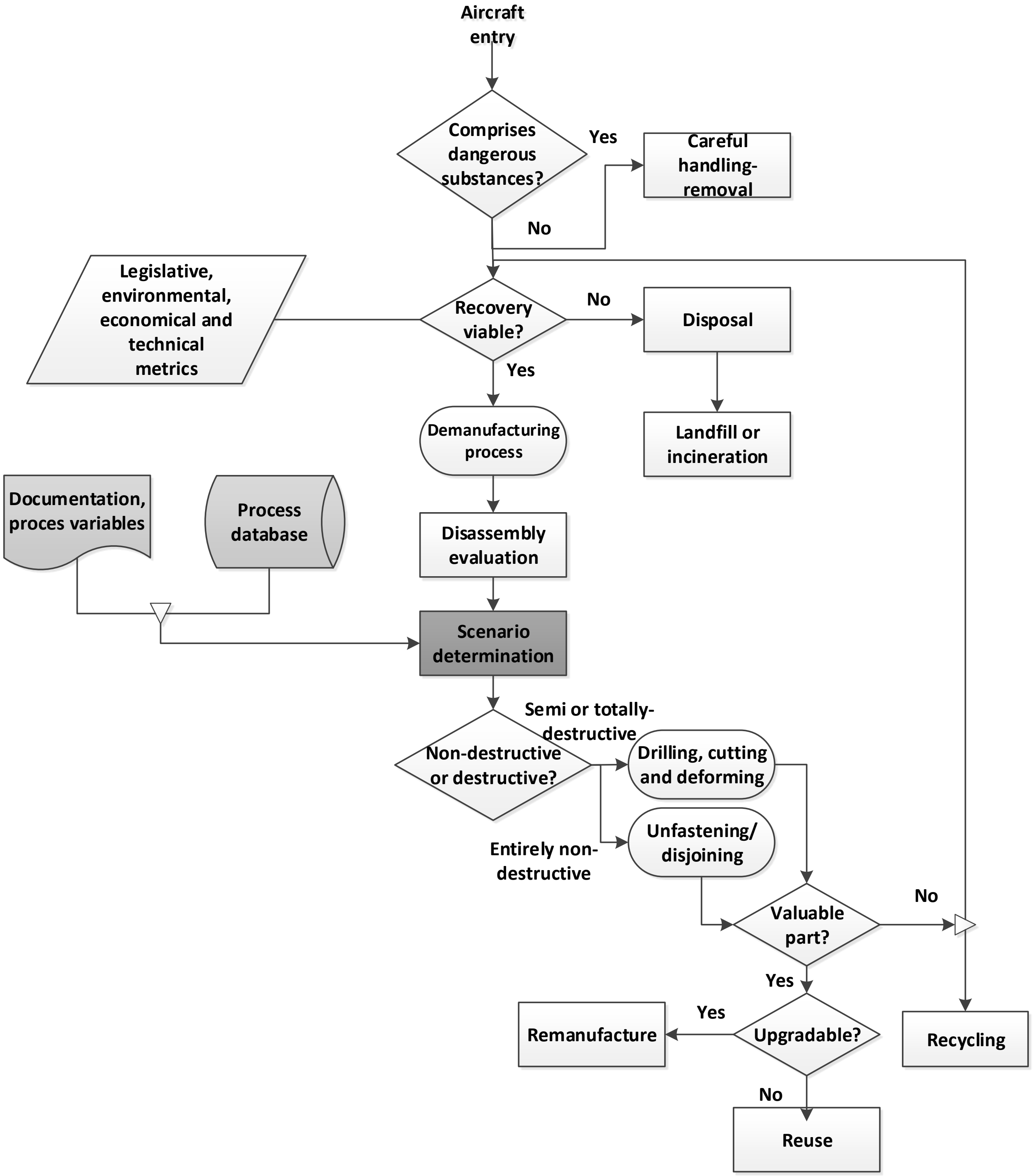

Figure 4-2 System architecture proposal of an aircraft end-of-life disassembly framework

4.6 Contributions to the design for disassembly

The EoL process is not explainable without discussing the Design for X concept as a part of the concurrent engineering. As the term “x” may suggest, there are many product design attributes depending on the selected design methodology. Here by X may refer to the disassembly, remanufacturing, environment, eco-design, end-of-life, upgrade, sustainability and/or recycling.

Furthermore, researches show that only 10-20% of all disassembly gains could be reached by optimizing the disassembly work, while 80-90% of the gain would be attained solely when the product is at the design phase [Desai and Mital, 2003].

Therefore, these design guides, under form of design for x, are the key strategies in a broader meaning for the sustainable development. Our findings indicate that the design strategies based on these attributes are more enabling and feasible than those without them. These designs for x are holistic tools to communicate the problems to the designers in order to incorporate new findings and directives into their design procedure paving the way for more sustainable products.

Figure 4-3 depicts how information sharing at the EoL phase could contribute to the formation of the new metrics, and as a result, would help the designers assess the aircraft at the very early stage of design. This will improve the versatility of the design for x concept since the results associated with each system configuration is compared and interpreted accordingly.

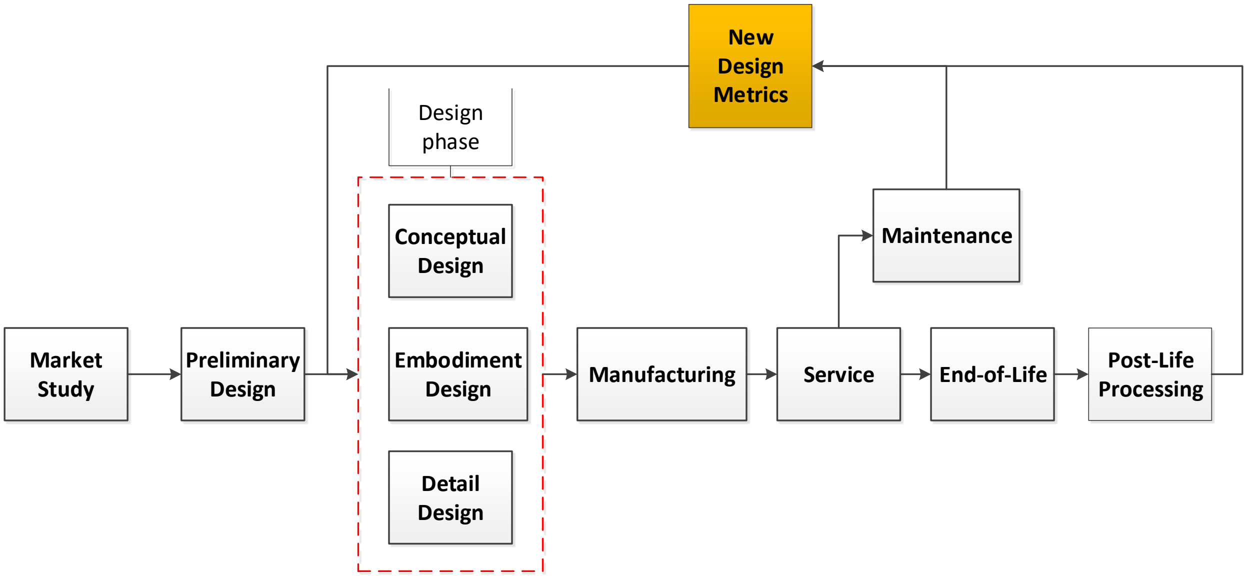

Figure 4-3 Communication linking between EoL phase (practitioners, disassembler, organizer etc.) and the designers

4.7 Summary

This study gives an in-depth insight into the issues related to the process and recovery operations of the aircraft as a complex product (with a particular look at the commercial airliners). Fundamental elements of an EoL treatment have been discussed and channeled into two principal separate categories as process-related and product-related features. Once the very first evaluation of the aircraft is carried out, a database is created based on the defined attributes which will be used to set a series of process variables. These variables will configure the operations set-up. This results in a more versatile methodology facilitating the decommissioning of an aircraft through helping:

1. The designers in order to better evaluate their products prior to the production phase;
2. The recyclers to better process an airframe before carrying out the physical operation. This may have a significant impact on the net profit and the simplicity of the corresponding operations.

4.8 Future researches

Aircraft processing at the end-of-life is a growing topic. Different researches around the world have been initiated or underway on a broad range of subjects, amongst which Life Cycle Assessment (LCA), marketability, disassembly sequencing and optimization have attracted the most interest. However, practical implications especially to the complex products have been so little. Researches are encouraged to deepen the study of materials, connection types and geometric features of the complex structures at the design stage since they are fundamental elements to increase the efficiency of the EoL disassembly once the product reaches the EoL stage.

4.9 Acknowledgements

This paper has been prepared within the CRIAQ ENV-412 project at École Polytechnique de Montréal. The authors would like to thank NSERC, CRIAQ, NanoQuébec, Bombardier Aerospace, Bell Helicopter, Sotrem-Maltech, Aluminerie Alouette, BFI as well as the other partners for funding the project.

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CHAPTER 5 ARTICLE 2: ADVANCED AIRFRAME DISASSEMBLY ALTERNATIVES; AN ATTEMPT TO INCREASE THE AFTERLIFE VALUE

H. Zahedi, C. Mascle, P. Baptiste - 1*3th Global Conference on Sustainable Manufacturing – Decoupling Growth from Resource Use*, vol. 40, pp. 168-173. (2016) – Elsevier

Abstract

End-of-life (EoL) related directives have got a unique position in the design philosophy of almost every competitive product in the market. However, compared to the neighbouring domains (i.e., automotive and electronics), aviation EoL evolvements are seen marginal up to the present. In the present paper, a new systematic airframe disassembly is designed incorporating a set of destructivity-variable operations in order to disassemble a carcass to a defined depth. The improvements and the aptitudes are highlighted compared to the traditional methods. Meanwhile, the so-called "disassembly alternatives" are presented and tested on a real jet airliner carcass (40-50 seats). An analysis of the feasibility with respect to the practicality degree is carried on. It is shown that substantial profit is attainable; the dismantling becomes more organized and the associated performance of each airframe disassembly sequence significantly increased with regard to the defined performance indexes.

5.1 Introduction

Today's product design process is increasingly inspired by the sustainable standards. A brief look at the strict European end-of-life vehicle directives (see European commission environmental regulations) besides the aircraft manufacturers such as Boeing and Airbus initiations (i.e., AFRA and PAMELA) supports this global notion. Manufacturers try to incorporate environmental attributes in their design procedures. The closed-loop production system and the post-use product provisions are made before the parts meet the production lines. Ecological perspective and legislative mandates also take their places in both Original Equipment Manufacturer (OEM) manufacturers as well as societies. It is in such environment that the End-of-Life (hereinafter called EoL) of products takes on an even greater importance to proceed with sustainable production. However, EoL technological advances are not the same in every field. Unlike automotive industry, where part recycling has been successfully commercialized, aviation EoL still encounters important challenges. The increasing number of the retired aircrafts, each containing noticeable amount of potentially hazardous materials (such as explosives, flammables, chromate coatings, etc.), lack of well-structured regulations and unfitted methods call for new solutions in aviation EoL processes. Statistics indicate that around 12,000 aircrafts will come to the retirement phase within the next two decades [AFRA, 2014a]. A nearly 8,450 aircrafts have also been reported by Airbus to be retired from 2009 to 2028 [Van Heerden and Curran, 2011]. While these are mostly published by western organizations and companies, a considerable number of the obsolete aircrafts (mostly manufactured in the soviet-union) in eastern European countries is not hard to expect. In this regard, the aforementioned challenges can be mostly channeled into: 1- ecological; 2- economic; and 3- technical categories. Our findings based upon a real airliner carcass dismantling, however, indicate that the technical parameters have a more decisive impact on the EoL treatment of a product. This is due to the fact that even both of the ecological and economic status of an airframe dismantling can be driven by the technical specifications. Here by the term “technical” we mean the real performance of the operations either in dismantling and/or post-dismantling until the part/module is safely recycled or given rebirth. In this research, we present a pre-sort-embedded systematic dismantling of an airframe. Besides, a classification of the existing dismantling methods, their advantages and disadvantages with regard to the aviation disassembly requirements is also highlighted. Thanks to the selected disassembly pathway based on the material cartography of the parts, a pre-sorted dismantling operation is done successfully. Then, the most enabling alternative in terms of the spent time and profitability is selected to proceed with an efficient dismantling. The importance of this approach is that quite well-sorted scraps and/or parts are recoverable through easier, faster and more organized set of operations. Operators can select the best available method (or a set of methods) to proceed with the dismantling work with respect to the defined strategy. This can be done prior to the disassembly physical work(s) and is a favorable tool destined to both aircraft manufacturer and disassembly organizer/practitioners at disassembly sites to perform EoL dismantling efficiently.

5.2 Previous studies

The aircraft EoL treatment process may be studied from various perspectives since it is a multidisciplinary problem. It principally involves the decontamination, removing valuable parts, airframe dismantling and reuse, valorized and/or non-recovered wastes. Meanwhile, to establish an understanding of the topic and assemble the current body of the literature, we would rather concentrate on the technical aspects following a highlight of the current statues of the aviation EoL.

5.2.1 Aviation EoL status

Today, aircraft retirement is subjected to the further academic and industry researches. The industry, however, was quite more active in this field. Different projects and programs (i.e., PAMELA by airbus and AFRA by Boeing) have been initiated by the manufacturers and their industrial partners [AFRA, 2014a, PAMELA, 2008]. Other active companies dealing with the spare part services, having acquired expertise in the topic, also shared their knowledge with the manufacturer to help boosting the aircraft EoL treatment. In the meantime, the academic counterparts also initiated various research projects to tackle the problem from different channels. From the conceptual point of view, the authors in [Ribeiro and de Oliveira Gomes, 2014] proposed a decision support framework in order to integrate the gathered feedbacks from the EoL stages to the design phase of the aircrafts. This, as a key step where the materials are selected, would help to facilitate the aircraft EoL treatment. However, the technical aspects of disassembly besides the evaluation scenarios could be further explained since, together, they form an imperative part of their methodology. A strategic conceptual framework is also proposed by Keivanpour et al., where the multidimensional and collaborative opportunities and barriers have been stressed from the business, market, industry and knowledge sector perspectives [Keivanpour et al., 2013]. A global research of the state of the art in the aircraft EoL has been done by Asmatulu et al., [Asmatulu et al., 2013a]. The environmental benefits associated with recycling and reusing the components is highlighted in their work. Evaluations are also made for the components to brighten opportunities and difficulties with respect to the recycling and/or reuse alternatives selection. The authors in [Asmatulu et al., 2013b] also did an in-depth study within the post-dismantling sector through dealing with the real technical issues in this field. They have evaluated the recycling effort of the aircraft EoL from the recycling efficiency rate as well as the environmental standpoint. The researchers in [Feldhusen et al., 2011] determined the analogies between automobile, railroad, naval and the aviation sector underlying the challenges in aircraft EoL treatment process. The economic and ecological driving factors associated with the EoL process are also addressed in this work. Besides, the necessity of maintaining a balance between the economic and environmental forces is also bolded. A profitable rebirthing process has been proposed in [Mascle et al., 2015] to help designing easier-to-dispose aircrafts of the current and future generations. It involves detailed study of the BOM, identification of the dismantling parameters, defining dismantling strategies, a decision support system to select the best strategies and also finding the best dismantling sequence.

5.2.2 Disassembly effort assessment

A fundamentally important parameter in proceeding with a cost-effective discard of a carcass is to determine the effort associated with each disassembly process. In other words, a relatively "difficult operation" ought to be performed only if it is well rationalized. Most of the time, a demanding disassembly process also necessitates engagement of a higher skillful practitioner which has an extra impact on the final operation cost. An extensive research in the literature revealed that very little works have been done in this field. While, the totally-destructive and semi-destructive operations have been left barely touched, some efforts have been done in non-destructive level. A quantitative evaluation of the disassembly has been proposed in [Kroll and Hanft, 1998]. It is based upon assigning the difficulty scores to the tasks printed on spread-sheet-like charts. It is applicable to the relatively small products undergoing the disassembly process by a seated person. A similar approach including the "use of force", "mechanism of disassembly", and the "use of tools", as a time-based approach, is also presented by Desai and Mital [Desai and Mital, 2003]. Sonnenberg did proposed an innovative approach based on the extensive study of the fasteners [Sonnenberg, 2001]. He has introduced an unfastening calculation concept known as "U-effort" model to evaluate the disassembly easiness of a product at the design stage. This model picks up a quantitative evaluative approach incorporating the geometry, shape of the fastener as well as the condition of use in the design procedure to assess the unfastening effort.

5.2.3 Disassembly process planning (DPP)

Due to the extensive number of sub-structures, disassembly of a complex structure may become a demanding issue. This is especially true as the number of disassembly sequence may grow exponentially. Thus, an optimized disassembly process planning (DPP), can lead to an optimal EoL procedure from the cost and environmental perspectives. Many researches have been conducted on Disassembly Sequence Planning (DSP) in order to find the optimal/near-optimal solutions [Kaebernick et al., 2000, Kara et al., 2006, Wan and Krishna Gonnuru, 2013, Smith and Chen, 2011, Xia et al., 2014]. A DSP is a sequence of disassembly which starts by a product and finishes by a subassembly based on connection graph, direct graph, AND/OR graph, etc. Nonetheless, in order to generate a feasible disassembly sequence for an airframe, a sufficient accessibility to the aircraft maintenance documents or CAD files are seen inevitable [Mani et al., 2001]. The geometrical relationships have also been used to form the disassembly precedence trees in order to prioritize the disassembly operations in some researches of this field [Kuo, 2006b, Tang et al., 2002]. It is apparent from the literature review that, a few researches have extensively focused on the impact caused by the selection of the different airframe EoL alternatives on the disassembly performance.

5.3 Systematic Airframe EoL Disassembly

Cutting operations (Cut.): The process of dividing a part's surface into two separate sub-sections through exertion of an external force (e.g., cutting wheel and oxy-fuel cutting). The force could be exerted using either hands or any other external power sources (e.g., electricity, pneumatics, hydraulics, etc.)

Deep drilling operations (D.dr.): To create a hole in a jointed surface(s) of parts/module(s) or fastener(s) in order to eventually unfasten or even ease (by creating a starter guiding bit) the disjoining process. This is a practically fast, or in some cases, the only alternative in order for the practitioners to disassemble the parts/modules non-destructively. It should also be noted that due to the type of fastening/attachments used in aerospace sector, there might be resemblance between drilling and manual disassembly. Nonetheless, a part/module is to be labled manually disassembled only when it includes only the safe (a non-destructive) dismounting. In other words, removing a rivet by drilling through the head and the shank until it comes off, is rather a drilling operation than manual disassembly.

