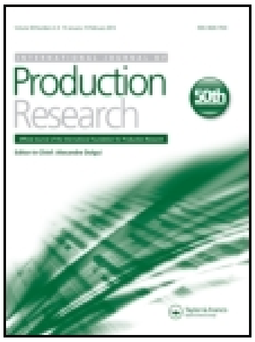

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A quantitative evaluation model to measure the disassembly difficulty; application of the semi-destructive methods in aviation End-of-Life

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A quantitative evaluation model to measure the disassembly difficulty; application of the semi-destructive methods in aviation End-of-Life

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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 solutions 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 Stabiliser 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 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

Introduction

Design and manufacturing of today's products are increasingly oriented towards 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, Sonnenberg, and Das 2004) and 3- semi-destructive disassembly (Vongbunyong, Kara, and Pagnucco 2013; Shiraishi et al. 2015; Umeda et al. 2015).

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 utilising 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 (Shiraishi et al. 2015; Umeda 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

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full-destructive techniques (a common practice in this field) provides recycling of only 20% of the scrap materials (Asmatulu, Twomey, and Overcash 2013).

In semi-destructive techniques, as an irreversible operation, the need for complex calculations, sensors and multiple tools is also minimised while at the same time the success rate remains high (Vongbunyong, Kara, and Pagnucco 2015). 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, 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.

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.

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 (PAMELA 2008; AFRA 2014a). 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 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.

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, Overcash, and Twomey 2013). Zahedi et al. developed a conceptual EoL framework for a comprehensive integration of process and product-related features (Zahedi, Mascle, and Baptiste 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. (2015). Evaluation of the disassembly economy is the subject of a

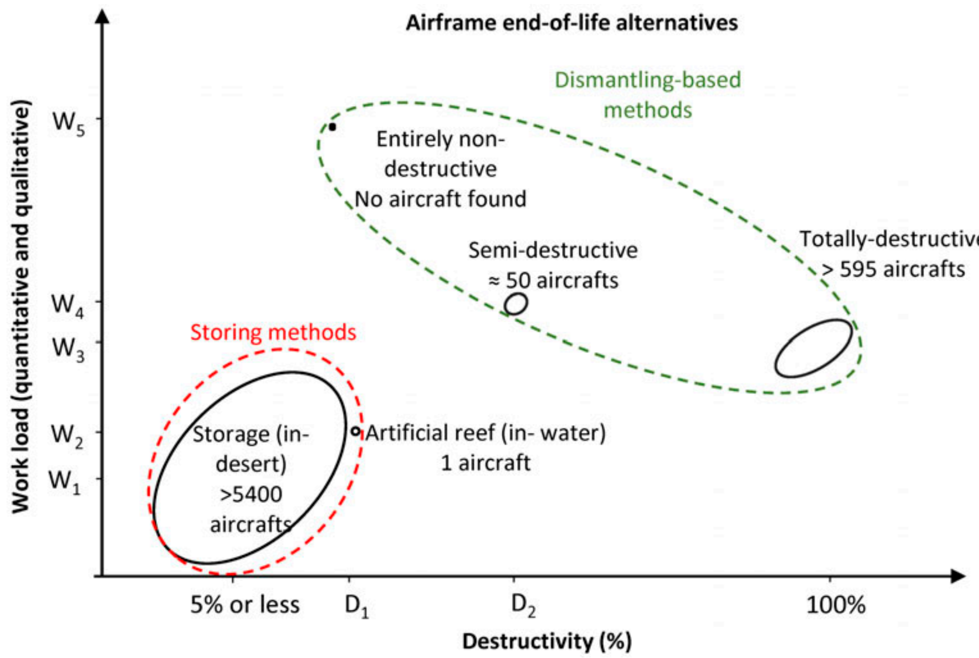

Figure 1. Aircraft EoL alternatives' share in the market; D_1 and D_2 denote minor (reversible) and controlled-major (irreversible) operations, respectively.
Source: Aircraft demolitionArtificial Reef Society of British Columbia, Tarmac Aerosave, AELS, Davis-Monthan Air, ASI, BBC 'the secrets of the deserts', Mojave Airport and Murtala Muhammed International Airport, Lagos, Nigeria.

research by Tang et al.; a methodology to help making better decision on the disassembly strategy to improve the economic gain (Tang*, Grubbström, and Zanoni 2004).

