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Research and Development of a Basic Criteria Model for Evaluation of Design for Disassembly and Disassembleability of Aerospace Industry Products

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Research and Development of a Basic Criteria Model for Evaluation of Design for Disassembly and Disassembleability of Aerospace Industry Products

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LIST OF ABBREVIATIONS

Abbreviation	Meaning
ACO	Ant Colony Optimization
ACS	American Chemical Society
ADG	Accessory Drive Gearbox
AELS	Aircraft End-of-life Status
AFRA	Aircraft Fleet Recycling Association
ALC	Air Logistics Center
AMARG	Aerospace Maintenance and Regeneration Group
ANP	Analytic Network Process
ASIP	Aircraft Structural Integrity Program
ASR	Automotive Shredder Residue
ATOX	Atomic Oxygen
BHEC	Bolt Hole Eddy Current
BILP	Binary Integer Linear Programming
BMI	Bretby Maintainability Index
CAA	Chromic Acid Anodising
CAD	Computer-aided Design
CASTLE	Center For Aircraft Structural Life Extension
CBR	Case Based Reasoning
CCC	Chromate Conversion Coating
CFC	Chlorofluorocarbon
CFRP	Carbon Fibre Reinforced Plastic
CNC	Computer Numerical Control
CSN	Cycles Since New
CV	Configuration-value
CVI	Close Visual Inspection
DCG	Disassembly Constraint Graph
DEI	Disassembly Effort Index
DESSC	Digital Engine Start System Controller
DFD	Design For Disassembly
DFDI	Design For Disassembly Index
DPN	Disassembly Petri Net
DSM	Design Structure Matrix
EASA	European Aviation Safety Authority
EC	European Commission
ECMPRO	Environmentally Conscious Manufacturing and Product Recovery
ECSS	Eddy Current Surface Scan
EGT	Exhaust Gas Temperature
ELS	End-of-life Status
ELV	End of Life Vehicle
EMR	European Metals Recycling
EoL	End of Life

Abbreviation	Meaning
EPR	Extended Product Responsibility
EPSRC	Engineering and Physical Sciences Research Council
ESA	European Space Agency
ESS	Engine Starting System
EVI	Enhance Visual Inspection
FAA	Federal Aviation Administration
FFS	Full Flight Simulator
FPI	Fluorescent Penetrant Inspection
FTD	Flight Training Devices
GA	Genetic Algorithm
GOX	Gaseous Oxygen
HAF	Hellenic Air Force
HAI	Hellenic Aerospace Industry
HSEC	Health, Safety and Engineering Consultants
HSM	Hydraulic Start Motor
IDRS	Integrated Disassembly and Recycling Score
ISTAT	International Society of Transport Aircraft Trading
IT	Information Technology
JFS	Jet Fuel Starter
JGPP	Joint Group on Pollution Prevention
JTP	Joint Test Protocol
LEO	Low Earth Orbit
LIFE	L’instrument Financier Pour L’environment
LOW	d. List of Waste
LOX	Liquid Oxygen
LRM	Laboratory For Responsible Manufacturing
MDM	Multi Domain Matrix
MDO	Multidisciplinary Design Optimization
MEERP	Ecodesign of Energy-related Products
MEEURP	Methodology For The Ecodesign of Energy-using Products
MOM	Measure of Merit
MOST	Maynard Operation Sequence Technique
MPI	Magnetic Particle Inspection
MSFC	Marshall Space Flight Center
MTM	Methods Time Measurement
NASA	National Aeronautics and Space Administration
NDE	Non Destructive Evaluation
NDI	Non Destructive Inspection
NDT	Non Destructive Testing
OEM	Original Equipment Manufacturer
P2	Pollution Prevention
PAMELA	Advanced Management of End of Life Aircraft
PN	Petri Net
PPE	Personal Protective Equipment

Abbreviation	Meaning
PTO	Power Take Off
RPA	Remote Piloted Airplane
RPM	Rounds per Minute
SAE	Society of Automotive Engineers
SARS	Severe Acute Respiratory Syndrome
SCP	Strontium Chromate Primer
TAC	Technical Adaptation Committee
TAP	Teardown Analysis Program
TMU	Technical Manual
TMU	Time Measurement Unit
TO	Technical Order
TSN	Time Since New
TTCP	The Technical Cooperation Program
TUC	Technical University of Crete
USAF	United States Air Force
WB	Wide Bodied
WEEE	Waste Electrical and Electronic Equipment
WINGNET	Waste Reduction in Aircraft-related Groups