Minor drilling operations (M.dr.): It refers to make a shallow hole in the two mated-surfaces and/or fastener(s) in order to disassemble the parts/module(s). Beginning with drilling, a secondary operation is also necessary to remove the fastener. It could be done using a metal pry bar, crowbar or any other methods to make a gap between two mated-parts and even removing the head of a fastener off by a grinding wheel or a chisel.

Manual disassembly (Manual dis.): It is the act of taking a module apart without causing any damage to the fastener(s) or part(s) in a way that both part(s) and fastener(s) remain reusable and assemblable. It constitutes various steps such as part(s)/fasteners localization, tool selection, approaching, exerting the force and grasping the part(s).

The performance of the disassembly operations may be evaluated from the criteria that follow.

Operation speed: Disassembly speed is a decisive criterion affecting the total disassembly time and the final net profit. It depends upon various factors such as difficulties, disassembler's expertise, the selected disassembly method and tools, etc. However, our observation indicates that, generally, the more an operation goes destructive, the easier it would be to perform by the practitioner. Based on the average values measured from the random experiments during the disassembly the following relations are formed. Suppose that the V stands for disassembly speed (a function of time), we can write:

$V_{\text{Totally dest.}} > V_{\text{Cut.}} > V_{\text{D.dr.}} > V_{\text{M.dr.}} > V_{\text{Manual dis.}}$

Operation precision: Depending on the methods, tools and the disassembler's expertise, the relative damage to the parts/module can vary. However, this might not be particularly applicable to the carcass since almost all its valuable and care-demanding parts are already separated at the "removing the valuable parts" stage. Nonetheless, if PR denotes the precision, the following relation is usually the case in aviation EoL:

$PR_{\text{Manual dis.}} > PR_{\text{M.dr.}} > PR_{\text{D.dr.}} > PR_{\text{Cut.}} > PR_{\text{Totally-dest.}}$

Damage risk: Although a carcass might usually seem less beneficial to be meticulously disassembled, a destructive method can result in increased creation and loss of the metal chip containing potentially valuable metals (e.g., titanium, copper and/or aluminum), as seen commonly in aerospace rivets. Likewise, a more destructive operation increases the risks associated with accelerated creation of the undesired metallic and non-metallic mixes, which must be avoided. Thereby, let DA denotes the relative damage to the part, the following relations are observed:

$DA_{\text{Totally-dest.}} > DA_{\text{Cut.}} > DA_{\text{D.dr.}} > DA_{\text{M.dr.}} > DA_{\text{Manual dis.}}$

Cost-effective recycling of an airframe scraps necessitates certain qualifications. It can be defined simply through maximization of the net profit. In other words, this is reachable by minimizing the total expenditures and maximizing the income (i.e., the quality of the recycled material output).

This could be pertained to the quality of the obtained material output, the required dismantler's expertise, and the demanded sorting technology. In this regard, a short look at successfully applied and recommended methods and solution in the neighboring domains may help improving the aviation EoL procedure. This is bolded in a research by Feldhusen et al., where it is stated that only automotive EoL process can be used to develop a comprehensive aviation EoL treatment regime [Feldhusen et al., 2011]. Likewise, Das et al., also stressed two crucial steps to be taken in order to proceed with an optimized alloys recycling process in automotive: 1- pre-sorting and 2- controlling the dismantling process [Das et al., 2007]. Thereby, our approach is set to incorporate a boosted pre-sorting-embedded operation within the dismantling process. Figure 5-1 illustrates a common practice in aviation EoL incorporating both rebirth subsequent operations (i.e., refurbishment, reuse, remanufacture and recycling), introduced by [Mascle, 2013], and landfill operation. The red-dashed line encircles the affected process steps by our approach. This zone does not encompass the reuse, remanufacture or refurbishment since the carcass supposedly does not contain a considerable amount of high added value parts/modules (e.g., engines, landing gears, avionics systems, etc.). A common practice, in this field, is to turn the carcass into a bulk of scraps unsystematically and in a very poorly organized fashion. In this case, the process includes using shredders so as to produce smaller and also easier-to-sort objects. However, the material output stream of such trend does result in a poor metal composition and alloy elements. Although there are few reports showing a total amount of 80-85% of total weight recovery [AIRBUS, 2014, LeBlanc, 2013], it is believed that most of the aircrafts recovery rates have not been more than 50% [LeBlanc, 2013]. Nonetheless, the authors in [Asmatulu et al., 2013b] gives an even more disappointing rate of only 20% for the total weight recovery.

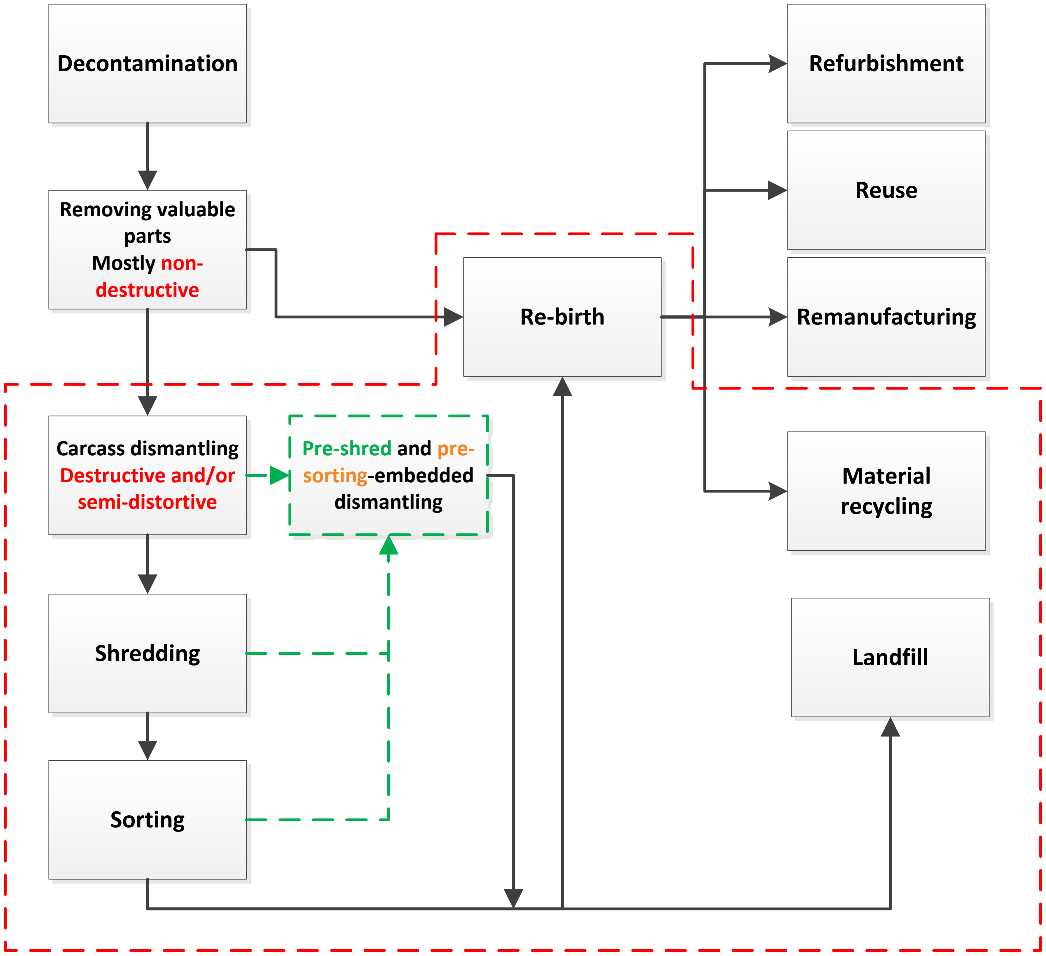

Figure 5-1 Aerospace EoL treatment procedure; red-dashed line indicates the affected fields in our approach; the green-dashed line illustrates the pre-sorting-embedded dismantling procedure

5.4 Methodology

In order to precede with a sustainable airframe EoL treatment, a methodology is designed to systematically incorporate the principal steps that follow.

- Real airframe disassembly work observation and determination of the dismantling driving factors;
- Study of the non-metallic and miscellaneous materials;
- Study of the fastening;
- Part data-base formation and pre-shred dismantling strategy definition based on the aircraft standard documentations (disassembly factsheet);

- Selection of the airframe target part/module and determination of the material cartography;
- Disassembly pathways definition.

5.4.1 The study of the non-metallic and miscellaneous materials

One of the biggest issues of the airframe disassembly that should be addressed is the amount of non-metallic substances and also the types of these materials which exist within a module. This simple issue can drastically lower the quality of the output materials, if a systematic material sorting process is not proceeded with. We are particularly looking for the following materials: organic coatings, tapes, adhesives, resins, composite materials, solvents and cleaners, chemical strippers, chemical products, sealants, abrasives, painting pre-treatments and miscellaneous. In order to achieve a superior quality at the end of recycling, a so-called "early-purification strategy" should be considered at the forefront of the dismantling operation. This step encapsulates a sufficient evaluation of the interfacial connections between non-metallic and metallic parts/modules as described by the following suborders:

A: Study of the content: each specific module (i.e., fuselage, wings, stabilizer, etc.) prior to the disassembly process should be verified in order to identify and localize the non-metallic parts/modules. In other words, an analysis of the constituents has to be done at this level. It is also required to estimate the total weight of the non-metallic parts to remove.

B: Extraction planning: as the objects and their material structures are identified, an analysis is needed to find the best and also the fastest way to extract them. This is essentially important in order to reduce the total time spent performing the disassembly process.

C: Valorisation analysis: a sustainable notion through which non-metallic dismantled parts (which are mostly supposed to be landfilled) gain another lifespan, and the value is restored by being used alternatively.

5.4.2 The study of the fastening

Each part/module in a mechanical structure may have a number of fastening connections and/or an attachment line by which it is connected to other parts/modules. These connection lines are the first elements to be processed, to ensure a successful semi-destructive approach, as described below.

A: Connection analysis: deals with the determination of the connection types and the number of connections. It consists of the steps which follow.

First-release connection analysis: to determine the type and the number of connection points by which a break loose or removing action is needed to dismount the whole module. It is an essential step since the given module should be dismounted before any further disassembly operations can start.

Principal connection analysis: the principal connection refers to the most dominant (i.e., most-frequently used) connection types within a module in order to generate the most feasible disassembly path in terms of the time and effort required for the disassembly operation.

B: Structure analysis: geometrical shape and dimensions are fundamental elements to be dealt with since the disassembly alternative selection and the associated performance are based upon the geometry of the fasteners as well as the part/module.

C: Analysis of the recovery: prior to any disassembly physical work, the potentially recoverable parts in a module should be identified. This can significantly reduce the chance of damaging a valuable part inside a module by miss-selection of the disassembly alternative.

D: Analysis of the feasibility: the part/module should be analysed in terms of the disassemblability. This entails an observation and early decision on whether or not a particular disassembly alternative could technically be feasible to select.

The provided information is used to create the “disassembly factsheet”. Microsoft Excel is used to create the factsheet due to the flexibility and calculation easiness. The factsheet is a disassembly database from which detailed information (e.g., unfastening and/or cutting time, effort, number of fasteners, geometrical specifications, etc.) are extracted. Table 5-1 lists the parts to create a systematic disassembly pathway.

Table 5-1 Horizontal stabilizer specifications

Horizontal Stabilizer (primary & secondary structures)	**Material**	**Number of subordinate units**
Upper Stringer	Al 7xxx	4
Lower Stringers	Al 2xxx	4
Spars	Al 2xxx and 7xxx	28
Ribs (including inboard and outboard closures)	Al 2xxx and 7xxx	13
Skin doublers	Al 2xxx and 7xxx	6
Skin stiffeners	Al 2xxx	1
Panels Access panel covers (PCU + flutter-dampener)	Al 2xxx and 7xxx	2
Fillets and Fairing	Composites, resin sheet, Al 2xxx, 5xxx and 6xxx)	17
Shroud	Al 2xxx	1
Upper Skin	Al 2xxx	1
Lower Skin	Al 7xxx	1

5.5 Results

The studied airframe is composed of various parts each imposing certain limitations to the EoL dismantling decision making process. In other words, a selected alternative might be seemingly inefficient with respect to one criterion while maintaining a high value with respect to another aspect. As illustrated in Figure 5-2, the disassembly pathways are fixed based on the extracted data given in Table 5-1, in order to reach the maximum pre-sorting possibility. Then, the relative time to perform each operation is measured for each alternative operation to eventually calculate the final performance metrics. Table 5-2 shows the relative values of the measured performance indexes with respect to the highlighted criterion.

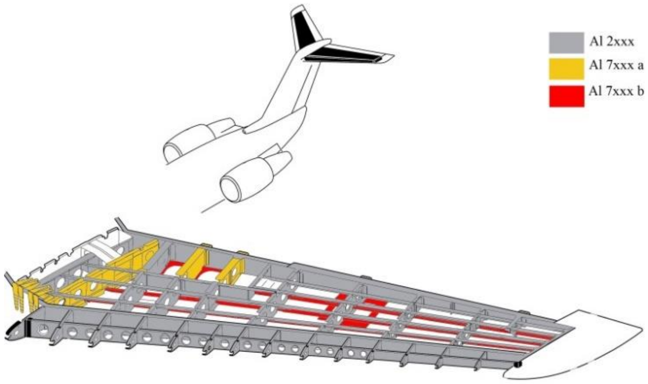

Figure 5-2 Horizontal stabilizer material cartography derived from the aircraft standard documentations prior to the dismantling works

As screened in Table 5-2, while “Deforming” is noticeably time-consuming in dismantling causing extra economic load, the “Totally dest.” alternative is significantly faster. However, the amount of the unwanted metallic and non-metallic mixture is highly escalated. Therefore, dismantling of the H.Stab (horizontal stabilizer) (containing majorly aluminum-made rivets with respect to the current market status) is seemingly more profitable through using the cutting alternative. It is worth mentioning that the great variations in the “Mix” column values are due to the inherent significant differences of each method with respect to the degree of destructivity that they have. For instance, drilling a rivet (weighing only few grams) results only in a negligible mixture rate (with respect to the total 250 kg weight of the whole module) while deconstructing the whole module causes a noticeable undesirable heterogeneous material mixture (equals to a total of 250 kg material mixture). Nonetheless, dismantling of the parts/modules where the following conditions are the case may differ from the presented case-study:

- Fasteners and/or parts are made of precious metals (e.g., titanium-made rivets);
- Where an increased amount of the risk and the hazards are present (e.g., explosions and toxicity);
- Realization and/or commercialization of the new technics (e.g., automated processes);
- Significant changes in the regional and/or international markets and legislations.

Table 5-2 Airframe EoL performance indexes (the values are given in case of one worker in charge of the unit disassembly); the values given in (%) are based upon the total unit weight

Alternatives	Mix (%)	Lost (%)	Cost ($)	Fastness (hours)
Cutting	5 to 10	Almost 1	Moderately low	1 to 1hr 30 min(s)
Deep-drilling	0	1 to 2	Moderately High	12 to 18
Minor-drilling	0	Less than 1	High	18 to 32
Totally dest.	Near 100	Almost 0	Noticeably low	Less than 1/2

Further researches are ongoing by authors to proceed with a dismantling tool to ease strategy definition based on a comprehensive study of the entire airframe. Although today's metallic raw material reserves do not impose serious limitations, in near-future/future this may experience severe changes. Strictly speaking, the amount of the mixture and unrecoverable mixes (see the third column in Table 5-2) with respect to the metallic composition can vary from one place and operation time to another. In other words, it is not a matter of tool selection to disassemble a part/module although the tool itself can have undeniable impacts. Nonetheless, the alternative classification by itself has some inherent features that drive the disassembly and can remarkably affect the ultimate disassembly performance.

5.6 Summary

Recently, aircraft EoL process has got a unique place due to the increased number of the decommissioned aircrafts and the potential associated benefits. In this regard, an optimized airframe dismantling is a key element to reach an environmentally viable and economically profitable treatment process. Meanwhile, an efficient airframe dismantling is technically complex due to the large number of materials designed for the maximum durability. However, to define a systematic dismantling procedure is almost not possible unless a deeper knowledge is acquired in the aviation disassembly methods. In this research, the disassembly alternatives are classified into four principle categories and comparisons are made amongst them. An alloy-oriented pre-sorting strategy is embedded into the dismantling process by proceeding with a systematic disassembly involvement. This has resulted in more accurate and alloy-sorted scraps while reducing the ultimate dismantling time. In other words, such process allows for obtaining output materials with higher qualities. As a result, the recycled materials would be more likely to be used in less fracture-critical industries such as automobiles and/or constructions. This systematic treatment also allows the disassemblers and designers to reduce the environmental footprints, and help increasing the net profit associated with airframe EoL process.

5.7 Future research insights

The authors believe that further studies in systematic dismantling evaluation and management seem to be the key elements in order to make the airframe EoL process economically and environmentally feasible. In this regard, the authors are currently working on the evaluation of the disassembly associated with each presented alternative in order to find the most feasible mix of alternatives based on the technical conditions of the airframe part/module. The authors are also conducting some pragmatic researches on the systematic performance analysis of the complex metallic structure disassembly which will be published continually in future.

5.8 Acknowledgements

This paper has been prepared within the CRIAQ ENV-412 project at École Polytechnique de Montréal. The authors would like to thank NSERC, CRIAQ, NanoQuébec, Bombardier Aerospace, Bell Helicopter, Sotrem-Maltech, Aluminerie Alouette, BFI as well as the other partners and project members for funding and helping the project.