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, Sonnenberg, and Das 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.

Objectives and methodology

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 and so on), 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.

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.

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 2 presents the classification of design-related (product-related) and process-related parameters.

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

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) (Pak 2002; Vongbunyong, Kara, and Pagnucco 2013). 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

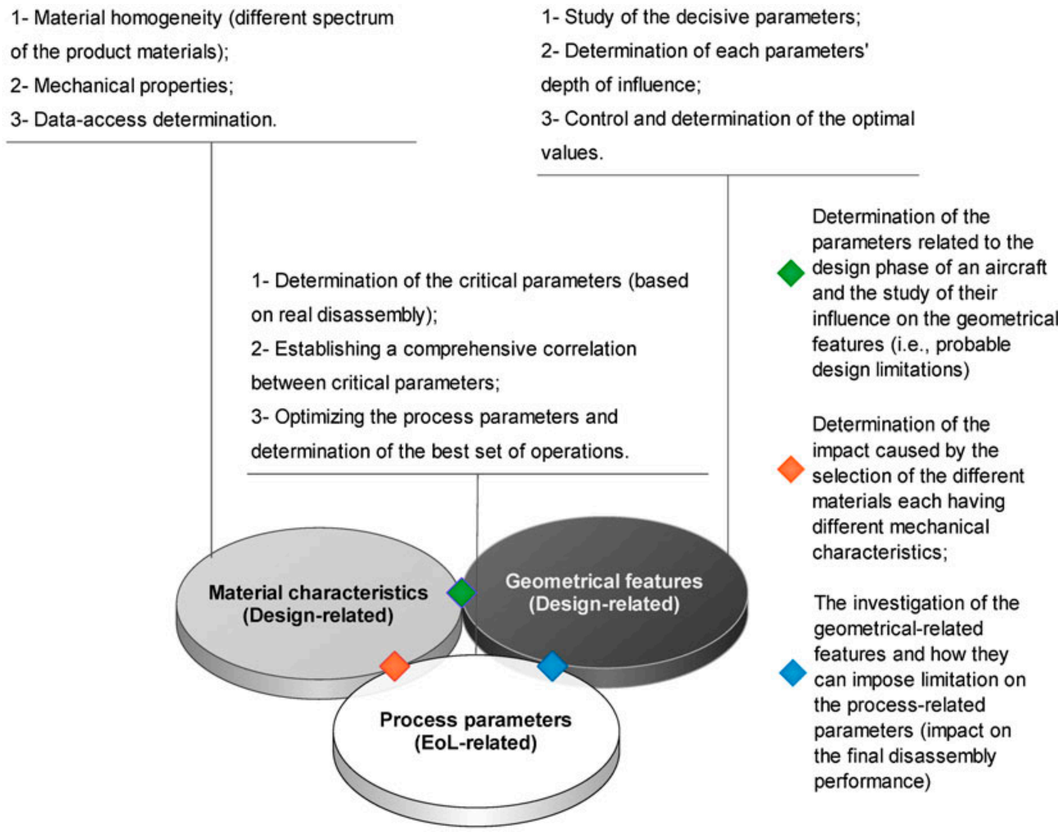

Figure 2. Semi-destructive disassembly analysis of the driving parameters.

Table 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

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.