ABSTRACT

For decades, component reuse and material recycling of complex products were essentially limited to discarded cars. Nevertheless, it was recently proven that for Aerospace Industry products, disassembly is not only executed extensively in the products' useful life, but it can also offer at their End-of-Life processing, considerable environmental and cost savings, as well as compliance with both the current legislation and the wider concept of sustainable development. In Aerospace Industry however, disassembly is predominantly performed by humans and not by robotic or CNC means. Therefore, addressing and enhancing the ease of disassembly in aerospace product's early design stages (Design for Disassembly or DfD) and thus reducing disassembly time and costs (labor, tools, error risks), is a major objective. At the same time, it is also a challenge, since most existing disassembly algorithms focus on the theoretical part of disassembly process and disregard ergonomic factors which prevail in aerospace products real-life disassembly, especially in areas such as physical and work envelope limitations, accessibility and visibility, prolonged irregular working postures, personel skills and protection.

For this dissertation, extensive and intensive research was performed in open sources and literature of academic and regulatory nature, to collect and study existing technologies, concepts, methodologies, guidelines, practices and evaluation tools of manufacturing, disassembly and DfD in the wider manufactured goods industry, as well as in automotive and Aerospace Industry specifically. Aviation Literature and regulations were also studied and aircraft recycling international programs were reviewed. Then, a model of DfD criteria was built, as a first-cut proposal of a tailorable and advisory DfD tool for aerospace product design. The model follows a hybrid approach, with weight factors per lifecycle phase and scores per criterion, as well as with binary criteria interrelations captured in a Design Structure Matrix (DSM). The model's synthesis process accounted real life experience in military aviation maintenance and design, safety and human factors considerations, as well as scoring concepts like that of the Bretby Maintainability Index (BMI). The adaptive use and applicability of the proposed model was demonstrated in a case study (partial disassembly of a fighter aircraft Jet Fuel Starter). Applicability assessment was based on disassembly processes documented in aircraft's technical publications and used daily for aircraft maintainance. The proposed model is provided in Appendices A and B of the dissertation.

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INTRODUCTION

The progress in top notch technologies and virtual reality in the last decades launched industrial design capabilities to such levels that nowadays, even the most complex modern products, are being designed in exhaustive details for all their assembly stages. However, in recent years a new problematic is highly emerging, which stems from the need to respect the environment and to achieve optimal recycling - remanufacturing - recondition of the products or their individual parts and materials, in compliance with both the current legislation and the wider concept of sustainable development.

Designers are becoming steadily aware of the problem, and employ techniques that allow them to design with greater responsibility against the environment. Design for Disassembly is one such technique. It involves designing a product to be disassembled for easier maintenance, repair, recovery and reuse of components/materials. As part of Design for the Environment (DfE) and sustainable product design, Design for Disassembly is becoming increasingly recognised as an effective tool by designers, manufacturers and legislative boards alike. Reducing waste in the manufacturing and recovery processes using DfD techniques can significantly reduce production costs and allow for greater technical efficiency. Modular design principles within DfD techniques allow for greater flexibility during product development, shorter development timescales and reduced development costs. Implementing DfD into a design specification allows the product and its components to be better suited for re-use or recycling when it has reached its end of life, thus reducing the scale of resources required to create new products.

Obviously, the products of the Aerospace Industry make no exception but rather, a very interesting area to apply the philosophy of DfD, as the worldwide fleet of such products like aircrafts, flight simulators, RPAs (Remotely Piloted Airplanes) is aging or being replaced, with impacts to the environment and the respective markets. This is also illustrated by the emphasis given by both the European Union and companies in the industry.

The aim of this dissertation is to make an initial “first-cut” approach in **DfD (Design for Disassembly)** methodology and its applicability considerations in the Aerospace Industry, in order to formulate a “high-level” but at the same time extensive model, with key criteria for applying and evaluating both the DfD and End Of Life (EoL) exploitation potential of aerospace products.