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CHAPTER 6 ARTICLE 3: A QUANTITATIVE EVALUATION MODEL TO MEASURE THE DISASSEMBLY DIFFICULTY; APPLICATION OF THE SEMI-DESTRUCTIVE METHODS IN AVIATION END-OF-LIFE

H. Zahedi, C. Mascle, P. Baptiste – Published, *International Journal of Production Research (IJPR)*, Vol. 54, Issue 12, pp. 3736-3748. (2016) – Taylor & Francis

Abstract

Sustainable decommissioning of aircraft with a high content of metallic and non-metallic components is a current challenge in the industry. This process has historically appeared to be economically, environmentally and socially unviable. Literature indicates that, unlike entirely-destructive and totally non-destructive techniques, semi-destructive disassembly may bring significant benefits. However, despite their use in a wide variety of applications, there are currently no feasible solution on how to measure the associated physical difficulties and required efforts without any dependencies on expert views or filling out spreadsheet-like forms. In this paper, a new model is developed to accurately evaluate the disassembly easiness of an airframe quantitatively incorporating both product and process features. Based on a real disassembly of a passenger jet, the cutting and thrust force vectors are selected to evaluate and find the best operation sets. An airliner Horizontal Stabilizer (H.Stab) is analysed as a case-study. The results indicate that minor drilling, as a hybrid operation, can reduce the disassembly-efforts significantly while offering an increased material recovery chance. Such quantitative evaluation can help to: proceed with a viable End-of-Life (EoL) strategy; and implement newer approaches like automated disassembly by designing better disassembly robots, tool selection and process control.

Keywords: Aircraft decommissioning; Semi-destructive disassembly; Disassembly model, Aircraft EoL dismantling; Aircraft skeleton disassembly.

6.1 Introduction

Design and manufacturing of today’s products are increasingly oriented toward incorporation of End-of-Life (EoL) provisions in accordance to new sustainability standards and requirements.

Limited natural reserves, increasing environmental pollution (imposed by non-responsible products) and social awareness are amongst the major motivators pushing companies to take further steps in establishing a viable EoL process. Unlike other neighbouring domains like automotive, progress in the aerospace EoL sector is still marginal, although several efforts have been initiated around the world by manufacturers including Boeing, Airbus and Bombardier. Adding semi-destructive to the traditional disassembly methods presented by [Desai and Mital, 2003], these methods can be classified into three categories: 1- destructive or brute force approach; 2- non-destructive disassembly or reverse-assembly [Sodhi et al., 2004] and 3- semi-destructive disassembly [Umeda et al., 2015, Shiraishi et al., 2015, Vongbunyong et al., 2013a].

The active disassembly, as a non-destructive approach, is also gaining momentum due to the variety of advantages it can offer. According to a research by Yang et al., recent developments in shape memory technology allow for implementation of hydrogels with excellent stimulus-responsiveness and reasonable strength resulting in easier disassemblability and reusability of products [Yang et al., 2014]. Sun et al. have also conducted a comprehensive review on utilizing Shape Memory Technology (SMT) for active assembly/disassembly where fundamentals, applications, and recent achievements are discussed in details [Sun et al., 2014]. Programmable disassembly mechanism has also been achieved for some NiTi based alloys as reported by Tang et al. and Sun et al [Tang et al., 2012, Sun et al., 2014]. The split-lines partial disassembly is another enabling semi-destructive approach introduced by Shiraishi et al. and Umeda et al. that can result in more effective disassembly processes [Umeda et al., 2015, Shiraishi et al., 2015]. In this method, designated components are disassembled through destruction of product in desired shapes based on a supportive design specifying the split-lines. Although the disassembly can be carried out in a more efficient way (reducing the number of operations), more pragmatic research contributions are needed to ensure the mechanical performance (i.e., stiffness and rigidity) of components. Meanwhile, a research paper by Asmatulu et al. shows that the dismantling of an aircraft skeleton using full-destructive techniques (a common practice in this field) provides recycling of only 20% of the scrap materials [Asmatulu et al., 2013b].

In semi-destructive techniques, as an irreversible operation, the need for complex calculations, sensors and multiple tools is also minimized while at the same time the success rate remains high [Vongbunyong et al., 2015a]. This is a particularly enabling choice for airframe disassembly because the number of fasteners is remarkably high. A fighter jet, for example, might require more than 100,000 fasteners and a commercial airliner more than 1 million [Eastman, 2012]. Despite these advantages, our literature review revealed that implementation of semi-destructive disassembly and its fundamentals are not well understood. Even though addressing the disassembly difficulty scale is an important issue in this field, there are currently no feasible solutions (i.e. practical and easy-to-perform model) on how to measure the associated physical difficulties and required efforts without any dependency on expert views or filling out spreadsheet-like forms [Desai and Mital, 2003] or rating-based methods [Güngör, 2006] (which also depends on qualitative measures) regardless of the part/module's size.

This study presents a new evaluative model to quantitatively assess the disassembly difficulty of semi-destructive operations before the physical process starts. It strives to include multiple variables including mechanical properties of the work-piece, direction of application (i.e., tool path), cutting tool geometry and feed rates known as critical elements in the field. The cutting and thrust force vectors are selected to evaluate the required disassembly effort and eventually to find the best set of operations. This can significantly help to:

(1) Increase the dismantling efficiency of the current EoL air fleet;
(2) Evaluate alternatives in the design stage when creating EoL-oriented products;
(3) Establish a dynamic liaison between product design and disassembly phases.

The results could be used both prior to the airframe dismantling and during the design stage of the aircrafts in order to define strategies in favour of ease of disassembly and to improve the disassemblability of the airframe respectively.

6.2 Background

EoL treatment of an aircraft requires execution of several tasks, each with their own particular complexities. Mascle et al. describes four principle stages: decontamination, disassembly and valuable parts/modules removal, airframe dismantling and materials recovery and, valorisation and/or landfill [Mascle et al., 2015]. Challenges begin to appear during dismantling of the remaining structure (the third stage), which has significantly less value than parts such as engines or landing gears and is more difficult to process. In order to provide an overview of the state of knowledge in this field and to establish a better understanding of the topic, three different research areas are covered as follows.

6.2.1 Air fleet EoL recycling status

In addition to the opening of pragmatic research channels by academia, fundamental projects have been initiated by aircraft manufacturers. Process for Advanced Management of End of-Life-Aircraft (PAMELA) by Airbus and Aircraft Fleet Recycling Associations (AFRA) are examples of these efforts [AFRA, 2016, PAMELA, 2008]. According to AFRA, the aircraft retirement rate will reach over 1000 per year within a decade while 12,000 aircraft will come to the EoL phase within the next two decades [AFRA, 2014b]. Airbus has also predicted that as many as 8543 aircraft (narrow and wide body aircraft) will arrive at their retirement phase within the period from 2009 to 2028 [Van Heerden and Curran, 2011]. Figure 6-1 presents a comprehensive survey of the aircraft EoL with respect to each specific alternative in the market. In this illustration, the bigger the ovals are, the more significant the market share is.

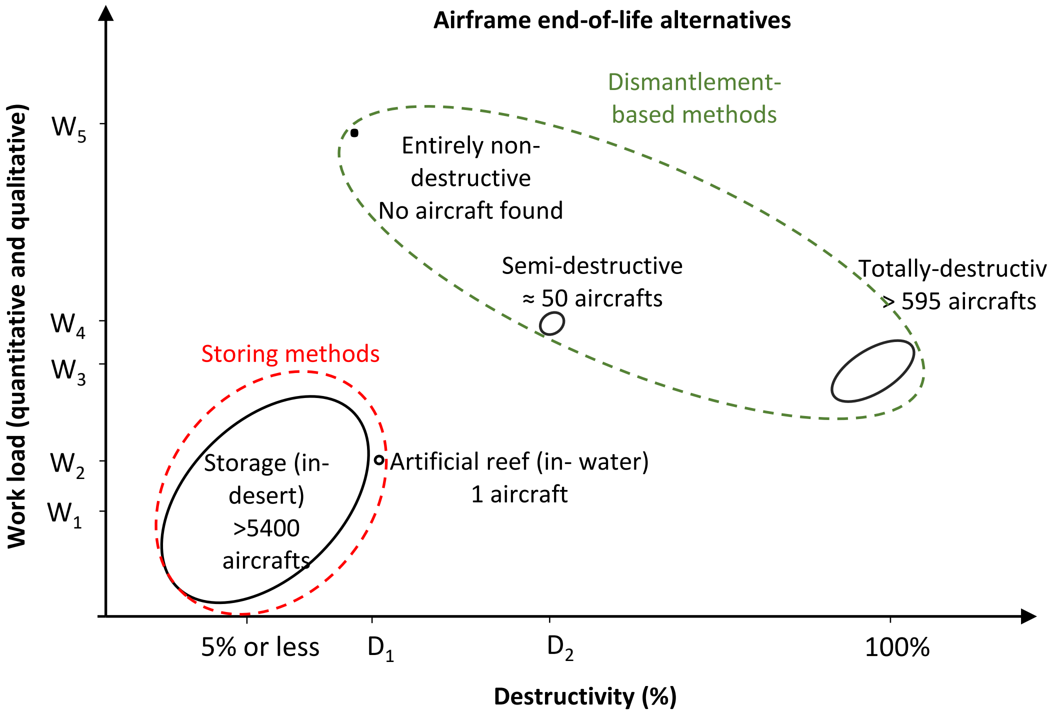


Figure 6-1 Aircraft EoL alternatives' share in the market; D_1 and D_2 denote minor (reversible) and controlled-major (irreversible) operations respectively

Source: Aircraft demolitionArtificial Reef Society of British Columbia, Tarmac Aerosave, AELS, Davis-Monthan Air, ASI, BBC "the secrets of the deserts", Mojave Airport and Murtala Muhammed International Airport, Lagos, Nigeria.

6.2.2 Aircraft EoL process methodologies

A study of relevant literature shows that there are relatively few studies discussing aircraft EoL treatment. A state-of-the-art research by Asmatulu et al. focuses on recycling of aircraft to determine the environmental benefits of aircraft recycling. It highlights recent progress in aircraft recycling and marketability of the recycled materials [Asmatulu et al., 2013a]. Zahedi et al. developed a conceptual EoL framework for a comprehensive integration of process and product related features [Zahedi et al., 2015]. This work discusses the importance of both product and process features in terms of defining optimal strategies in EoL aircraft treatments. Increasing the profitability of the EoL process and eliminating impediments to disassembly, recycling and reducing the environmental footprint are also stressed in a research work by Mascle et al. [Mascle et al., 2015]. Evaluation of the disassembly economy is the subject of a research by Tang et al; a methodology to help making better decision on the disassembly strategy to improve the economic gain [Tang* et al., 2004].

6.2.3 Current state-of-the-art evaluative progress

Basically, two different approaches exist for quantitative disassembly evaluation: 1- expert consultation and data gathered from disassemblers and, 2- effort calculation models.

Kroll and Hanft presented a method to evaluate ease-of-disassembly by printing difficulty scores on a spreadsheet-like chart to be filled out by the practitioners [Kroll and Hanft, 1998]. This method has some limitations since it is designed for seated workers so only small products are disassembled. The “number of parts”, “number of hand manipulations” and “number of task repetitions” are some of the important criteria in their work. Meanwhile, Desai and Mital proposed another evaluative time-based approach to be incorporated directly in the product design phase [Desai and Mital, 2003]. This scoring system includes several design attributes, features and parameters, each assigned a specific score that can be used to evaluate the disassembly procedure. Effort calculation models on the other hand, use a different approach that includes consideration of product-related features (geometry, installation mechanism, etc.). Sonnenberg and Sodhi present a solid approach with more pragmatic research contributions by introducing two models, “U-Effort” and “U-Force” (as non-destructive methods) in their works [Sonnenberg, 2001, Sodhi et al., 2004]. The U-Effort or unfastening effort is a scoring model capable of reflecting the total effort required to perform disassembly tasks by virtue of a scoring system. The U-Force however, tries to calculate the required mechanical disengaging force of snap-fit fasteners.

Despite its importance, it is apparent from the literature that almost no research is clearly aimed at exploring the semi-destructive operations and its role in strategy definition within the context of disassembly (where it is supposed to be defined). For this reason, this research focuses on “disassembly difficulty” as a core-attribute in any disassembly strategy definition and discusses this aspect in detail.

6.3 Objectives and Methodology

6.3.1 Main objectives

Although each of the first three steps mentioned earlier requires disassembly work at different intensities, processing the remaining carcass is of greater importance. Pre-disassembly works (i.e. acquiring and collecting the essential documentation/data, observations, planning, etc.), disassembly operations (providing the necessary tools, educating the specialists and disassembly practitioners with different levels of expertise, personnel briefing, etc.) and the post-disassembly chain of operations (sorting and shredding) are all classified within the airframe dismantling and disassembly framework. Thus, in this study the stress is put upon evaluation of the disassembly procedure as an essential step in aircraft EoL treatment in order to: 1- facilitate the disassembly operation, 2- reduce the environmental footprint of the procedure and, 3- help designers create future generation aircrafts with more EoL-oriented incentives.

6.3.2 Methodology

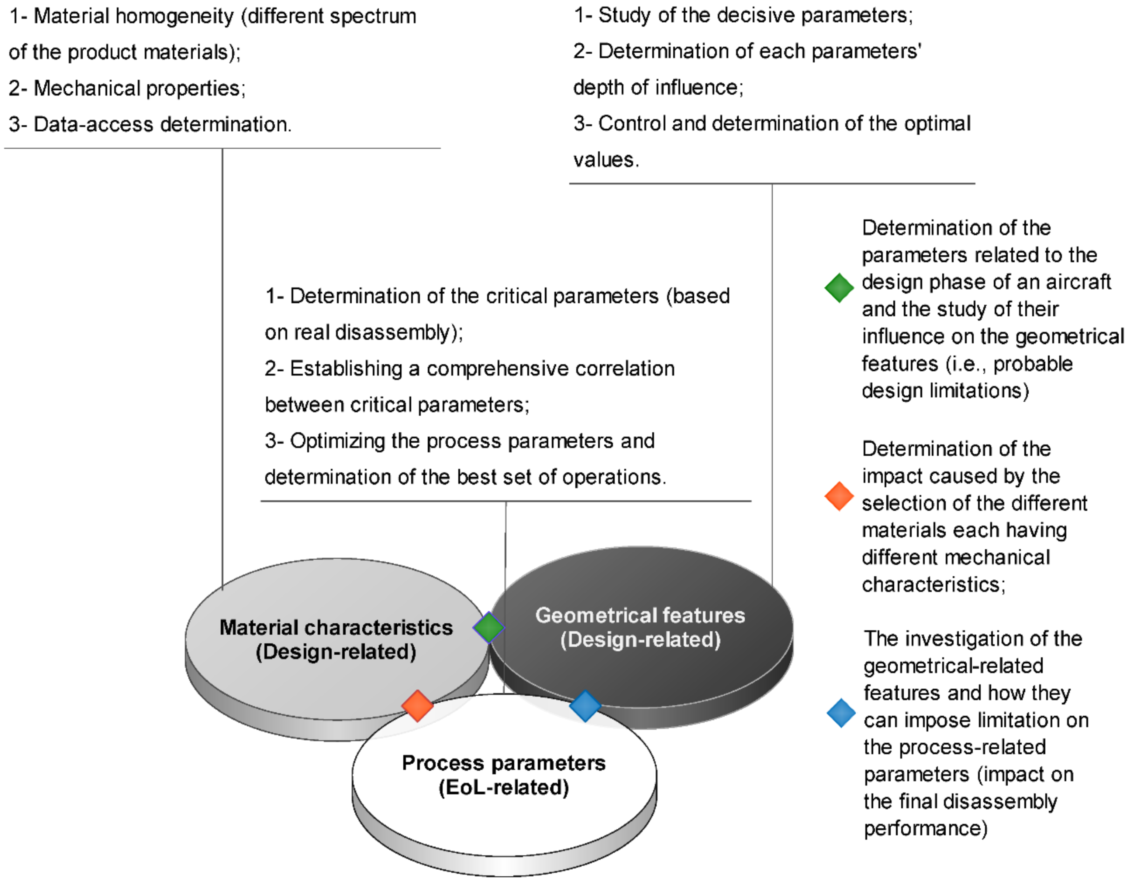
Keeping an eye on the trade-offs between all the driving elements, a series of actions are to be followed in this methodology prior to the post-disassembly set-of-operations:

- Determination of the driving parameters (based on observation and real airframe disassembly tests);
- Exploring the mechanics of disassembly;
- Development of a disassembly difficulty calculation model to reflect the real effort associated with disassembly of the parts/modules;

- Case study and applications.

6.3.3 Determination of the driving parameters

Analysis of semi-destructive disassembly is more challenging than conventional operations (reversible) because it includes a certain number of fluctuating parameters due to the destructive operations. In addition, the presence of such parameters makes it necessary for them to be classified separately according to their characteristics. Figure 6-2 presents the classification of design-related (product-related) and process-related parameters.



1- Material homogeneity (different spectrum of the product materials);
2- Mechanical properties;
3- Data-access determination.

1- Study of the decisive parameters;
2- Determination of each parameters' depth of influence;
3- Control and determination of the optimal values.

1- Determination of the critical parameters (based on real disassembly);
2- Establishing a comprehensive correlation between critical parameters;
3- Optimizing the process parameters and determination of the best set of operations.

🟩 Determination of the parameters related to the design phase of an aircraft and the study of their influence on the geometrical features (i.e., probable design limitations)

🟧 Determination of the impact caused by the selection of the different materials each having different mechanical characteristics;

🟦 The investigation of the geometrical-related features and how they can impose limitation on the process-related parameters (impact on the final disassembly performance)

Figure 6-2 Semi-destructive disassembly analysis of the driving parameters

Incorporation of this classification necessitates clear accommodation of the subsequent parameters in each cluster as presented in Table 6-1.

Table 6-1 Semi-destructive disassembly operation technical indicators

Dependencies	Driving clusters	Subsequent driving parameters
Product related	Material characteristics	*Number of materials in a component and Brinell hardness scale (BHN).*
	Geometrical features	*Instant sheet thickness**.
Process related	Process parameters	*Tool speed (rotational, linear), depth of cut, work-piece speed, machine nominal power, machine efficiency and feed rate, coolants, stability.*
	Tool-related parameter	*Tool dimensions (diameter, cutting angle, thickness, etc.) and tool-material, sharpness.*

*The sheet thickness may vary from one place to another without being noticed when other elements (i.e., doublers, skins, layers) are added to the disassembly path(s). This can significantly affect the disassembly difficulty.

6.4 Mechanics of disassembly

Disassembly is defined as a systematic approach for recovering desired part(s), sub-assemblies or group(s) of component(s) of a given product, which requires separating them from the recyclable ones for a specific purpose [Gungor and Gupta, 1998, Lambert and Gupta, 2004]. Semi-destructive disassembly operations include certain levels of destructivity in order to facilitate parts/module disconnection. This flexibility can boost the recovery of the product's value and increase the benefits/gains (i.e. subtraction of the operation(s) expenses from the output(s) earnings) when: 1- the number of products is not high; 2- the value of the product is not significant (economic, strategic, etc.) and/or the after-market demands are marginal and 3- the required process-effort (logistic planning, required certification, personnel security, practitioner's expertise, public health, etc.) is relatively high.