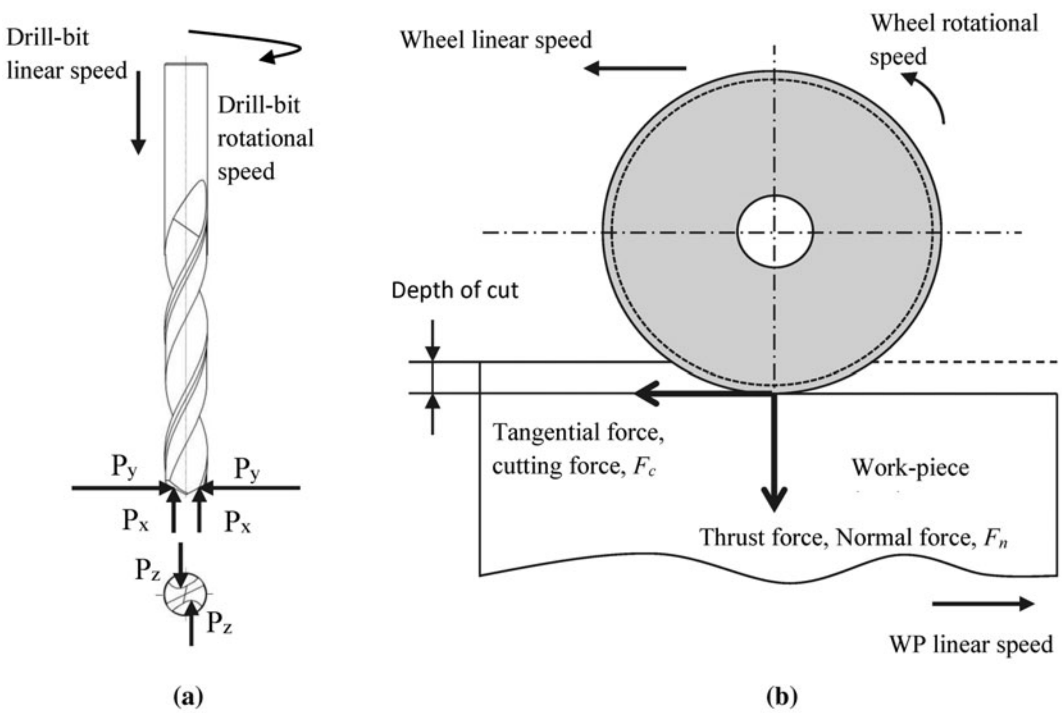

Figure 3. Semi-destructive disassembly force-analysis of an airframe; (a) drilling operations, (b) grinding operations.

Figure 3 illustrates the cutting and drilling operation force analysis when metal cutting processes are used for disassembly of an airframe. As seen in Figure 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 (Hindustan Machine Tools Limited) 2001; El-Hofy 2013).

The cutting and thrust force vectors for the grinding metal cutting process are depicted in Figure 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.

Disassembly difficulty calculator

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

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

where F_{Grinding} and F_{Drilling} are summation of the thrust and cutting force component associated with the appropriate selected metal working procedure(s), $F_{\mathrm{Disengaging}}$ 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 force 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 (2) (Kannappan and Malkin 1972).

$$e_c = e_{ch} + e_p + e_s \tag{2}$$

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 2 for various materials.

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 (3). The removed cubic rectangle is the result of cross-sectional area, dw, and the feed rate linear pass (v).

$$MRR = dwv \tag{3}$$

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

$$\text{Power} = u \times \text{MRR} \tag{4}$$

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

Table 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
Aluminium and alloys	30–80	6.5	0.36

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

$$\text{Power} = T \times \omega; \quad \text{and} = F_c.\left(\frac{D}{2}\right) \tag{5}$$

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, acceptable 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-sectional area (A_c), as described earlier, and the specific cutting energy for the drilling operation (u_d) (see Table 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:

$$A_c = \frac{Sd}{4} \tag{6}$$

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):

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

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, Budynas, and Shigley 2008) is used as follows:

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

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

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

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 (10):

$$F = \mu.\mathrm{PR}.A \tag{10}$$

Using Equation (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.

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.

Case study and results

In order to verify the suitability and performance of the model, an airliner Horizontal Stabiliser (H.Stab) including skin and under-skin parts fastened by a line of rivets is presented in Figure 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.

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 disc 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 disc can also perform non-precision tasks related to the non-ferrous operations satisfactorily (Petzow 1999; Rowe 2009). 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 (Hindustan Machine Tools Limited) 2001; Davim 2011). The set-ups for the grinding disassembly process are shown in Table 3. Based on Equations (3)–(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.