It is also stressed, that in the areas of aerospace electronics, this dissertation addresses DfD only up to the level (disassembly depth) of the Avionics “box” unit, which may be removed from the aerospace product (spacecraft, aircraft, helicopter, Remotely Piloted Airplane (RPA), ground support equipment etc) to be reused or send to some specialized installation for further recovery of materials. This dissertation does not address DfD to the next lower disassembly levels that go down to the internal or embedded electronic boards, chassis, microchips and any other electronic or optoelectronic compontents. These levels (disassembly depths) are deemed as “out of scope”. The main reason for making this distinction is that the DfD of such electronic lower level products, is either addressed in other engineering efforts which develop specialized algorithms for high accuracy disassembly using robotic technologies, or is not cost-effective to retrieve electronic components which are usually "buried" within an electronic module and most probably have already become technologically obsolete.

The methodology followed in this dissertation included among other actions:

a. Continuous research and data collection from open sources, to obtain respective literature and to investigate the scope and the main criteria used in Design for Disassembly with existing industrial production systems.

b. Contact representatives of Greek and international industries and companies in the wider Aerospace Industry area. Overview of disassembly techniques which are applicable in aviation and defense industry and presentation of their key scope sectors and purposes.

c. Formulation and proposals for further development, of an initial adaptive model to facilitate DfD, evaluation of DfD and the process of dismantling aerospace products after their useful life, but also during the operational useful life of the platform and/or the products themselves.

d. Optimizing the model via evaluation of applicability per criterion and via usage of DSM (Design Structure Matrix) methodology to map and partition the internal dependencies of the model criteria.

e. Tailoring the model in one case study of an aerospace product to demonstrate and prove its completeness and applicability to DfD.

The chapters of the dissertation have the following structure:

a. Chapter 1 discusses disassembly and DfD scope, principles and methodologies.

b. Chapter 2 discusses DfD in Aerospace Industry and in particular, what it consists of, which is the framework of its application and which are the tiger aircraft recycling programs that employ DfD today.

c. Chapter 3 presents the proposed DfD criteria full model for aerospace products, describes the model's characteristics and few techniques to tailor it for each case of aerospace product. The same chapter presents a case study of adapting the model to a complex aerospace product.

d. Appendix A lists the adaptive DfD criteria full model with respective weighted scores for disassembleability.

e. Appendix B lists the interdependencies of the DfD criteria for both the aforementioned full model and the adapted DfD criteria model created in Chapter 3.

f. Appendix C lists the Bretby Maintainability Index which has been developed by the Engineering community for maintainance of complex machines and mechanical components. This matrix was used for more dilligently assigning scores to the DfD criteria of the proposed model, also to define interrelations among each pair of criteria in the proposed DfD model.

1 CHAPTER 1 – INTRODUCTION TO DISSASEMBLY

1.1 GREEN ENGINEERING – ENVIRONMENTALLY CONSCIOUS PRODUCT DESIGN

The main topic of this dissertation is Design for Disassembly (referred also as DfD or DFD), which implements principles of Green engineering, viz. the design, commercialization, and use of processes and products, which are feasible and economical while minimizing generation of pollution at the source and risk to human health and the environment. Green engineering embraces the concept that, decisions to protect human health and the environment can have the greatest impact and cost effectiveness, when applied early to the design and development phase of a process or product. Following this concept, engineers and scientists defined the following principles to use as guidance in the design or redesign of products and processes:

a. Engineer processes and products holistically, use systems analysis, and integrate environmental impact assessment tools.

b. Conserve and improve natural ecosystems while protecting human health and well-being.

c. Use life-cycle thinking in all engineering activities.

d. Ensure that all material and energy inputs and outputs are as inherently safe and benign as possible.

e. Minimize depletion of natural resources.

f. Strive to prevent waste.

g. Develop and apply engineering solutions, while being cognizant of local geography, aspirations and cultures.

h. Create engineering solutions beyond current or dominant technologies; improve, innovate, and invent (technologies) to achieve sustainability.

i. Actively engage communities and stakeholders in development of engineering solutions.

Added to that, the Green Chemistry Institute of the American Chemical Society (ACS) adopted the Twelve Principles of Green Engineering, which were introduced by two researchers, Dr. Paul Anastas and John C. Warner:

Table 1-1: The 12 Principles of Green Engineering

1.	Inherent Rather Than Circumstantial:	Designers need to strive to ensure that all materials and energy inputs and outputs are as inherently nonhazardous as possible.
2.	Prevention Instead of Treatment:	It is better to prevent waste than to treat or clean up waste after it is formed.
3.	Design for Separation:	Separation and purification operations should be designed to minimize energy consumption and materials use.
4.	Maximize Efficiency:	Products, processes, and systems should be designed to maximize mass, energy, space, and time efficiency.
5.	Output-Pulled Versus Input-Pushed:	Products, processes, and systems should be "output pulled" rather than "input pushed" through the use of energy and materials.
6.	Conserve Complexity:	Embedded entropy and complexity must be viewed as an investment when making design choices on recycle, reuse, or beneficial disposition.
7.	Durability Rather Than Immortality:	Targeted durability, not immortality, should be a design goal.
8.	Meet Need, Minimize Excess:	Design for unnecessary capacity or capability (e.g., "one size fits all") solutions should be considered a design flaw.
9.	Minimize Material Diversity:	Material diversity in multicomponent products should be minimized to promote disassembly and value retention.
10.	Integrate Material and Energy Flows:	Design of products, processes, and systems must include integration and interconnectivity with available energy and materials flows.
11.	Design for Commercial "Afterlife":	Products, processes, and systems should be designed for performance in a commercial "afterlife."
12.	Renewable Rather Than Depleting:	Material and energy inputs should be renewable rather than depleting.

DfD promotes green engineering as most of the principles above also have applicability in the design and DfD of aerospace products. For example, the progressively expanding use of commercially produced parts and equipment in military aerospace products, promotes the applicability of the 7^{th}, 8^{th}, 9^{th} and 11^{th} principles, since such products and equipment are manufactured and standardized with the usual commercial practices and standards, not with the highly demanding and stringent military ones.

Traditional product development aims at achieving improvements in design with respect to cost, functionality and manufacturability. However, increasing importance of the environmental issues forces product designers to consider certain environmental criteria in the design process and to make environmentally friendly design choices, using a number of methodologies which have been developed for this purpose. Currently, the disassembly of the product is a separate activity and methods for Design for Disassembly are developed, aiming at backward integrating them into the design stage of product development. This section first presents the commonly available methods for product recovery and then presents an overview of these methodologies by organizing them into three main categories, viz., Design for X, Life Cycle Analysis and material selection.

1.2 PRODUCTION – LIFE CYCLE - RECOVERY - DISASSEMBLY

1.2.1 PRODUCTION – LIFE CYCLE

The production of a complex product usually involves three main phases, each with its own characteristics.

a. **Materials production.** The processes where the physical and chemical intrinsic properties of the materials are tailored according to the manufacturers' requirements.

b. **Component production.** The manufacture of discrete components, which characterize their extrinsic properties, such as the geometry and the surface conditions of the components.

c. **Product assembly.** The assembling of discrete components into modules, which in turn are assembled to produce a complete product with the desired functionality.

After production, the product enters its life cycle, which includes the conceptual life cycle and the physical life cycle.

a. The conceptual life cycle refers to the duration of time in which a product is considered viable in the market. It comprises the design phase, the production phase, the state-of-the-art (useful) phase, and finally the phase of product's decline. In this final phase, the product becomes outdated and needs replacing even though the product is technically sound. Depending on the product, the conceptual life cycle may encompass an appreciable period of time.

b. The physical life cycle refers to the duration of time that spans from the production of a product up to the moment that it is discarded.

If the end of product's physical life cycle surpasses the end of conceptual life cycle, its components cannot be reused, even if the service that is offered by the product is still relevant. Apart from this, some materials, particularly plastics, may have become obsolete. The fastener types may also be different from the current ones. In some cases also, a product could essentially disappear from the market. For example, mechanical and electric typewriters, duplicators, tape recorders, phonographs, centrifuges, manual sewing machines, matrix printers, and many other types of appliances are no longer produced or popular. These products, however, have to be processed at the end of their lives and may need special attention, if they contain obsolete products that do not comply with current environmental regulations. For example, electric heaters containing asbestos and refrigerators containing hard chlorofluorocarbons (CFCs) fall into this category. These kinds of products require special handling (as dictated by the prevailing regulations because of their hazardous contents) as opposed to the modern version of the same product.