Two common operational procedures in semi-destructive disassembly are metal cutting and deforming (mainly caused by mechanical impact to generate plastic deformation) [Vongbunyong et al., 2013a, Pak, 2002]. Depending on the type of disassembly, the release mechanisms of the connections can vary. Consequently, the requisite force, as a vector, can vary both in magnitude and direction. This resisting force has a decisive role during disassembly difficulty analysis, and is a result of two different vectors called *cutting* and *thrust*. Unlike the *cutting* component, the normal force (*thrust*) is unknown most of the time unless a dynamometer is used to measure the exerted force (which is mostly neglected due to use of hydraulically-powered feed-sliding systems) [King and Hahn, 1986]. However, due to the fact that the disassembler does not use hydraulically-powered feed-sliding systems in airframe disassembly, any reliable model should also consider the normal force component. During hours of technical discussions with disassembly personnel, it was revealed that most semi-destructive disassembly works are composed of three principal techniques as follows (neglecting Manual Disassembly which is out of the scope of this research):

- *Cutting (Cut):* the process of dividing a part's surface into two separate sub-sections through exertion of an external force using hard abrasive particles. The force could be exerted using either hand power or other external sources (electricity, pneumatics, hydraulics, etc.).
- *Deep drilling (D. Dr.):* To create a hole in a jointed surface(s) of parts/module(s) or fastener(s) in order to eventually unfasten or even ease (by creating a starter guiding bit) the disjoining process. This is often a practical choice because it is relatively fast, but in some cases it is the only alternative practitioners have to disassemble parts/modules non-destructively.
- *Minor drilling (Min. dr.):* This refers to a series of sequential operations such as making a shallow hole into the rivet (drilling), and then disengaging the rivet's shank by applying force in a secondary operation (i.e. using a metal pry bar, crowbar or another method to open up a gap between two mated parts). It is an enabling approach since it helps the disassembler to preserve the fastener material for further recycling. This is particularly important in cases where more valuable and scarce materials are used. The approach is also quite rapid.

Figure 6-3 illustrates the cutting and drilling operation force analysis when metal cutting processes are used for disassembly of an airframe. As seen in Figure 6-3 (a), the cutting force can be decomposed into three components; 1- tangential force (P_z), 2- radial components (P_y) and, 3- axial force, known as thrust force, (P_x) [Hmt, 2001, El-Hofy, 2013].

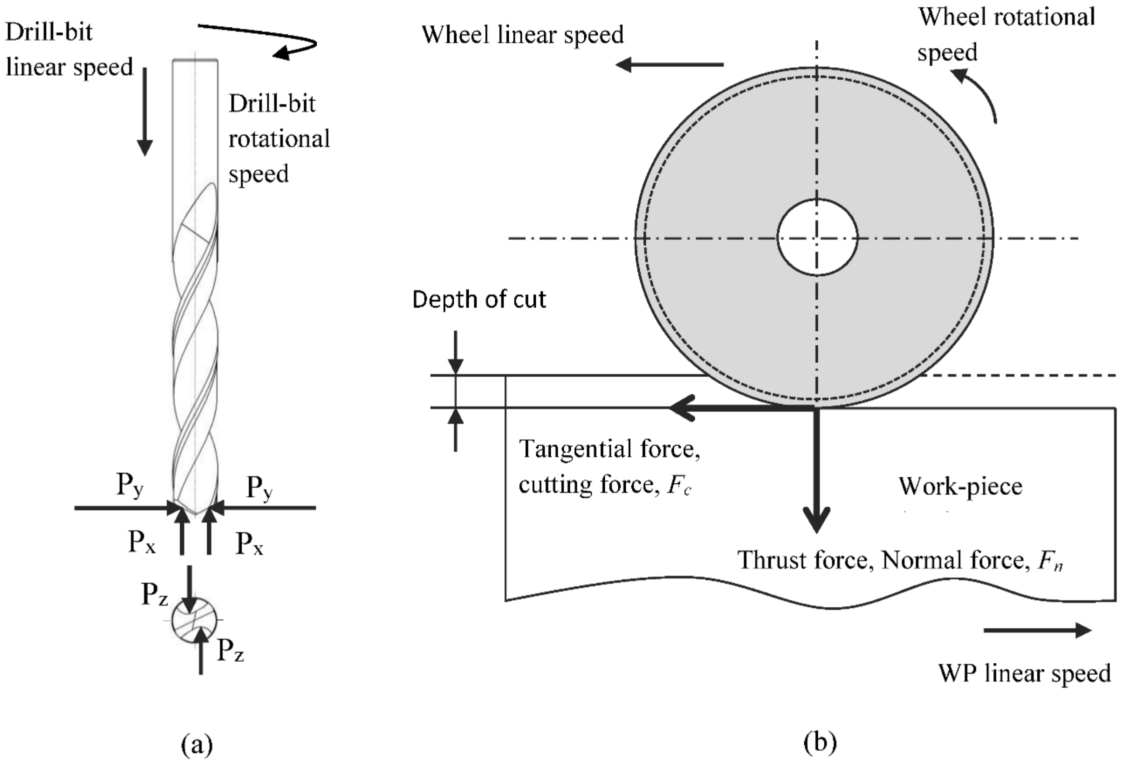


Figure 6-3 Semi-destructive disassembly force-analysis of an airframe; (a) drilling operations, (b) grinding operations

The cutting and thrust force vectors for the grinding metal cutting process are depicted in Figure 6-3 (b). Also, if Min. Dr. is selected the remaining rivet shank must be eliminated using a different technique. It should be noted that specifications for installation of fastener/fittings in aerospace have changed from clearance to interference fit in order to improve structural fatigue performance [Speakman, 1986]. Due to the high number of fasteners used to assemble an airframe, this adds extra difficulties for EoL disassembly.

6.5 Disassembly Difficulty Calculator (DDC)

The Disassembly Difficulty Calculator (DDC) is developed to analyse the difficulty associated with semi-destructive/destructive disassembly of metallic structures. This is a quantitative process assessment incorporating the disassembly driving parameters shown in Table 6-1. The general format of the equation is:

$$DDC = \sum_{i=0}^{n} \left(F_{Drilling} + F_{Disengaging} + F_{Grinding} \right) \qquad (6-1)$$

Where,

$F_{Grinding}$ and $F_{Drilling}$ are summation of the thrust and cutting force component associated with the appropriate selected metal working procedure(s), $F_{Disengaging}$ represents the disengaging vectors and n denotes the number of each individual operation. It is reported that the tangential force, like the coefficient of friction, is a fraction of the normal force (ranging approximately from ¼ to ½) [King and Hahn, 1986]. However, based upon the method of disassembly, each force component must be calculated separately in order to highlight the differences between disassembly difficulties associated with each method. Most of the calculations used to quantify the required forces are based on the assumption that the chip is "uncut or undeformed" [Shaw, 1996]. To signify other parameters, researchers use either the specific power (Z'_w) notion, as seen in [King and Hahn, 1986] which denotes the volumetric removal rate, or the specific cutting energy parameter, u, which was used by Kalpakjian and Schmid [Kalpakjian and Schmid, 2003] denoting *power/* Z'_w. Although use of one may be more appropriate than the other in a given specific research, in this study the specific cutting energy, u is used due to its simplicity and availability of standard measured values. The specific cutting energy, as a fundamental parameter in this study, is used in all metal cutting operation force calculations and depends upon the Work-Piece (WP) material hardness and tool sharpness. It is usually quoted in either, Watt-Second per square millimetre, Joules per cubic millimetre or Horsepower (HP) per cubic inches per minute depending on the units in which it is defined and/or measured. According to Kannapan and Malkin, the specific cutting energy, u (or e_c) is composed of three main energy forms, each corresponding to a particular physical mechanism; e_{ch} (plastic deformation), ploughing energy e_p (plastic deformation but no chip removal), and sliding or rubbing energy e_s, *as* shown in Equation 6-2 [Kannappan and Malkin, 1972]:

$$e_c = e_{ch} + e_p + e_s \qquad (6-2)$$

The energy attributed to these three individual components dissipates differently based on their physical mechanisms. The specific cutting energy value therefore varies significantly based on the type of metal cutting operation. The suggested values of u for grinding and drilling operations are given in Table 6-2 for various materials.

Table 6-2 Specific cutting energy for grinding and drilling operations for various materials

WP material type	Hardness in Brinell No. (BH)	Specific cutting energy for grinding, u_c (hp/in.3/min)	Specific cutting energy for drilling, u_d (hp/in.3/min)
Low carbon style (free machining)	150-200	13	-
Low carbon steel	150-200	13	1.10
Medium and high carbon steel	200-250	13	1.60
Alloy steel (free machining)	150-200	14	1.30
Stainless, ferretic (annealed)	135-185	14	1.70
Tool steel	200-250	14	1.50
Nickel alloys	80-360	22	2.15
Titanium alloys	200-275	16	1.25
Copper alloys (soft) (free machining)	40-150	11	0.72
Zinc alloys (die cast)	80-100	6.5[a]	0.40
Magnesium and alloys	40-90	6.5	0.18
Aluminum and alloys	30-80	6.5	0.36

Source: specific cutting energies are adapted from the Machining Data Handbook. Vol. 1, 2 and 3rd editions. Metcut Research Association Inc., 1980, [Songmene, 2014].

[a] Estimated value.

The Material Removal Rate (*MRR*) can be calculated using the depth of cut (*d*), the width of cut (*w*), and the grinding feed rate (*v*) (i.e. the amount of tool travel per unit time) as shown in Equation 6-3. The removed cubic rectangle is the result of cross-sectional area, *dw*, and the feed rate linear pass (*v*).

$$MRR = dwv \qquad (6-3)$$

The cutting power can also be calculated using the specific cutting energy (see Table 6-2) and the *MRR* according to Equation 6-4:

$$Power = u \times MRR \qquad (6-4)$$

The cutting force (F_c) (see Figure 6-3) can then be easily calculated using values of rotational speed (ω), power (P), and wheel diameter (D) as seen in Equation 6-5:

$$Power = T \times \omega;\ and\ T = F_c\,.\,(\frac{D}{2}) \qquad (6-5)$$

By referring to the literature and the experimental data and considering the grinding normal force component (F_n) to be 30% higher than F_c , required values can be calculated [Kalpakjian and Schmid, 2003].

However, if the semi-destructive disassembly includes a drilling operation, F_c can be calculated using the chip cross-section area (A_c), as described earlier, and the specific cutting energy for the drilling operation (u_d) (see Table 6-2). The A_c for a drilling operation is a function of the drilling feed rate (S) and the drill bit diameter (d), written as:

$$A_c = \frac{Sd}{4} \qquad (6-6)$$

The depth of cut can be calculated using the nominal power of the drilling machine and the specific cutting energy for drilling. Subsequently, the number of required passes and the total force to reach the required cutting depth can be calculated. The drilling F_n is more difficult to calculate however, [Kalpakjian and Schmid, 2003] since there are various parameters dynamically changing during this operation (i.e. rotational speed, WP material strength, feed, etc.). Despite this difficulty, the following equation provides good results with respect to the objectives of our research [Shaw, 2005]:

$$\frac{F_n}{d^3 H_B} = 6.962\frac{f^{0.8}}{d^{1.2}} + 0.68\left(\frac{c}{d}\right)^2 \qquad (6-7)$$

Where,

d = drill diameter in mm, H_B = Brinell hardness in kg mm^{-2}, f = drill feed rate in mm/rev. and F_n = drill thrust force component in N.

If the case under study requires disengaging of fasteners, the required force can be obtained by calculating the necessary disengaging pressure (*PR*). To calculate the pressure generated at the interface of an interference-fit connection, the elastic deformation (Lame's equation) presented by authors in [Nisbett et al., 2008] is used as follows:

$$PR = \frac{\delta}{\frac{d_d}{E_0}\left(\frac{d_{d.0}^2 + {d_{d.}}^2}{d_{d.0}^2 - {d_{d.}}^2} + \upsilon_0\right) + \frac{d_{d.}}{E_i}\left(\frac{{d_{d.}}^2 + d_{d.i}^2}{{d_{d.}}^2 - d_{d.i}^2} - \upsilon_i\right)} \qquad (6-8)$$

When the shaft and the hole are both of the same materials, Equation 6-8 takes the following form:

$$PR = \frac{E\delta}{2{d_{d.}}^3}\left[\frac{(d_{d.0}^2 - {d_{d.}}^2)\,({d_{d.}}^2 - d_{d.i}^2)}{d_{d.0}^2 - d_{d.i}^2}\right] \qquad (6-9)$$

Where $d_{d.}$ is the nominal shank diameter (in case of disengaging operation) with o and i denoting the outer member (hole) and inner member (shank), respectively, E is Young's module, δ is the diametral interference between rivet shank and the hole, and v is Poisson's ratio.

Once the pressure PR is calculated, the required force to disassemble the fastening is found using the friction coefficient μ and the area of contact A between the shaft and the hub as in Equation 6-10:

$$F = \mu\,.PR.A \qquad (6\text{-}10)$$

Using Equation 6-1, all tangential and normal force vectors can be assembled in order to calculate the average module/part disassembly difficulty (DDC). This will be further discussed in the next section.

6.5.1 Data-extraction and data source

Accessibility to the aircraft structural data source is an imperative element in ensuring good results in terms of the quality of recycled material, the mass of the landfill and other important factors. As addressed by Das et al., disassembly of vehicles based on preliminary separation and segregation of known alloy compositions is highly encouraged to ensure the best outputs [Das et al., 2010]. To acquire the necessary knowledge of the material types of a structural part/module, full accessibility to the following alternatives was provided: 1- Aircraft standard documentation such as the Aircraft Maintenance Manual (AMM) and Structural Repair Manual (SRM) (which provides supplementary relevant information on geometrical-related features) and, 2- a handheld X-ray Fluorescence (XRF) analyser to analyse the part/module material.

6.6 Case study and results

In order to verify the suitability and performance of the model, an airliner Horizontal Stabilizer (H.Stab) including skin and under-skin parts fastened by a line of rivets is presented in Figure 6-4 for disassembly using semi-destructive operations. The skin and its underneath fastened parts are made of aluminium alloy with the total thickness and length equal to 5.82 mm and 1390 mm respectively.

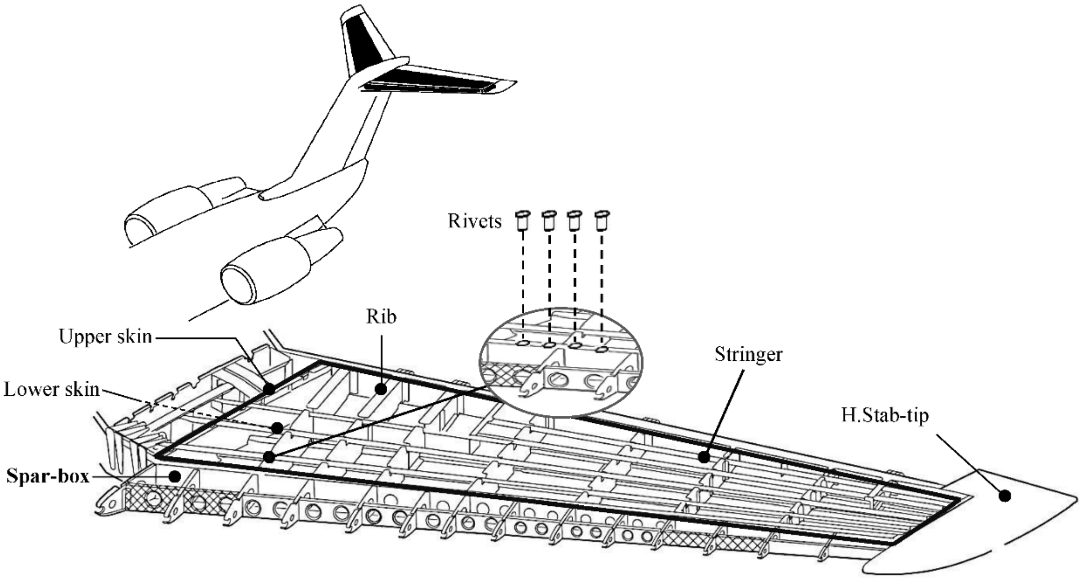


Figure 6-4 Horizontal stabilizer structural elements; the rivets are shown in magnified view

The fasteners are high-strength 5/32 CherryMAX® (Cherry Aerospace) rivets. A total of 88 countersunk blind rivets with a maximum grip-length and diameter equal to 7.92 and 3.97 mm respectively are distributed along the skin length. Disassembly using a grinding operation is done with a standard handheld Bosch cutting machine with 1320 Watt nominal power and a metal cutting disk of aluminium oxide (Al_2O_3) with external diameter and thickness equal to 115 (mm) and 2.5 (mm) respectively. According to Rowe and Petzow, a silicon carbide (SiC) cutting disk can also perform non-precision tasks related to the non-ferrous operations satisfactorily [Rowe, 2009, Petzow, 1999]. The fastener stem material is a nickel-based alloy X 750, AMS 5667, which is used in many aircraft structure and rocket engine applications. If drilling operations are chosen for disassembly, the suggested material, point, helix and lip relief angles are; High-Speed Steel (HSS) grade T15, $118 - 125°$, $29°$ and $12°$ respectively [Davis, 2000, Hmt, 2001, Davim, 2011]. The setups for the grinding disassembly process are shown in Table 6-3. Based on Equations 6-3 to 6-5, the MRR and depth of cut (v) are equal to 4462.7 mm^3/min and 4.46 mm respectively. The calculated total tangential and normal force components (including the skin and fastener sleeve, stem and collar) are 5.72×10^6 N and 7.44×10^6 N respectively.

Table 6-3 Operational setups for the grinding disassembly process

Specific cutting energy, *u* (N/mm^2)			Feed rate *v* (mm/min)	Width of cut *w* (mm)	Cutter speed, *V*, (rev/min)	Machine power (*P*)	Disassembly sequence length (mm)
Rivet-sleeve	Rivet-stem	Rivet-collar					
17747.1	60067.1	17747.1	400	2.5	3700	1320	1390

If a drilling disassembly technique is selected, a new operational setup must be prepared. The drill bit tip diameter, feed rate and specific cutting energy for removal of nickel-based alloys are 12.5 mm, 0.2 mm/rev and 5460.65 N/mm^2 respectively as suggested by [Davim, 2011, Songmene, 2014]. The calculated cross-sectional area and total tangential (cutting) force required to perform the whole sequence of operation including disassembly of 88 rivets are 0.625 mm^2 and 11.89×10^6 N respectively. Equation 6-7 is used to calculate the normal force component (thrust force). For our case, d, H_B and f have values of 12.5 mm, 326 kg mm^{-2} and 0.2 mm/rev respectively, and the total normal force for the whole sequence is obtained as 20.37×10^6 N.