If a drilling disassembly technique is selected, a new operational set-up 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 (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 (8)–(10) are useful, as well as the information presented in Tables 4 and 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

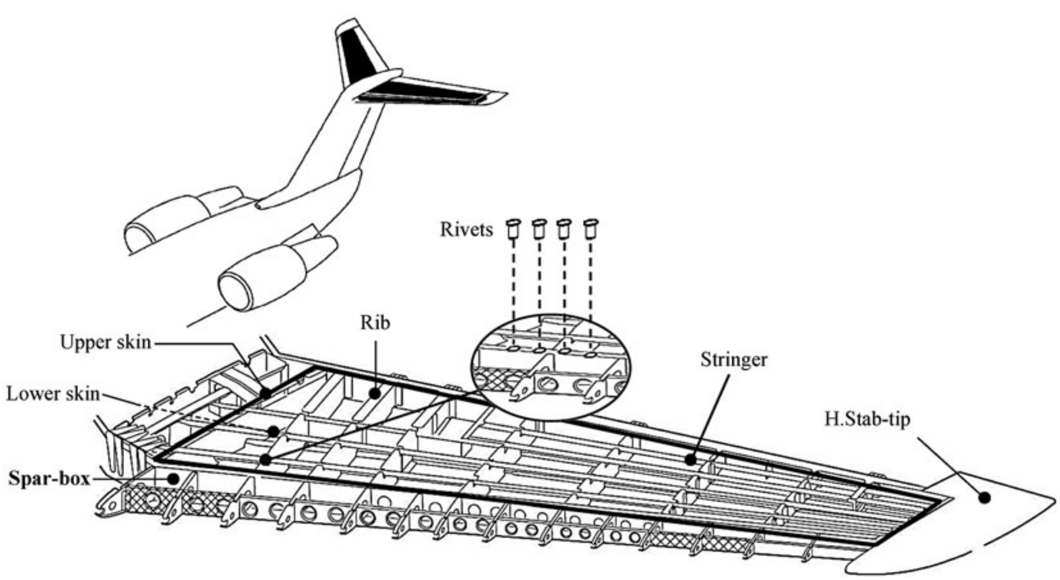

Figure 4. Horizontal stabiliser structural elements; the rivets are shown in magnified view.

Table 3. Operational set-ups for the grinding disassembly process.

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

Table 4. Rivet shank and the hole evaluative parameters and value to calculate 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 5. Calculation of the generated pressure between the rivet shank and the hole, the disengagement force and eventually the hammer speed to calculate 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, pmax (MPa)	137.3	Area of contact, A (mm^2)	78
Min pressure generated, pmin (MPa)	21.1	Required force, F (N)	**3193**

component (including the total rivet disengagement force component) are 2.55×10^6 (N) and 4.65×10^6 (N), respectively.

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 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.

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 are achievable only when an appropriate vision with respect to all of the variables is present. The authors are currently working on such multi-variable analysis which will be published in future.

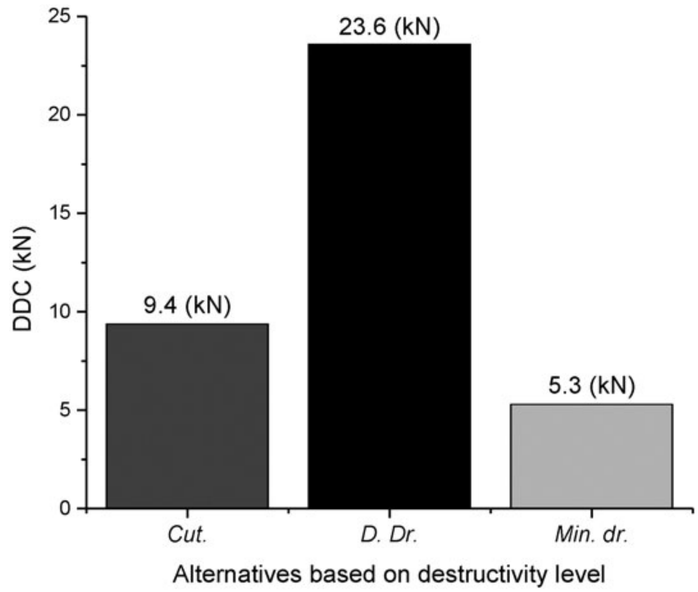

Figure 5. Calculated DDC (kN) for the complete set of operations.

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.), paving the way for further improvements to EoL treatment regimes.

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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Disclosure statement

No potential conflict of interest was reported by the authors.

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