1.2.2 END-OF-LIFE PROCESSING

At the EoL of the product, the usual chain of processes includes:

1.	Disassembly:	As discussed in previous paragraphs. If the whole product is not reused, a **selective disassembly** process may be carried out. The product is disassembled into modules and components up to some depth, depending on which modules or components are targeted. The retrieved modules and components may need testing and possibly repair. They may be either reused as "new" parts in new products, or reassembled into remanufactured products, or used as spare parts.
2.	Dismantling (also called dismounting):	A process in which directed destructive operations are applied. These operations destroy one or more components by breaking, sawing, cutting etc., thus devastating the component's value for reuse. Dismantling operations are frequently included in disassembly processes, especially if they enable further disassembly operations with the removal of components that obstruct accessibility and detachability of the desirable components.
3.	Sorting:	The process in which various components and materials are divided into groups, which are called clusters. Each cluster meets some specific criteria on materials composition or component specifications.
4.	Shredding:	An undirected destructive process, which breaks all the components into small pieces. The process is purely aimed at particle size reduction of products for increasing the materials homogeneity to enable the subsequent separation processes. Comparable processes such as milling, grinding, etc. are also included in shredding.

5.	Separation:	The postshredder process in which the shredder output is divided according to materials composition. The most frequently applied separation methods are magnetic separation and eddy current separation. A plethora of other physical and chemical separation methods are available, which originally come from the mining industry. For example, metallurgical and chemical methods are used to decompose compound materials such as alloys and composites, which are extensively used in aerospace products. The remainder after the chain of separation processes is called shredder residue, also called shredder fluff or shredder light fraction.
6.	Disposal:	The process of directing available residual waste to discharge, which includes incineration or landfill.
7.	Incineration:	Aimed at waste volume reduction and energy recovery. Residual products of incineration are filter, residue, and slag.
8.	Controlled landfill:	The landfill under special conditions, particularly in the case of hazardous materials.

From the product's application point of view, the following processes are relevant:

	Preconsumer phase:	
1.	Rework:	aimed at transforming products, which are not produced according to the standards, into products that meet the standards of properly produced items. Consumer phase:
2.	Maintenance:	aimed at enhancing the product's lifespan. It can include partial disassembly and reassembly, together with periodic replacement of components or modules.
3.	Repair:	aimed at restoring the product's functionality after its failure.
	Postconsumer phase:	
4.	Refurbishing:	includes the processing of an end-of-life product such that its full functionality is restored. The resulting product is usually made available on the second hand market.
5.	Remanufacturing:	the composition of reconfigured products with components derived from end-of-life products. Usually, refurbishing of some of the components and modules of the original products is necessary.

6.	Reuse:	the employment of components and modules obtained from endof- life products as spare parts or in other items.
7.	Recycling:	the recovery of materials out of scrap from end-of-life products.
8.	Recovery:	refers to both reuse and recycling.
9.	Cascading:	the application of recycled materials for a lower-grade purpose than what it originally was used for.
10.	Downcycling:	the application of materials out of scrap for low-grade purposes, such as a filling agent in asphalt, an additive to cement kilns, or a basis for roads and buildings.

Those EoL processes are presented in the block diagram of Figure 1-1.

When selective disassembly is used for end-of-life disassembly, both nondestructive and semi-destructive operations might be permitted. The selective disassembly process results in three types of outputs:

a. **Homogeneous components**, which cannot further be physically separated. Typical examples of homogeneous components are the covers and casings, frames and parts removed from chassis of electronic products.

b. **Complex components** consist of several discrete homogeneous subcomponents but are normally not further disassembled because they are often connected via fasteners that require destructive disassembly for separation. Examples include cathode ray tubes, printed circuit boards, switches, rotors, stators, and transformers. Sometimes, individual electronic components, such as capacitors, also fall into this category.

c. **Modules** can normally be further disassembled, but sometimes are not disassembled as they possess their own functionality and thus may be reusable as such. Examples include electric motors, populated printed circuit boards, optical units, cables, engines, and batteries.

It should be noted that at EoL, the selective disassembly serves a variety of purposes, namely:

a. Recovery of modules and components used for remanufacturing, spare parts, and secondary (“as new”) modules and components for new products.

b. Removal of hazardous modules, components, and materials.

c. Regulatory requirement for removal of hazardous and nonhazardous components.

d. Removal of components that obstruct the removal of the components of interest.

e. Recovery of valuable materials.

f. Enhancement of the purity of materials.

g. Decrease of the quantity of shredder residue.

h. Increase of the quality of shredder residue.