Eventually, if disengaging operations are required (i.e., *Min. dr.*), Equations 6-8 to 6-10 are useful, as well as the information presented in Table 6-4 and Table 6-5. The rivet disengaging force (for each rivet shank removal) can be calculated as 3193 N. The calculated total cutting force (drilling through the countersunk head only), and the total normal force component (including the total rivet disengagement force component) are 2.55×10^6 N and 4.65×10^6 N respectively.

Table 6-4 Rivet shank and the hole evaluative parameters and value to calculate Disassembly Difficulty Calculator (DDC); these are applicable if a hammer and chisel are used for disengagement

Rivet Shank		Hole	
Factors	Values	Factors	Values
Young's Modulus, *Ei* (GPa)	75.8	Young's Modulus, *Eo* (GPa)	73.1
Poisson's Ratio, *vi*	0.292	Poisson's Ratio, *vo*	0.330
Shank Internal Diameter, *di* (mm)	0.000	Hole Outer Diameter, *do* (mm)	800.00
Shank Nominal Diameter, *d* (mm)	3.968	Hole Nominal Diameter, *d* (mm)	3.968
Shank Upper Tolerance (mm)	0.030	Hole Upper Tolerance (mm)	0.013
Shank Lower Tolerance (mm)	0.015	Hole Lower Tolerance (mm)	0.000
Shank Maximum Diameter (mm)	3.998	Hole Maximum Diameter (mm)	3.981
Shank Minimum Diameter (mm)	3.983	Hole Minimum Diameter (mm)	3.968

Table 6-5 Calculation of the generated pressure between the rivet shank and the hole, the disengagement force and eventually the hammer speed to calculate Disassembly Difficulty Calculator (DDC); these are applicable if a hammer and chisel are used

Pressure generated between rivet shank and hole		Required Force to Disengage rivet shank and hole	
Factors	Values	Factors	Values
Maximum Radial Interference, δmax (mm)	0.0150	Width of Hub, w (mm)	6.22
Minimum Radial Interference, δmin (mm)	0.0011	Friction Between Shaft and Hub, μ	0.30
Max Pressure Generated, *p*max (MPa)	137.3	Area of Contact, *A* (mm^2)	78
Min Pressure Generated, *p*min (MPa)	21.1	Force Required, *F* (N)	**3,193**

The DDC is calculated for *Cut.*, *D. Dr.* and *Min. dr.* providing that $\theta = 90°$ between the thrust and cutting components, as shown in Figure 6-5. The *Min. dr.* difficulty in both tangential and normal components is preferable over the *Cut.* and *D. Dr.* operations, according to the presented results. It should be noted that the final results would vary significantly with any change(s) in product and process-related features. Decisions made during the design and manufacturing stages (with respect to the attachments, fastening methods, Bill of Material (BOM), etc.) as well as in the final disassembly phase can all bring new dimensions to the disassembly difficulty of an aircraft structure.

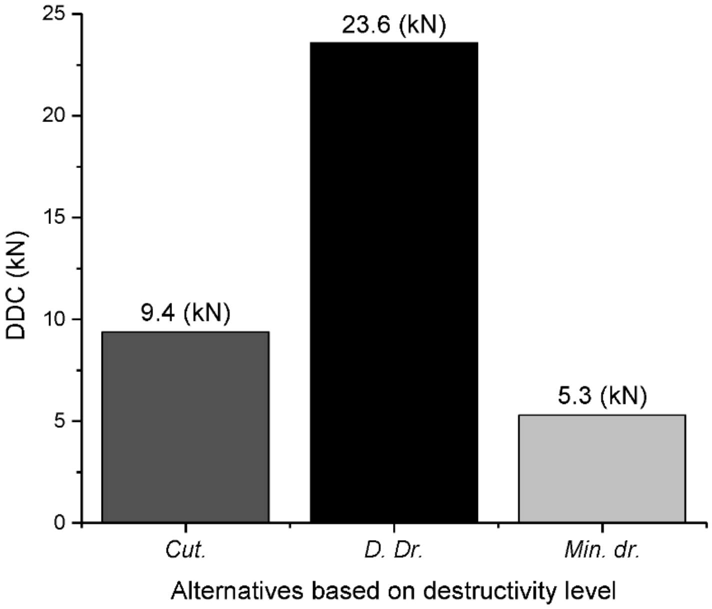


Figure 6-5 Calculated DDC (kN) for the complete set of operations

The presented approach tackles the problem from the disassembly-easiness perspective. From the corporate side, such quantitative assessment can significantly contribute to the selection of the more appropriate materials at the design stage of the aircraft structure (i.e., airframe materials including the parts/modules, fasteners and attachments) when small changes would be highly effective to the EoL performance of the whole aircraft (thousands of aircrafts coming to the EoL phase in future.) From the disassembly industry however this can considerably facilitate the selection of the convenient tools and disassembly methods paving the way for more coordinated disassembly planning processes. Nevertheless, the optimal disassembly strategy and the selection of the operations in a disassembly sequence is achievable only when an appropriate vision with respect to all of the variables are present. The authors are currently working on such multi-variable analysis which will be published in future.

6.7 Conclusion

In this study, a new evaluative model is presented to quantitatively assess the disassembly difficulty before the physical operations start, based on the full application of the product and process-related features. In terms of the mechanics of semi-destructive disassembly, the tangential and normal force vectors are shown as key factors that indicate disassembly difficulty. To allow the disassembly friendliness of an airframe to be taken into consideration during the design and EoL stages, related driving parameters are also identified and classified. Using this method, the disassembly becomes easier, time spent decreases, accurate tool selection is achievable and the overall process becomes economically viable. More importantly, new connections are established between designers and EoL sectors to boost their collaboration in favour of disassembly and EoL-oriented products. Applications in other domains such as ship and train industries are also expected due to the similarities. Moreover, this can facilitate performing automated-disassembly processes (robot design, tool selection, etc.), allowing for further improvements to EoL treatment process.

6.8 Continuing and Future studies

From a technical perspective, researchers are strongly encouraged to conduct new works in defining pre-sort strategies as well as improving post-disassembly operations since frequent problems are encountered in these areas, according to our experience in the field. This is a growing field and new challenges continue to appear in both academic and industrial areas. The authors are currently working on other technical aspects of disassembly operations including multi-variable evaluation of the disassembly process as a complementary work to this research. Our findings will be presented in a future publication.

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CHAPTER 7 ARTICLE 4: A MULTI-VARIABLE ANALYSIS OF AIRCRAFT STRUCTURE DISASSEMBLY - A LEARN-BY-PROGRESS APPROACH FOR APPLICATION OF A SEMI-DESTRUCTIVE METHOD

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Abstract

End-of-Life (EoL) process of aircraft is becoming an urgent issue in today's aviation industry. Airframe disassembly, as a principal step, has always been a challenge in terms of the required effort and regained values. In this paper, results of our experiments on disassembly and decommissioning of a mid-range airliner indicate that multiple-variable analysis is essential in order to determine the performance of each operation prior to commencing physical work. There are various driving factors in each of these processes and failing to apply this analysis to any one of them could result in either significant economic loss or environmental and/or social inconvenience. The methodology used in this study is an in-depth quantitative assessment known as a Multivariable Disassembly Evaluator (MDE). It explores; (1) time, (2) difficulty and, (3) material compatibility of the airframe parts/modules to ensure that the defined disassembly strategies meet technical, economic and environmental objectives. For a defined strategy including a definite set of operations, this approach allows an ideal EoL-customized disassembly operation to be selected. A Horizontal Stabilizer (H.S) on a regional airliner is chosen as a case study to provide thorough, detailed illustrations comparing the proposed approach to conventional disassembly. The method used for the case study includes airframe disassembly site visits, aircraft documentation analysis, interviews with experts and disassembly examination over a three-year period. The findings demonstrate that the proposed method is easier to complete, faster and allows the user to gain more recovery than other current approaches for an aircraft H.S. These advantages are an important contribution to the field of airframe disassembly since they can be used by disassembly sites, aircraft owners and manufacturers.

Keywords: Airframe disassembly; quantitative disassembly assessment; Aviation EoL; Aircraft decommissioning; Semi-destructive disassembly.

7.1 Introduction

Decommissioning of aircraft is becoming a global issue as today's society works towards sustainable production. The increasing number of retired aircraft plus the scarcity of materials makes it necessary to systematically process huge metal reserves that have been abandoned around the globe. Mascle et al. summarize the aircraft EoL process as 4 discrete steps: 1- decontamination, 2- disassembly of re-usable or remanufactured parts, 3- dismantling of the remaining carcass and, 4- material recovery, revalorization and/or landfill [Mascle et al., 2015]. Amongst the available methods of airframe EoL processing (storage, artificial reef, semi-destructive disassembly, totally-destructive and entirely non-destructive), semi-destructive disassembly has several advantages: 1- superior speed, 2- considerable ease of application and, 3- operational flexibility. In comparison, EoL performance of totally destructive and entirely non-destructive approaches can suffer from either economic or environmental perspectives. EoL treatment of products is often governed by economic considerations [Chen et al., 1993]. For example, the piece-by-piece or detailed disassembly that occurs systematically in entirely non-destructive methods significantly increases the total time required and also requires specialized knowledge to complete. This can be a logical alternative for certain cases such as maintenance purposes or disassembly of re-useable or remanufactured parts (second step of the aircraft EoL process). However, according to *in-situ* tests, application of this alternative for dismantling a remaining carcass will likely result in an operational cost surplus and is therefore not feasible from an economic standpoint. The other extreme alternative, totally-destructive disassembly is a relatively fast process but presents further difficulties in terms of the quality of the recovered-materials (mostly aluminium alloys for the case of airframe EoL). It is apparent that each method has its own inherent advantages and disadvantages. An optimal operation is a trade-off between driving factors. Making these trade-off choices requires a well-rounded knowledge of aircraft structural elements (types of materials, types of fastening and joining parts, etc.), disassembly challenges and also post-disassembly constraints (i.e. recycling requirements). In this study, a multivariable disassembly model is proposed for determination of the most economically feasible disassembly scenarios for the case of semi-destructive operations. An aircraft Horizontal Stabilizer (H.S) on a retired mid-size passenger jet is presented as a case study to demonstrate the application and effectiveness of the proposed methodology.

7.2 Literature review

Disassembly, as stated in research works, is applying a systematic approach to recover desired part(s), sub-assemblies or group(s) of component(s) of a given product. Reusable parts required for a specific purpose must be separated from the recyclable ones [Zandin, 2003, Lambert and Gupta, 2004, Gungor and Gupta, 1998]. The process could be either partial or complete disassembly. Dasai and Mital classified them from a perspective of destructivity as follows; 1- destructive or brute force approach, 2- non-destructive disassembly or reverse-assembly [Desai and Mital, 2003]. The semi-destructive approach was not included in these classifications. It is a flexible and productive technique and has been successfully used and proven beneficial in more recent studies [Vongbunyong et al., 2015a, Vongbunyong et al., 2013a]. This technique can be particularly useful for airframe disassembly because the number of fasteners can reach 100,000 (military fighter jet) or even 1 million (commercial airliners) depending on the type of aircraft [Eastman, 2012]. The study of aircraft disassembly can be subdivided into several research fields at various levels. The following literature review provides a survey of current knowledge according to applicable research areas.

7.2.1 Disassembly evaluation

Product disassembly addresses the issues related to the facility of its components/subassemblies to be disjoined and/or unfastened for different purposes (servicing/maintenance, recycling, remanufacturing, etc.). Often referred to as ease-of-disassembly, this process depends upon various parameters such as the required force exertion, accessibility, weight, size of the parts, etc. Kroll and Hanft used a quantitative approach, defining task difficulty scores printed on a spreadsheet-like chart to be assigned to the different parts [Kroll and Hanft, 1998]. In a similar manner, a time-based numeric approach is presented by [Desai and Mital, 2003] in which they apply a systematic methodology by assigning various indices to different design factors to allow a quantitative evaluation of the disassembly process. Anomalies identified can then result in a series of design modifications which will significantly increase disassemblability of a product. These results stress the following design anomalies as they gain the highest scores; 1-need for excessive force, 2-

component shape, size and weight and, 3- accuracy of tool positioning. Although these results are useful, these methods may face limitations when dealing with giant sophisticated structures such as airframes; the number of parts may become overwhelming. Wang et al. proposed a disassembly evaluation method in a Virtual Environment (VE) based upon incorporation of principle criteria such as visibility of the sub-assembly part and disassembly angles [Wang et al., 2016]. The method's ability to deal with complex structures by virtual simulations may be advantageous for sophisticated structures. Ng et al. also proposed a quantification method to evaluate the tendency of a product to facilitate the EoL decision-making procedure [Ng et al., 2014]. The process principally deals with returned-product management. The quantification method includes several criteria such as "wear-out life", "change of dimension" and "cleanliness level" to enhance bottom line performance and to ensure sustainability. Product EoL performance assessment is also the subject of a study by Lee et al; a so-called "EoL index" is defined to evaluate the EoL performance of products during the design stage [Lee et al., 2014]. The procedure to calculate this index takes into consideration various EoL criteria such as joint types, detachability and recycling processes. A weighting scale is then applied using the Analytical Hierarchical Process (AHP.)

7.2.2 EoL Airframe disassembly

According to the Aircraft Fleet Recycling Association (AFRA), the number of obsolete aircraft are increasing and will reach 12,000 in next two decades [AFRA, 2016]. Airbus is expecting 8453 narrow and wide body aircraft to be retired during the period from 2009 to 2028 [Van Heerden and Curran, 2011]. Asmatulu et al. have conducted research on the possible benefits of recycling aircraft parts [Asmatulu et al., 2013a]. They show that recycling of these parts can noticeably reduce energy consumption, labour and emissions, bringing both economic and environmental benefits. A similar recycling-oriented research in aerospace EoL is carried out by Asmatulu et al., analyzing the recycling effort associated with aircraft EoL at aircraft companies in Wichita [Asmatulu et al., 2013b]. This research includes a cradle-to-gate inventory analysis to perform a life-cycle assessment. The study indicates that the potential energy saving from aircraft recycling (1,765 planes and 1,029 major components) is equivalent to the annual electricity consumption of 10,510 local households. Feldhusen et al. studied the applicability and similarities between naval, automobile, railway and aviation EoL life-cycle approaches [Feldhusen et al., 2011]. Economic and environmental driving forces are set forward and analyzed more deeply due to their decisive role in the EoL process.

7.2.3 Aerospace material recycling

According to our experience gained in the ENV-412 project (Process for Advanced Management and Technologies of Aircraft End-of-Life), recycling of airframe materials is one of the biggest challenges in the aircraft EoL procedure. This complexity has several dimensions, most notably the presence of toxic and hazardous materials as well as impurities. Even though research work in this field includes studies that have been initiated with synergy between academia and industry, the overall volume of literature dedicated to this topic is low and there is still much to learn. Paraskevas et al. conducted a parametric LCA research for determination of optimal metal inputs into the Al recycling process based on the target alloy specification [Paraskevas et al., 2015]. This research focuses on the contamination of Al scraps by alloying and impurity elements, a common challenge in the field of recycling. Their results highlight the importance of material selection, which is the subject of research by Prendeville et al. [Prendeville et al., 2014]. In this research, essential material information is provided by external stakeholders through a supplier development program to ascertain the eco-efficiency of the products. Recovering and separation of the metal layers during aircraft disassembly/recycling is the subject of research by Benyahia and Hausler [Benyahia and Hausler, 2016]. The most obvious finding to emerge from this analysis is that use of high amounts of concentrated hydrochloric acid and application of an electrochemical process greatly boost the speed of layer separation, making it fourteen times faster. This results in separation of several waste metal layers of an aircraft wing (i.e. aluminum). Eckelman et al. carried out research to determine the reduction in greenhouse gas (GHG) emissions associated with recycling of aerospace alloys [Eckelman et al., 2014]. The results demonstrate a strong and consistent reduction in GHG emissions for ten common aerospace alloys, as a substitution for virgin materials. An interesting study was conducted by Lerma et al. with the aim of thermal decoating of aerospace-grade aluminum [Lerma et al., 2016]. The study addresses a very common, yet complex difficulty in this field which has resulted in massive disposal of untreated aluminum in graveyards.

In summary, there are many important parameters that significantly influence the EoL disassembly process. Failing to properly address any of these variables causes inefficient solutions, which are currently being practiced in actual disassembly works. It is apparent from this literature review that there is currently no solid study scrutinizing all of these crucial parameters together on a real airframe EoL with particular attention to semi-destructive techniques.

7.3 Objectives and methodology

7.3.1 Objectives

Dismantling an airframe consists of disassembly using either destructive or non-destructive techniques or a portion of each based on the defined EoL scenario(s). Defining the overall scenario is extremely important since it directs elaboration of the individual EoL procedures outlining the details of each disassembly operation. A scenario answers the questions presented in Table 7-1.

Table 7-1 Principle questions answered by a disassembly scenario

Questions	Description
Operation Placement	Which part/module of the product should be targeted first to be disassembled (mainly for complex products where disassembly could be started in different places)?
Disassembly Process-Selection	Once the place is fixed, what distinct kind of operation should the product undergo?
Disassembly Depth	To what degree a part/module should be disassembled (semi-destructively) to meet the performance objectives?

A defined scenario is not feasible to perform if not properly analyzed and evaluated. This is due to; 1- uncertainties associated with disassembly operations, 2- disassemblers frequently do not have a precise vision on disassembly efficiency other than performing punctual decisions that appear logical. These are the main reasons for technical difficulties as a result of inappropriate disassembly configuration set-up (selection of an inappropriate module/part, disassembly method, and pathway). The aim of this research project is therefore to develop a multiple-variable disassembly model of metallic structures and to evaluate its effectiveness. We are concentrating on smart, selective material recovery rather than total recovery to ensure the satisfaction of three parallel interests; environmental, economic and technical. Our goal is to establish a systematic framework for a technical assessment with the capability to select the most feasible disassembly scenario.

7.3.2 Methodology

A thorough step-by-step methodology is proposed in order to meet the defined objectives. The following flowchart illustrates the disassembly process steps required to reach the desired depth.

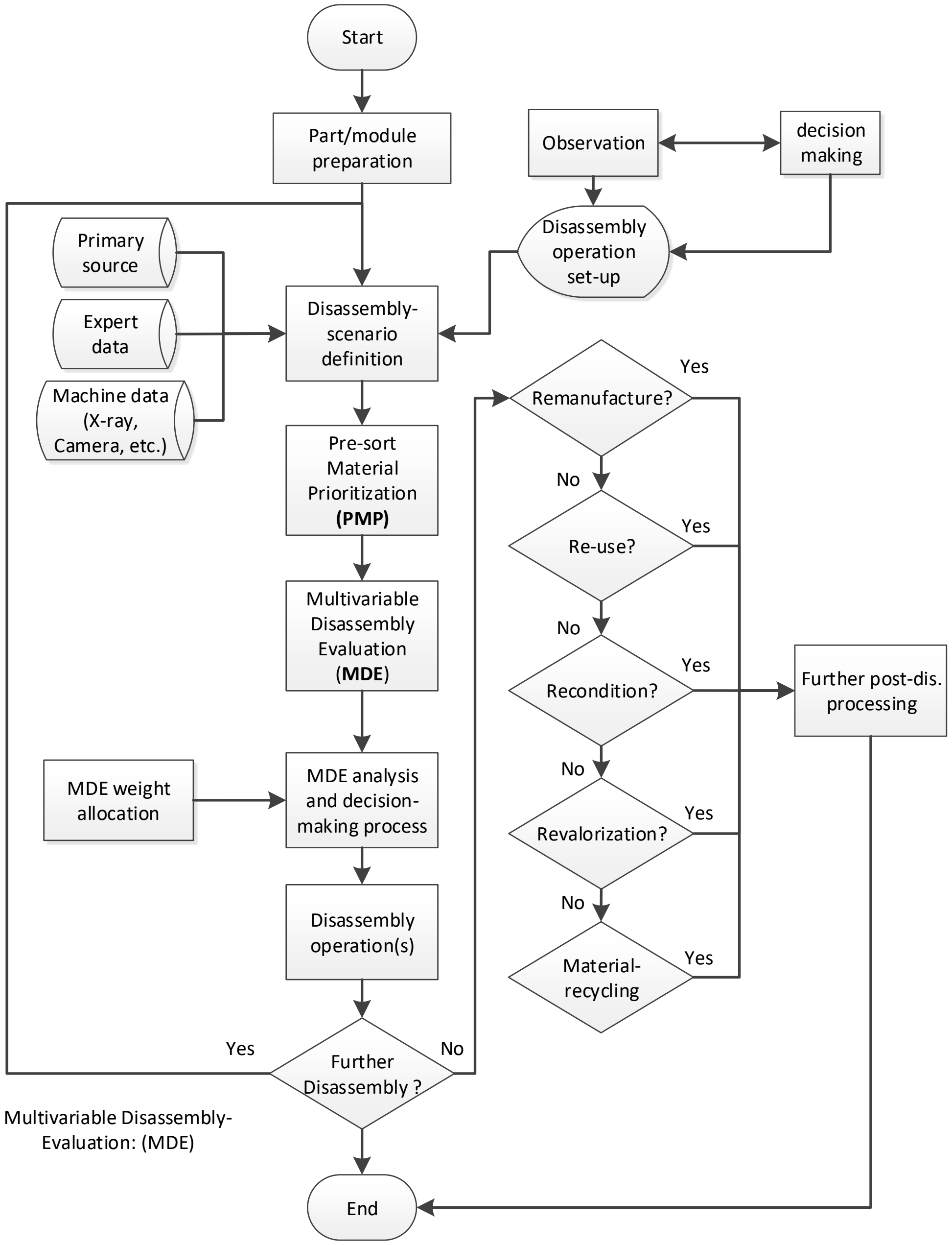

Figure 7-1 aircraft structure disassembly process steps incorporating the scenario definition, PMP, MDE and physical operation stages

The key steps are:

- Preparation of the part/module.
- Formation of structural knowledge and database (conventional and *learn-by-progress* approaches);
- Disassembly crude scenario definition;
- MDE formation and calculation of the associated MDEs for each scenario;
- Comparing and analysing the MDEs results with respect to each scenario and analysis;
- Determination of the best strategy with respect to MDE comparison and PMP analysis;
- Preparation of a set of recommendations for aircraft breaker sites.

In an attempt to answer the first of the principle disassembly questions in Table 7-1, the specific module has to be selected. This is especially important when dealing with a relatively complex structure such as an aircraft, where the body is composed of various metallic elements and alloys with considerable weights, and various degrees of complexities. Once the operation placement is made, disassembly scenarios are defined by allowing the MDE model to proceed with a series of evaluations and analysis to find the most fitting solution with respect to our previously defined objectives.

7.3.3 Preparation of the part/module;

EoL disassembly parts/modules are often large, heavy and awkward shaped, resulting in extra difficulties when it comes to stabilizing, handling and moving them. Depending on the domains and the conditions of application they might contain hazardous materials capable of causing significant damage to both humans and the surrounding environment. As such, preparation for EoL part/module disassembly includes a primary observation to identify and plan for retrieval of all potential hazards in order to pave the way for further disassembly operation steps.

7.3.4 Formation of structural knowledge and database (conventional and learn-by-progress approaches);

Accessibility to aircraft standard documentation is essential for EoL aircraft disassembly analysis, particularly because of differences in design procedures for each aircraft. Although there are also similarities between aircraft (especially those made by the same manufacturer), design variations can significantly contribute to disassembly inefficiencies (increased time, difficulties and low-class material quality) and in some cases even lead to severe damage and injuries (i.e. machinery and facility damage, explosives, toxic materials etc.). These standard documents are principally; 1- Structural Repair Manual (SRM), 2- Aircraft Maintenance Manual (AMM) and, 3- Aircraft Illustrated Parts Catalogue (AIPC). They provide essential knowledge required for an optimal disassembly process including the aircraft structural and cabin layouts, principle structure locations and cargo compartment layout (location, entry, dimensions, etc.), shapes and cross-sections of the fuselage, wings and stabilizers, distribution of fuel and fastener and attachment types (wing spars, stabilizers and fuselage). A promising disassembly scenario is feasible only when a minimum amount of information, known as “essential data”, is available. This information needs to be created, and is not available by default in the conventional disassembly process.

7.3.4.1 Conventional data-creation

Conventional data is obtained from the following sources; 1- primary sources, 2- expert data and, 3- machine data.

A primary source includes any data sheets, documents at the time of manufacture (or later), illustrations, etc. that can help disassemblers gain a deeper understanding of the product at the disassembly stage. It is important to consider that most of these products are outdated, and probably manufactured years or decades ago. For this reason, access to this type of information is not guaranteed. For aircraft, accessibility could be severely limited due to the sensitive/confidential nature of manufacturer’s data, insufficient infrastructure and security issues both at National, and sometimes International levels. In these circumstances technical domain specialists should be consulted to provide a set of observations and analysis, referred to as “expert data creation”. Regardless of these impediments, today’s technological advancements, especially in reverse engineering, provide an efficient means of data creation which is very helpful for the case of EoL disassembly. Modern techniques have paved the way for the introduction of autonomous disassembly approaches. Non-Destructive Testing (NDT) techniques and visual inspection (vision-based approaches) are processes that have been successfully applied for product disassembly and are capable of locating fasteners and scanning the product geometry [Liu et al., 2006]. In this study, analysis for material ID is completed using a handheld Niton X-ray gun by Thermoscientific. This allows rapid alloy verification of parts/modules to be disassembled and can significantly facilitate critical decision making.

7.3.4.2 The learn-by-progress technic

One of the biggest challenges in EoL disassembly is the large number of uncertainties and geometry variations that need to be taken into account. Although having full access to conventional data formation (which cannot be easily acquired or in some cases might be impossible) is crucial, our experiments on Bombardier's Canadair Regional Jet (CRJ) series airframe disassembly revealed far more uncertainty-related complexities than expected. A more flexible approach, known as "learn-by-progress" is therefore proposed to boost data extraction while the disassembly process is in progress. It includes partial disassembly of part(s) in order to gain access to disassembly-critical elements that are not visible. Using the example of a metallic chamber composed of three parts (excluding the fasteners) illustrated in Figure 7-2, a disassembly operation is planned to recover the metallic materials. Parts A, B and C are made of aluminum 2024, 7075 and 7050 alloys (typical commercial aircraft structure materials) respectively. Provided there is neither conventional insight nor any visual assistance on space D, no further information associated with the parts accommodated within space D is available without removing part C. For this reason, two series of fasteners (twelve a_1 and a_2 countersunk head fasteners) connecting parts A and C (referring to the mating surfaces $M.S_{CA1}$ and $M.S_{CA2}$ respectively) are removed and retrieved. The appropriate information within space D (the number of fasteners, their positions, materials, etc.) is now attainable. The connection between part B and part A using mating surfaces $M.S_{BA1}$ and $M.S_{BA2}$ and two series of fasteners (twenty-two b_1 and b_2 cheese-head fasteners) is fully identified and processed using the learn-by-progress technique. This would not have been possible if the parts were disassembled using conventional techniques (i.e., ignoring the pre-sort operations with respect to the necessary data generation, as seen in total crush technic) due to the lack of knowledge of the content. This experience shows that the conventional data source *per-se* could easily lead to unintended damage and inappropriate material mixture (or loss) resulting in a drastic reduction in performance (quality of output materials, difficulties due to possible extra-rigid materials, hazards, etc.). This technique is particularly useful for modeling and trade-off assessment decision making.

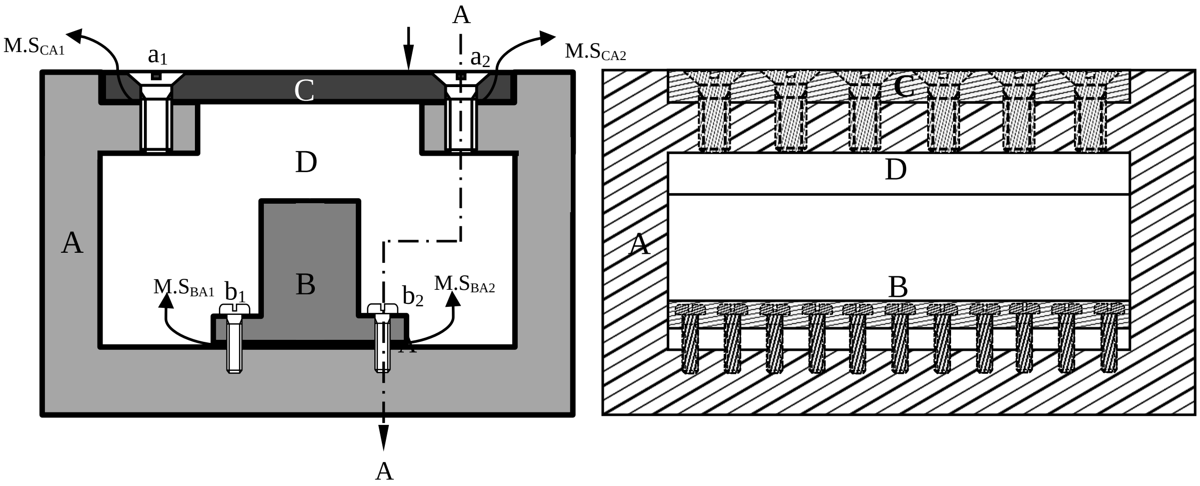

Figure 7-2 Learn-by-progress disassembly technic applied on a metallic chamber. a) front-view; b) side-view cross-section

7.3.5 Crude scenario

The so-called “crude scenario” is a baseline incorporating a very initial disassembly layout to define the operation placement (see Table 7-1). This primary scenario is based upon identification of two elements; 1- fasteners (generally lines of fasteners) and, 2- a primary level of material alteration (material change of the part/module’s outer skin). Considering the metallic chamber example, fastener lines a_1 and a_2 including twelve fasteners are the first targets. Following this, parts A and B consisting of two different alloys, 2024 and 7075 respectively, should be unfastened. In this example, the removal of fasteners and material changes accidently require identical disassembly actions, which is known as “overlapping-rules”. Regardless, it should be mentioned that the MDE analysis must take place before the most fitting scenario can be delineated.

7.3.6 EoL disassembly method definition

Various disassembly techniques are used principally by on-site practitioners to perform disassembly tasks according to the given scenario. Semi-destructive disassembly includes three major disassembly techniques as follows:

Cutting (C): This process includes parts division using brute force. It treats mainly surface-visible materials such as fasteners and skins, although in-depth disassembly is also possible.

Deep drilling (DD): The process of deep drilling a hole into a permanent fastener, such as a rivet, to disjoin mating surfaces.

Minor drilling (MD): Similar to the “deep drilling” technique, it consists of light drilling only to remove the fastener’s head and then using a starter guiding bit to punch out the internal sleeve.

Each of these disassembly methods has various operation set-ups that, once configured, together can perform the given tasks.

7.3.7 Multivariable Disassembly Evaluator (MDE)

MDE is a linear disassembly evaluator used to bring a multi-variable vision of disassembly performance based on four principle disassembly axes;1- difficulty, 2- time, 3- material compatibility and, 4- weight.

7.3.8 Disassembly Work (W_D)

Evaluation of disassembly difficulty has always been amongst the top-priority criteria of disassembly assessment approaches. The objective is to provide either qualitative or quantitative evaluation of the disassembly effort prior to beginning disassembly work. This is very helpful in order to select; 1- the right module/part, 2- the right disassembly operation method and, 3- the appropriate disassembly tool. According to a model developed by Zahedi et al. [Zahedi et al., 2016], a disassembly-effort assessment is measured quantitatively using thrust and cutting force vectors when semi-destructive/destructive operations are performed. Depending on the type of operation, the associated required forces are calculated using the Disassembly Difficulty Calculator (DDC) presented in Equation 7-1.

$$DDC = \sum_{i=0}^{n} \left(F_{Drilling} + F_{Disengaging} + F_{Grinding} \right) \qquad (7-1)$$

Where,

F denotes the associated disassembly force vector, *i* is the selected part/module to disassemble at any time and *n* is the total number of disassembly operations for a given part/module. In this study, the semi-destructive disassembly process includes either a single drilling, disengaging and grinding force vector or a combination of these vectors, known as a hybrid operation. The selection procedure is based on the defined scenarios. The corresponding force vectors are calculated using the following relations:

$$MRR = dwv \tag{7-2}$$

$$Power = u \times MRR \tag{7-3}$$

$$Power = T \times \omega;\ and\ T = F_c\,.\left({}^{D}\!/_{2}\right) \tag{7-4}$$

Where, *MRR* stands for material removal rate, *d* for depth of cut, *w* for the width of cut, and *v* for the grinding feed rate (the amount of tool travel per unit time). The cutting power (*Power*) is calculated using the *MRR* and the specific cutting energy (*u*). Grinding power is calculated based on grinding specific energy and *MRR*. If a drilling operation is selected, F_C is calculated using the chip cross-sectional area (A_C) and the specific cutting energy for the drilling operation (u_d):

$$A_c = {}^{Sd}\!/_{4} \tag{7-5}$$

The A_C for a drilling operation is a function of the drilling feed rate (*S*) and the drill bit diameter (*d*). The thrust force component is more difficult to calculate, although Shaw suggests the following equation which provides good results [Shaw, 2005]:

$$\frac{F_n}{d^3 H_B} = 6.962\frac{f^{0.8}}{d^{1.2}} + 0.68\left(\frac{c}{d}\right)^2 \tag{7-6}$$

Where,

d = drill diameter in mm, *HB* = Brinell hardness in kg mm-2, *f* = drill feed rate in mm/rev. and F_n = drill thrust force component in N. If disengaging a rivet is selected, the following equation is used [Nisbett et al., 2008]:

$$P = \frac{\delta}{\frac{d}{E_0}\left(\frac{d_0^2 + d^2}{d_0^2 - d^2} + \upsilon_0\right) + \frac{d}{E_i}\left(\frac{d^2 + d_i^2}{d^2 - d_i^2} - \upsilon_i\right)} \tag{7-7}$$

Where d is the nominal shaft diameter, E is Young's modulus, δ is the diametral interference between rivet shank and the hole, d_i is the inside diameter of the shaft (if applicable), v is Poisson's ratio, and d is the nominal shank diameter. o and i denote the outer member (hole) and inner member (shank), respectively.

7.3.9 Disassembly time

The disassembly time-spent is one of the most qualitative parameters to measure since it can significantly differ from one operation, module or even practitioner to another. In this study the disassembly time measurement has two components; 1- primary operation time (T_{POT}) and 2- secondary operation time (T_{SOT}). The T_{POT} component, as a theoretical approach, measures a series of elapsed times associated with each metalworking disassembly operation (grinding, cutting, drilling and/or disengaging). T_{SOT}, however includes calculation of the average elapsed time by different practitioners through a series of direct on-site data-collection rounds, practical approach. The latter includes values associated with tool-changing or even tool re-positioning operations (secondary operations). T_{SOT} includes tool verification time ($T_{T.Ver.}$) and operator downtime (fatigue), referred to as ($T_{O.D.}$).

In this study the "practical approach" is used whenever secondary operations are applied whereas the "theoretical approach" is used when primary operations are in progress. The total time spent, T_T can then be written as follows.

$$T_T = T_{POT} + T_{SOT} \qquad (7-8)$$

$$T_{SOT} = T_{T.Ver.} + T_{O.D.} \qquad (7-9)$$

This measurement consists of several components depending on the type of metal-cutting operation. Table 7-2 demonstrates the relevant parameters in calculating the disassembly time with respect to *POT* and *SOT*. The required time in POT related parameters are calculated based upon the associated MRR (Equation 7-2) of each sequence operation (i.e., in metal cutting processes as discussed under cutting or drilling operations).