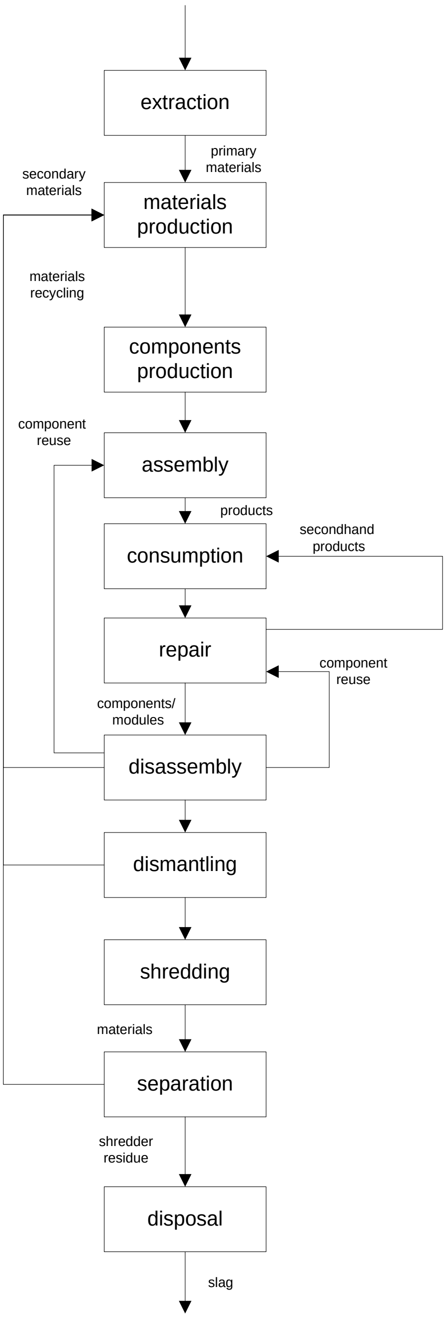


Figure 1-1: Disaggregated Product-Process Chain of a Complex Product, with Reuse and Recycling.

It should also be noted that in recent decades, the tightening regulations have started to result in:

a. Avoiding the use of hazardous substances in the product.

b. Mandatory removal of hazardous substances (using selective disassembly) prior to shredding.

c. Ban on landfilling shredder residue.

d. Incineration of shredder residue separately from municipal and industrial waste.

e. Ban on the use of slag which results from incineration of shredder residue, in buildings and construction materials.

f. Obligatory disposal of incineration slag in landfills that are dedicated for hazardous waste.

After this discussion, the importance of disassembly to the environmental sustainability is obvious.

1.2.3 DISASSEMBLY

Disassembly is virtually as old as mankind. It is even older than assembly but as a process on its own, started to gain momentum during the 1990s when the number and variety of discarded complex products increased rapidly. Earlier, in the 1970s, component reuse and materials recycling were essentially limited to discarded cars, which were originally rich in ferrous metals constituting about three fourths of the car by weight. What remained from disassembly and subsequent shredding was the automotive shredder residue (ASR), which consisted of a mix of light materials such as glass, rubber, and plastics. This substance was usually heavily contaminated and necessitated the draining of the working fluids from the car, the removal of batteries, and some of the nonmetallic components such as tires, windows, seats, and bumpers before further processing. In European Commission (EC) countries, this practice has become a standard regulation via the Directive 2000/53/EC of the European Parliament on end-of-life vehicles (EC, 2000)

In Aerospace Industry, disassembly is a key process which is executed extensively in both the Life Cycle (useful life) of the products and at their EoL processing. During the Life Cycle of aerospace product, the importance of disassembly is higher, due to the fact that disassembly is executed numerous times (for inspections, repairs, servicing etc) and almost everytime is followed by reassembly and follow-on operational checkouts of the product which has to regain its safe and full operational condition. A substantially modified hierarchy, which covers a broad range of disassembly problems, is presented in Table 1-2:

Table 1-2: Hierarchy of Disassembly

1.	Physical level	deals with the physical properties of components, with an emphasis on forces and deformability. Technical constraints and stability are some of the issues addressed at this level.
2.	Surface level	deals with the aspects of individual components, such as free and mating surfaces, and is applied if detailed analyses of a disassembly operation are required. In many analyses, a rigid body approximation is assumed. Accessibility and movability analysis take place at this level.
3.	Component level	deals with the movement of components in the course of disassembly operations and their possible interaction with other components. It deals with topics such as geometric and topological constraints and, consequently, precedence relationships.
4.	Modular level	considers functional subsystems of a product. It is in-between the component and the product level. Modularity analysis is done at this level.
5.	Product level	applied if the analysis of a product as a whole is required, for studying the relationships between the disassembly operations and the sequence of those operations. It includes the establishment representations of the possible sequences of disassembly operations. It also embraces the selection of appropriate sequences.
6.	Batch level	used if the processing of multiple products has to be considered. This level involves demand-to-order problems and scheduling issues.