Table 7-2 Semi-destructive disassembly time measurement and driving attributes

Components	Symbols	Driving attributes	Description
POT	L_{POT}	Metal-cutting operation length (mm)	*Total length of the workpiece for a given disassembly sequence.*
	V_{POT}	Cutting feed-rate (mm/min.)	*The metal-cutting tool relative velocity through a given workpiece for a linear unit per minute.*
	$W.P_{POT}$	Workpiece velocity (mm/min)	*The W.P linear velocity given for one disassembly sequence.*
	VR_{POT}	Drilling speed (rpm)	*The rotational frequency or number of revolutions per minute.*
	D_{POT}	Disengaging-time (min)	*The average measured time for disengaging one rivet's internal collar.*
SOT	R_{Ver}	Verification-redundancy cycle (mm)	*The frequency of cutting tool verification process to avoid tool fails causing avoidable machine downtimes.*
	D_{Ver}	Downtime (min.)	*The average machine downtime to run a single process of T.Ver. based on numerous onsite measurements.*
	P_{OD}	Human-performance (min)	*The average metal-cutting length of a non-stop disassembly operation measured on an airframe-certified disassembly technician performance.*
	D_{OD}	Downtime (min)	*The average operation downtime due to human performance failure in one cycle.*

* T.Ver. (cycle) for drilling = x mm for a fastener application pitch of 3D or 4D (diameter of rivet) and not the number of fasteners.

7.3.10 Material compatibility

As noted by Das et al., the pre-sort strategy as well as the dismantling process are two principle challenges in increasing the EoL efficiency (recovery of alloys) of automotive products [Das et al., 2007]. Meeting these challenges effectively can remarkably facilitate the metal stream composition, allowing higher quality output material (i.e. avoiding the necessity to downgrade material while at the same time recovering at a reasonable cost and time investment). A pre-sort-oriented process plays a vital role in disassembly operations where various metallic alloys of homogenous or non-homogenous types are present. Airframe recycling, as in automotive recycling as noted by Das et al. [Das et al., 2010], is a relatively complex process. This is due to the existence of several alloy types, corrosion protection coatings and paint layers. These extra layers, depending on the type of substances, impose substantial difficulties requiring more advanced sorting and recycling technologies to obtain high quality output materials. That being said, some materials can be tolerated and processed (i.e. post-disassembly operations) together without significantly compromising output quality.

In this study, this possibility is referred to as “material compatibility” in reference to parallel studies on the processing of civil aviation EoL alloys in structural elements such as fuselage, stabilisers, wings, etc. If access is provided to the material composition of the part/module alloy(s), it should be possible to determine the compatibility of the materials. In this study we put emphasis on aluminium alloys for the following reasons; 1- up to 75% of aircraft total weight is composed of aluminium alloys [Airbus, 2008], 2- aluminium recycling energy consumption is only 5% of first-generation production [Asmatulu et al., 2013a, Das and Yin, 2007] at a recycling efficiency of 95% [Das, 2000]. The material characteristics of some Al alloys with notable aerospace applications are given in Table 7-3 [Schlesinger, 2007, Das and Kaufman, 2008]:

Table 7-3 Material characteristics of some alloys with noticeable aerospace applications

Alloys	**% Al**	**% Si**	**% Fe**	**% Cu**	**% Mn**	**% Mg**	**% Zn**
2014	93	0.8	0.7	4.4	0.8	0.5	0.5
2214	93	0.8	0.3	4.4	0.8	0.5	0.15
2024	93	0.5	0.5	4.4	0.6	1.5	0.25
2324	94	0.1	0.12	4.1	0.6	1.5	0.25
7050	89	0.12	0.15	2.3	0.1	2.2	6.2
7075	90	0.4	0.5	1.6	0.3	2.5	5.6
7475	90	0.1	0.12	1.6	0.06	2.2	5.7
7178	89	0.4	0.5	2	0.3	2.8	6.8
7175	90	0.5	0.2	1.6	0.1	2.5	5.7
7150	87.5	0.12	0.15	2.2	0.1	2.4	6.4

In this study, non-homogenous substances are classified into two levels of impurities; 1- first-level and 2- second-level. The first-level includes materials that do not belong to the module's dominant alloy pattern (i.e. small nickel-based parts in an Al-based module). The second-level consist of alloy pre-sorting operations (i.e. sorting of 7xxx and 2xxx Al alloys present in a given module.)

7.3.10.1 Pre-sort Material Prioritization (PMP)

In this research, a new approach is implemented to define a convenient material sorting strategy. Practicality is a key objective. A group of essential parameters are considered simultaneously to ensure the performance of the pre-sorting process. Material scarcity (*MS*), post-disassembly profitability (*DP*), and alloying tolerance (*ATr*) are the criteria of assessment to define the most fitting strategy. The PMP is then calculated according to the following relation:

$$PMP = MS \times DP \times ATr \qquad (7-10)$$

- *Material scarcity* is evaluated through analysis of the global material shortage with respect to the aeronautic market sector. As suggested by Bihouix and de Guillebon [Bihouix and de Guillebon, 2010], three criteria influence this calculation; 1- world production or aeronautic-sector consumption (*Pr*), 2- dependency or replicability (*Re*) and, 3- abundancy (*Ab*). If W_1, W_2 and W_3 denote weight factors associated to *Pr*, *Re* and *Ab* respectively, the material scarcity parameter can be defined and customized (according to the conditions of application) as follows:

$$MS = W_1.Pr. + W_2.Re + W_3.Ab \qquad (7-11)$$

- *Post-disassembly profitability* is the average value of pre-sorted (recovered) material(s).
- *Alloying tolerance* quantification requires a theoretical study of the composition of alloying elements to determine the depth of disassembly required for their recovery. Wider alloying element margins make the disassembly process easier. For example, consider a mix of two alloys containing 3 or 4% Zn. A target alloy requiring a maximum 1% composition of Zn needs more post-disassembly effort to recover than another target alloy with a Zn tolerance of 3 to 4%. It follows that the disassembly operation to recover an alloy that can tolerate 3-4% of Zn would be more economically viable.

7.4 Case study

In this section, a Horizontal Stabilizer (H.S) for a mid-size passenger jet, as illustrated in Figure 7-3, is studied in order to demonstrate application and suitability of the proposed approach (H.S structural details are shown in the Annex). The objective of this case study is to examine the performance of the PMP-based EoL scenario and MDE analysis, and validate its potential to boost the EoL disassembly process from multiple perspectives compared to the conventional scenario.

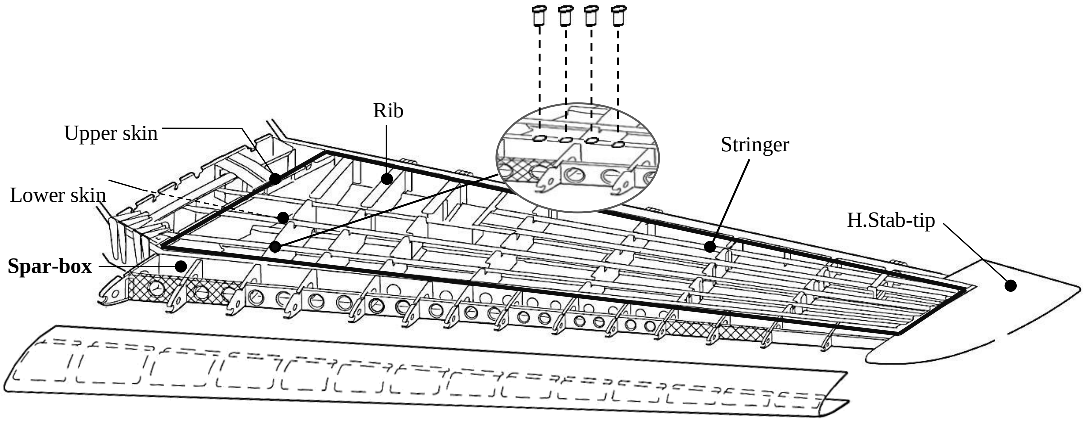

Figure 7-3 CRJ Horizontal Stabilizer (H.S) structural parts

The assessment procedure includes analysis of five different scenarios according to the following classifications; 1- conventional scenarios and 2- PMP-based scenarios.

7.4.1 Conventional scenarios

Scenario A: Master-module division

This scenario is the simplest approach to disassemble the H.S module. It consists of using a cutting operation to divide the whole module into two smaller sub-modules. This makes it easier to transport the parts, and also to verify the alloy content. On the other hand, since this scenario does not provide any information related to the internal structure of the module, pre-sort capacity and disassembly performance are expected to be very low.

Scenario B: Ordinary

This scenario includes drilling out all the fasteners along the rivet lines on the H.S skin layers. This allows for removing only non-homogenous materials (i.e., the fasteners' materials including nickel or steel alloys which are impurities in Al-dominant modules in recycling process). In other words, the objective is to remove the first source of impurities (i.e., fasteners' materials) rather than the recovery of the fasteners' materials themselves. This technique is a widely accepted practice for non-destructive disassembly.

Scenario C: Mild pre-sort

In an attempt to easily increase the efficiency of the disassembly operation without further complexities, a mild pre-sort scenario can be selected. This includes drilling of the fasteners, but only on the top skin and ribs. The bottom skin fasteners and rib structure remain intact. Although removing 1464 fasteners (58% of all the fasteners) on the top skin, doublers and stringers will reduce the impurities, the lower structure mix of Al alloys and fasteners can still cause issues during post-disassembly sorting and recycling operations.

7.4.2 PMP-based scenarios

Scenario D: Maximum alloy-level pre-sort

In this scenario, priority is given to the sorting operation prior to the post-disassembly phase, at the strictest possible level. This facilitates post-disassembly sorting and results in smoother procedures during alloy recycling. On the other hand, it may cause extra complexities with respect to the other driving criteria (i.e. work done, time, environmental, etc.). In some cases, it is not even necessary to do post-disassembly sorting (based on material compatibility and/or EoL accessible post-disassembly equipment.)

Scenario E: Hybrid scenario

This scenario includes crude disassembly of the upper skin (drilling), PMP assessment, cutting of the ribs and stringers, and cutting only the lower skin.

The crude scenario starts with processing of the outer extremity connections (i.e. fasteners, attachments) in order to gain access to the internal structure. Either *Dr* or *Min Dr* operations are selected due to their ability to conserve the internal structure by removing only the fasteners. This access to the internal space also helps improve pre-sorting capacity by removing extra sources of impurities (internal elements). More specifically, access to the H.S. control installation, elevator power control unit, mechanical path control element and PCU cantering mechanism is gained prior to the post-disassembly and recycling stages, as illustrated in Figure 7-4.

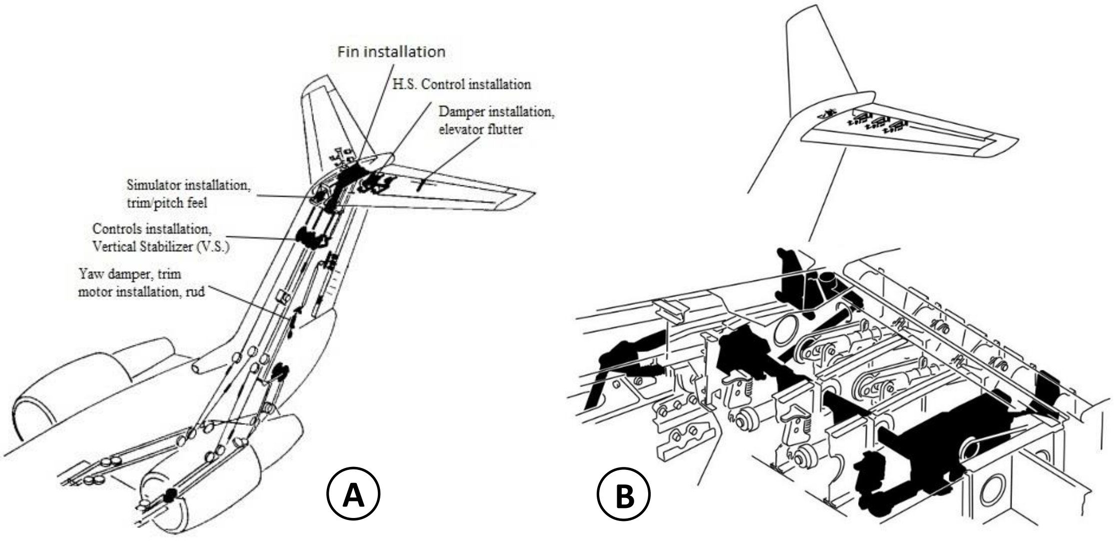

Figure 7-4 Accessing the H.S internal elements during disassembly prior to the post-disassembly and recycling stages to reduce the impurities; (a) Damper installation and elevator flutter; (b) Mechanical path control element

Once the secure access is provided to the internal structure, it can be X-ray tested to create fast and proper material mapping and a second-level impurity analysis.

If W_1, W_2 and W_3 are assigned values 0.2, 0.3 and 0.5 (values are set according to their relative degree of importance by the disassembly site or the manufacturer during the decision-making process), results of calculation of *Pr*, *Re* and *Ab* are given in Table 7-4 (according to [Bihouix and de Guillebon, 2010].

Table 7-4 Material scarcity status for alloys frequently used in the aerospace sector

Elements	Ab	Pr	Re	MS
Al	1	1	0.4	0.84
Ti	1	0.9	0.27	0.76
Ni	0.5	0.7	0.27	0.47
Cr	0.5	0.75	0.4	0.54

* these values are estimated; however, they accurately reflect the position of each element with respect to each criterion of comparison.

7.5 Results and discussion

PMP assessment is conducted to calculate material isolation priorities resulting in a more efficient disassembly procedure by avoiding unnecessary operations and/or reducing the use of less-efficient processes. *MS* values associated with metallic elements are calculated using Equation 7-11 and presented in Table 7-4. Since the content of aluminium in alloys used for aircraft structures/components is far higher than the other elements, the *MS* value calculated for Al is an acceptable estimation for these Al alloys. The corresponding *MS* values for Al 2024, 7050 and 7075 are 0.82 as shown in Table 7-4. The average post-disassembly market values of aerospace scrap metals are different depending on market location, scrap volume, recycling facility distance, etc., but 0.66 $/kg is an acceptable price for 7075 and 2024 alloys according to CMC [CMC, 2016]. Similarly, *ATr* values for Al 2024, 7050 and 7075 alloys, are also obtained with respect to their alloy families (i.e., 2xxx and 7xxx series respectively) and are 0.48, 0.14 and 0.1 respectively. The PMP values can be calculated using Equation 7-10, 0.11, 0.01 and 0.02. By dividing each value to the summation, the PMP prioritization values as 0.75, 0.10 and 0.15 are obtained respectively.

In addition to selection of disassembly process configuration and individual operations, the MDE analysis is carried out to determine the most efficient scenario. Table 7-5 presents the results of MDE analysis for alternative disassembly scenarios. The presented data indicate that, with the exception of scenario A, all scenarios eventually result in total material recovery (i.e. Al 2024 and 7075 alloys). Similarly, metallic impurities (related to the undesired blend of fasteners and internal structure control unit metallic materials) are also at lowest possible level for B, D and E scenarios. Scenario C can only remove 59% of metallic impurities due to drilling of only the top side of H.S fasteners. Note that scenario A does not provide any pre-sorting capability, which results in 100% metallic impurities.

Table 7-5 MDE analysis of alternative H.S EoL disassembly scenarios

Index	Op. type	Work done (kN.m)	Time (min)					Number of op. sequence	Dis.-Depth (%)	Material recovery (%)		Metallic-impurity (%)	Impurity recovery (%)
			POT	*SOT*	$T_{T.V}$	$T_{O.D}$	**Total**			2024	7075		
(A)	Cut.	0.1979	1.6	0.8	0.8	0	3.1575	1	0	0	0	100	0
(B)	Dr.	413.44	749.76	172.43	101.43	71	922.19	17+18	36	100	100	0	0
(C)	Dr.	215.15	392.11	97.11	62.41	34.7	471.48	17+18	34	100	100	41	0
(D)	Min Dr.	111.56	267.43	207.93	71	136.93	475.36	17	72	100	100	0	100
(E)	Min Dr. + Cut.	58.68	201.48	137.01	34.7	102.31	325.74	18+18+10	60	100	100	0.003	0.58

*the disassembly sequence includes a series of operations until there are no further feed rate direction changes.

Looking at Table 7-5, it is apparent that although scenario A requires the least work, it provides no material recovery capabilities, so no pre-sort or pre-shred possibility exists through its application. Further discussion will therefore focus only on scenarios B to E. As shown in Figure 7-5 and Table 7-5, scenario B requires the highest disassembly work and time investment. There is a clear trend of decreasing T_T down to scenario E, which requires only 325.74 min.

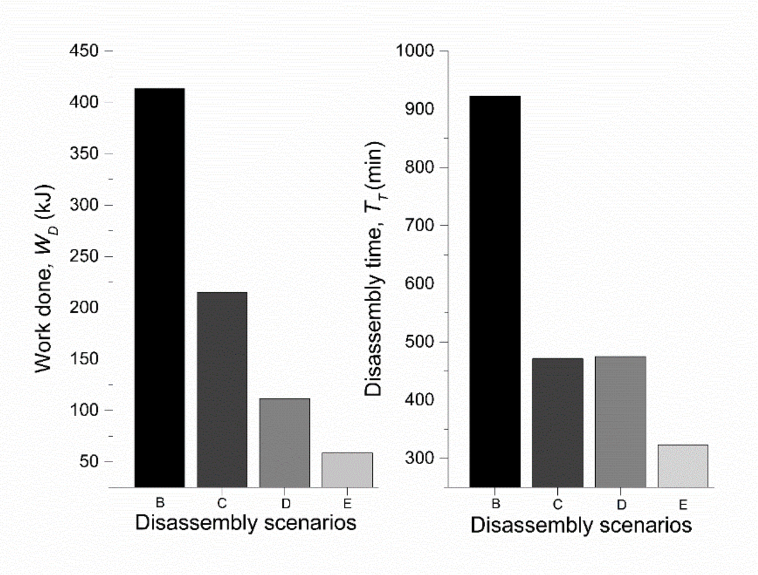

Figure 7-5 Disassembly work done and time analysis of scenario B to E carried on CRJ100 H.S aircraft

A striking observation from the data in Table 7-5 is the significant constant improvements in T_T and W_D based on a disassembly shift. This is also illustrated in Figure 7-6. However, an exception can be seen in T_T values shifting from C to D. Although the *POT* decreases by 31.8%, the results indicate increases in *SOT*, $T_{T.V}$ and $T_{O.D}$; 214.1%, 113.7% and 394.6% respectively. The results shown in Figure 7-6 also indicate a significant difference between scenario E and the others (esp. scenario B) which is a common trend in airframe EoL disassembly. This accounts for corresponding improvements of 85.8% and 64.96% with respect to T_T and W_D while offering the same 100% material recovery for both 2024 and 7075 Al alloys and very low metallic impurities of 0.003%.

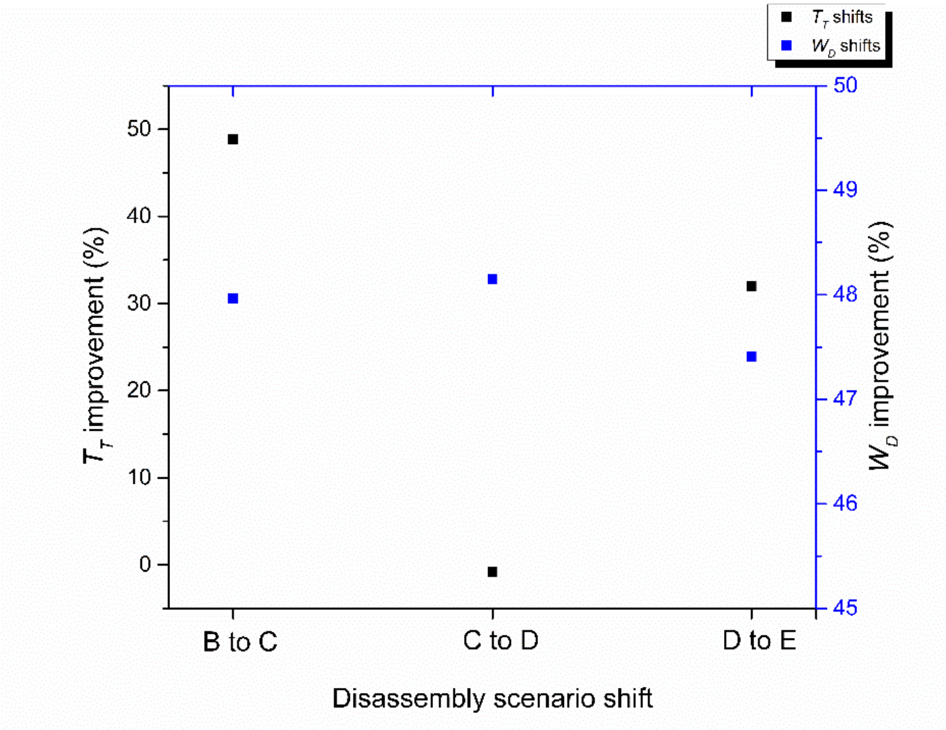

Figure 7-6 Disassembly T_T and W_D improvements due to scenario shifts

Similarly, scenario E compared to scenario B in conventional disassembly offers 74% and 22.5% higher performance with respect to *POT* and *SOT* respectively. Looking at scenarios E to D offers a close comparison between two MDE-based methods. Striking improvements in *POT* and *SOT* are observed; 27% and 35.6%. This remarkable performance associated with scenario E reflects the importance of systematic consideration of various disassembly metrics simultaneously. In other words, a common disassembly technique with a high sorting capacity can offer surprisingly poor performance with respect to time and required effort. Application of a combination of PMP and MDE is fundamental to allow these important observations to be made.

7.6 Conclusion

Disassembly of an airframe, a rich metallic structure, is a complicated task. This complexity is due to the presence of various fluctuating parameters each requiring proper attention. A literature review indicates that a multi-variable study with particular attention to semi-destructive disassembly approaches for the aviation sector does not exist. The aim of the present research was to develop a multiple-variable disassembly model to analyze the performance of disassembly processes. For the first time, crucial disassembly attributes on both technical (direct) and environmental (indirect) levels were studied extensively. The required effort, time, pre-sort/pre-shred capacity and impurity considerations are gathered and quantified as part of a comprehensive assessment procedure. MDE analysis of a real full-sized horizontal stabilizer belonging to a regional jet was completed by introducing five alternative disassembly scenarios. Results of this case study enabled us to conclude that an appropriate scenario based on PMP and MDE analysis outperforms common existing solutions for airframe disassembly by a large margin. This includes a drastic and consistent decrease in required effort (65%) and disassembly time (85.8%) while offering high rates of pre-sort and pre-shred capabilities. The case study reveals that the method provides a useful approach to identify a feasible EoL disassembly scenario. It demonstrates that multiple metrics should be tailored simultaneously to provide an efficient disassembly operation for aircraft structures. These important insights into airframe disassembly are relevant to both disassembly practitioners and aircraft manufacturers since they offer the potential to boost recycling of current airframes and make future aircraft easier to recycle.

7.7 Future insights

As a result of these investigations, suggestions were identified for future research. Despite these promising results, more pragmatic research is needed to gain a better understanding of alloy element recovery mechanisms and to provide greater insights into the analysis of the effect of impurities in sorting and recycling efforts. This new knowledge can be incorporated to develop reliable analytical methods for blend assessment and to establish effective methods to obtain fine recycled materials that can be re-injected into aerospace structures as high-grade materials without down-cycling.

7.8 Acknowledgments

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7.10 Annex.

Table 7-6 Horizontal Stabilizer (H.S.) structural details

Horizontal Stabilizer (primary & secondary structures)			**Fastener type** (Upper and Lower-skin)	**Number of fasteners** (Upper and Lower-skin)
Parts	**Material**	**Number of unit**		
Top skin	Al 2xxx	2	Rivet 5/32 (in) (upper); Bolt/screw VISU-LOK, (for lower)	1400
Bottom skin	Al 7xxx			1053
Stringers (7075 up, 2024 lower)	Mix (Al 7xxx + 2xxx)	4+4		Already counted in skins
Ribs (including inboard and outboard closures)	Mix (Al 2xxx + 7xxx)	13		
Attach/Attached fittings (Bracket + Flange +Web)	Mix (2xxx, 6xxx, 7xxx and steel)	37	**N/A**	
Skin doublers	Mix (Al 2xxx + 7xxx)	2		
Skin stiffeners	Mix (Al 2xxx +7xxx)	1		
Panels Access panel covers (PCU + flutter-dampener)	Mix (Al 2xxx + 7xxx))	2	Close-tolerance Bolts (in three types)	77 + 44
Leading Edges	6xxx	1	**N/A**	
Fillets and Fairing	Mix (composites, resin sheet, Al 2xxx, 5xxx and 6xxx)	11 + 5		
Spars	Mix (Al 2xxx + 7xxx)	2		
Shroud	Al 2xxx	1		
Total		**85**		**2574**

CHAPTER 8 GENERAL DISCUSSION

In this chapter, the general discussion of the thesis is presented highlighting the research incentives, topic development and findings.

Sustainable decommissioning of the aircraft with a high content of metallic and non-metallic components is a current challenge in the industry. The airframes’ rich metallic and non-metallic structure beside remanufacturability potential can provide significant economic, environmental and social advantages. Nevertheless, the literature indicates that only a small amount of airframe is currently disassembled due to the technical or economic constraints. The limited available resources, stricter EoL legislations and environmental restrictions are the key reasons pushing the manufacturers and disassembly sites to find new solutions.

The first stage of this thesis includes an establishment of a framework indicating what measures have to be taken in an efficient airframe disassembly. The developed roadmap suggests that the disassembly process be distilled into four principle questions to answer which explicitly settle:

1- the designation of the appropriate part/module to disassemble;

2- selecting the most fitting disassembly operation(s) to meet the efficiency requirements;

3- the determination of the depth of disassembly; this tends to increase the disassembly performance (directly affecting the effort-time criteria while also indirectly influence the economic and environmental measures) by fixing a disassembly depth to which a part/module has to be disassembled;

4- the appropriate post-disassembly operation(s) to carry out (e.g., the sorting technology, shredding measures, recycling strategy, etc.).

The first question is usually answered within a number of meetings with the technical domain specialists. The decision making process includes a series of visual inspections and some technical and hazard assessments. Compiling the methodology, it is shown that the stress has to be put upon an effective and accurate evaluation of the disassembly process. Over the years much has been written about the evaluation of the disassembly. However, only few researches have been conducted on the quantitative evaluation of the disassembly. Here, by quantitative evaluation, an accurate and reliable measurement of separation force is referred to rather than a set of scoring/ranking operations. The later may suffer from the lack of accuracy, inconsistency and repeatability by being highly dependent on the feedbacks obtained from the questionnaires. Unfortunately, the results of many papers do not represent the reality and might be unreliable with no formal inclusion of the domain-specific information (particularly in case of complex structures).

This spurred the research deep into the analysis of the disassembly mechanics due to its key role in the assessment procedure. The relevant study is channeled into the: 1- process related (low flexibility); and 2- product related features (high flexibility). This allows for an explicit separation of the variables with different natures. One refers to a category upon which there is relatively low control (product related features; since they are specified at the design stage) whilst the other provides higher flexibility and manageability (process related features; specified at EoL stage). The product features include the issues related to the material compatibility, geometrical features, and fastenings/attachments. Whereas, the process features encompass the selection of the disassembly place, process selection, process configuration and disassembly depth. It has been shown that neither the totally destructive nor manual disassembly may offer an efficient disassembly.

Consequently, semi-destructive (or partially destructive) operation is set to analyze due to: 1- its robustness leading to a better recycling of products; and 2- its current wide applications in EoL disassembly operations. The proposed approach is based upon the disassembly of a specific airliner. Thus, there might be a need for further researches in case of military airframes and/or airliners made by other manufacturers. The second question, outlined in the proposed roadmap earlier, is the subject of the next stage study presented in this thesis.

Four different disassembly technics are presented based on the simplicity, applicability and performance measures. This includes the: 1- cutting; 2- deep drilling; 3- minor drilling and 4- manual disassembly operations. A so-called “early purification strategy” is presented to fortify the pre-sort and pre-shred measures allowing for a promising separation of the incompatible alloys resulting in a higher grade recovery of material(s). The evaluation process encompasses the operation speed, accuracy and risks criteria. However, this does not englobe the quantitative evaluation of the difficulty, time and presorting variables which pleads to be discussed in the following separate researches.

The next topic is concerned with the evaluation of the disassembly difficulty using a quantitative approach. The four common disassembly technics, as presented earlier, are focused on in order to develop an assessment model. The disassembly operation, including the cutting and manual processes, depends upon several factors. The influencing parameters are determined and systematically classified into: 1- material characteristics (design related); 2- geometrical features (design related); and 3- process parameters (EoL related) channels. This encircles several driving metrics namely, material homogeneity (different spectrum of the product materials); mechanical properties; establishment of a comprehensive correlation between critical parameters etc.

The cutting and thrust force vectors are used in order to proceed with the analysis of the mechanics of the semi-destructive disassembly. As such, the product related features include the variables such as “the number of materials in a component”, “Brinell hardness scale (BHN)” and “instant sheet thickness”. Whereas, the process features consist of “tool speed (in both rotational and linear forms)”, “depth of cut”, “work-piece speed”, “machine efficiency”, etc. The advantages of this approach are that: it offers an accurate value of the disassembly effort once the operation place is fixed regardless of the type of parts/modules; it is also independent of the disassembly practitioner’s feedback (that may be influenced by the inconvenient worker’s posture resulting in the onset of static fatigue, absence of concentration, lack of knowledge, etc.) which provides a high degree of repeatability. However, assigning the appropriate values for all defined parameters may also further complicate the disassembly process.

The developed Disassembly Difficulty Calculator (DDC) including the grinding, disengaging and drilling force components is introduced for the first time. A Canadair Regional Jet (CRJ100ER) Horizontal Stabilizer (H.S) is presented as a case study highlighting the efficient disassembly operation with respect to the physical effort required. Nonetheless, the presented model could be improved by adding further parameters (i.e., disassembly tool selection difficulties, approaching problems, safety concerns, etc.) to improve its accuracy in real cases in future researches. Meanwhile, the non-destructive disassembly, as an important part of complex structure disassembly, is not considered in this work. Furthermore, there might also be other disassembly technics that can outperform the presented methods in terms of the disassembly difficulty. The data generation process could be improved in terms of the required time and quality in future researches. Eventually, a sensitivity analysis might also be of further interests to show which parameter(s), as compared to others, has (have) the most significant impact(s) on the difficulty level.

The last part of this thesis includes a Multivariable Disassembly Evaluation (MDE) process. The objective of this part is tailored to a complementary analysis allowing for selecting the efficient disassembly strategy. In the light of the above discussion, the disassembly effort criterion is only one element in the evaluation process although it is amongst the most important ones. The time, material compatibility and economic factors are also assessed and analyzed in this part. Various key attributes have been defined and put into practice, for the first time, in order to proceed with the disassembly time measurement. This includes machine downtime verification cycles, operator performance, cutting feed-rate, WP velocity, etc. The so-called "Pre-sort Material Prioritization" (PMP) is also proposed and implemented to organize a convenient material pre-sorting strategy. Based upon several discussion panels with project partners, the essential parameters are adopted and gathered under PMP category. It encircles the material scarcity, post-disassembly profitability and alloying tolerance. As such, various feasible disassembly scenarios are defined reflecting the most common operation schemes in industry. The most feasible scenario is then selected with respect to the calculated performance values associated with each principle attribute. Although a material prioritization is conducted in this research, deeper analyses are still needed to define more accurate scenarios with respect to the real experiments. The SOT is based upon some experimental tests which may vary from one disassembly practitioner and case study to another. Therefore, further researches are needed to conduct further analysis in different working conditions. The results do not consider the non-metallic impurities in the calculations. Similarly, this study lacks an analysis of sensitivity to specifically concentrate on the parameter with the most significant impacts on the defined metrics (i.e., time, difficulty and the quality of the output materials).

The developed approach besides the experimental work presented here provides one of the first investigations into how to perform a multiple-criteria assessment of the complex products EoL. It is hoped that the created knowledge will lead to the development of a new generation of EoL-oriented products by helping both manufacturers and disassembly specialists dealing more effectively with EoL design and operation issues.

CHAPTER 9 CONCLUSION AND RECOMMENDATIONS

This thesis set out to take an evaluative view on the efficient EoL disassembly of products using the semi-destructive method. It was designed to study the fundamentals of semi-destructive disassembly due to the various advantages it can offer in the EoL disassembly process. This chapter presents the conclusion, main contributions and recommendations for the future researches, as listed.

9.1 Conclusions and main contributions of the work

The general conclusions and contributions based upon the experimental and analytical findings are outlined, as follows.

- A conceptual disassembly framework is presented giving an in-depth vision on issues related to the airframe disassembly. The proposed methodology stresses the key role of the disassembly evaluation as a precursor to an efficient EoL process. It is shown that the systematic division of key parameters into the product and process related features could facilitate the analysis of the disassembly evaluation process. The developed approach acted as a roadmap towards the efficient disassembly process which follows.
- The most significant disassembly alternatives in airframe EoL are presented. The evaluation key factors (i.e., operation speed, accuracy and damage risk) with respect to each alternative are also determined. It is demonstrated that the required operation time (a function of speed) for totally destructive (i.e., crushing) technic is less than cutting, deep drilling, minimum drilling and manual disassembly. The findings indicate that the totally destructive method results in 100% mix of materials that could significantly affect the quality of the output materials. Moreover, it is shown that, the more an operation goes destructive, the easier it would be to perform. This is continued by a quantitative analysis that follows in the next step of research.
- In the initial phase of the development process, a quantitative evaluation model is proposed, to accurately measure the disassembly effort required for performing the semi-destructive operation(s). It is quantitatively indicated that the disassembly process selection, material and geometrical characteristics can have considerable impacts on the final difficulty levels of the disassembly process. Moreover, once the disassembly method is selected, the

operation setup (i.e., tool speed, depth of cut, machine efficiency, feed rate, tool thickness, angle, diameter, etc.) could also have significant impacts on the final disassembly difficulty. The results indicate that the *Min. dr.* disassembly difficulty level is preferable in both tangential and normal force components over *Cut.* And *D. Dr.* operations.

- The multiple-variable analysis demonstrated that significant improvements in terms of the presorting rates, difficulty and time required is achievable by systematically assessing the disassembly performance prior to the physical works. Five different EoL scenarios (i.e., A to E) are defined with respect to the common industry know-how in the airframe disassembly. The learn-by-progress approach allowed for refining EoL disassembly scenarios boosting the pre-sort and pre-shred processes. The results show that although scenario C and D are similar in disassembly time, D needs less effort while providing maximum presort. The scenario B has the best $T_{O.D}$ and the worst *POT* and $T_{T.V.}$ The scenario D has the highest disassembly depth (followed by E) while B has the least. The scenario E has also 46 disassembly operation sequences (highest in all scenarios) while offering the highest material recovery rate with the least metallic impurity level. The impurity recovery, however, is not comparable to scenario D. Having known the impurity total weight (which is close to zero), this downside is not significant either. Similarly, scenario E compared to scenario B in conventional disassembly offers 74% and 22.5% higher performance with respect to *POT* and *SOT* respectively.
- The scenarios E to D offers a close comparison between two MDE-based disassembly strategies where the striking improvements in *POT* and *SOT* are observed; 27% and 35.6%. Eventually, the disassembly performance improvements are observed for up to 86%, and 65% with respect to the disassembly time requirement and the difficulty level.

9.2 Recommendations for future research works

There is a growing body of literature on product disassembly analysis. Despite this general momentum, very few studies have explicitly analysed the semi-destructive method. There are obvious opportunities and difficulties that may need to be examined separately and meticulously. Taken together, the results of this study suggests the following subjects for further analysis:

- Initial observations suggest that there may be a link between the type of coating and the quality of the recoverable materials. This can be explained with respect to the encountered difficulties at the material recycling and disassembly stages. More capable material recycling strategies and/or design measures may offer extra benefits to the product EoL performance and treatment easiness. The ENV-412 project indicated that one of the reasonable approach to tackle this issue might be found within a deep analysis of the aerospace-grade material mix possibility at EoL stage. In other words, having a clear vision on what percentage of material mix could result in the best material output quality may be considerably helpful for the efficient disassembly operations. This subject besides the technological advances may provide substantial benefits to the EoL process.
- From a pure technical perspective, the fastening/joining technics are amongst the most important fields to study. Therefore, there seem to be a definite need for more disassembly-oriented fastening and joining technics to be developed. Obviously, this may have significant impacts on the required disassembly effort and time, as explained earlier.
- It is revealed that the geometrical pattern of the fasteners application may also have an influence on the time required for the disassembly process. Thus, separate researches might find it interesting to analyze the impact of the application pattern on the overall disassembly difficulty. This may become more important in case of some automated disassembly processes where the disassembly trajectories have to be defined explicitly.
- Another possible area of future research would be to develop further methods and technological solutions related to the information extraction/creation of the retired products. This may have significant impacts on the disassembly efficiency and the overall EoL performance due to the limitations associated with the information accessibility of the products.

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