Two main considerations for disassembly are Disassembly Sequencing and Disassembly Planning which are primary disassembly approaches in Aerospace Industry products. Disassembly sequencing addresses the question, “How to disassemble?” while disassembly planning delineates “How much to disassemble?” The domains of disassembly sequencing and planning both have given rise to a considerable number of papers, which cover the various topics of those domains. With regards to Aerospace Industry products, however, very little work can be found if the open literature and academic sources, despite the fact that both these questions are highly applicable in aerospace products, from the level of the whole airborne platforms like commercial airliners airplanes, down to the level of replaceable subassemblies, units, parts, components.

1.2.3.1 DISASSEMBLY SEQUENCING

Disassembly sequencing deals with determining the best order of operations in the separation of a product into its constituent parts or other groupings. Various graphical approaches were developed to solve the disassembly sequencing problem.

a. Lambert (1997) presented an AND/OR graph-based graphical method for the generation of the optimum disassembly sequence. Kaebernick et al. (2000) used a cluster graph which is created by sorting the components of a product into different levels based on their accessibility for disassembly.

b. Torres et al. (2003) developed an algorithm based on the product representation to establish a partial non-destructive disassembly sequence of a product.

c. Li et al. (2006) presented a Disassembly Constraint Graph (DCG) to generate possible disassembly sequences for maintenance.

d. Dong et al. (2006) proposed a method for the automatic generation of disassembly sequences from a hierarchical attributed liaison graph.

Some researchers presented Case Based Reasoning (CBR) applications for disassembly sequencing.

a. Zeid et al. (1997) applied CBR to develop a disassembly plan for a single product. In a follow-up paper, Veerakamolmal and Gupta (2002) present a CBR approach for the automatic generation of disassembly process plans for multiple products.

b. Pan and Zeid (2001) developed a knowledge base to assist the users in indexing and retrieving disassembly sequences.

Petri net (PN) modeling represents a popular alternative for disassembly sequencing problem.

a. Moore et al. (1998, 2001) presented a PN-based approach for the automatic generation of disassembly process plans for products with complex AND/OR precedence relationships.

b. Zussman and Zhou (1999, 2000) developed Disassembly Petri Nets (DPNs) for the design and implementation of adaptive disassembly systems.

c. Zha and Lim (2000) integrated expert systems and ordinary PNs (Petri Nets) to develop an expert PN model for the disassembly planning.

d. Tang et al. (2001) presented an integrated approach for disassembly planning and demanufacturing scheduling by developing PN models for workstation status, product disassembly sequences, and scheduling.

e. Tiwari et al. (2001) integrated cost-based indices with PNs to determine an effective disassembly sequencing strategy. Rai et al. (2002) develop a PN-based heuristic approach for disassembly sequence generation.

f. Kumar et al. (2003) and Singh et al. (2003) tried to deal with the unmanageable complexity of normal PNs by proposing an expert enhanced coloured stochastic PN which consists of a knowledge base, graphic characteristics and artificial intelligence.

g. Gao et al. (2004) proposed a fuzzy reasoning PN to deal with the uncertainty associated with the disassembly process. Tang et al. (2006) consider the uncertainty associated with the human factors in disassembly planning and propose a fuzzy attributed PN to deal with this uncertainty.

h. Grochowski and Tang (2009) integrated a DPN and a hybrid Bayesian network to develop an expert system capable of determining the optimal disassembly action without human assistance.

The use of mathematical programming techniques in disassembly sequence generation is another popular approach.

a. Lambert (1999) presented an algorithm based on straightforward LP for the determination of optimal disassembly sequences. Lambert (2006) proposed a methodology based on the iterative use of Binary Integer Linear Programming (BILP) in case of sequence-dependent costs and disassembly precedence graph representation. Lambert (2007) applied the same methodology for the problems with AND/ OR representation. Due to combinatorial nature of the disassembly sequencing problem, there is an increasing trend in the use of metaheuristics.

b. Seo et al. (2001) developed a GA-based heuristic algorithm to determine the optimal disassembly sequence considering both economic and environmental aspects. Li et al. (2005) integrated DCG and a GA to develop an object oriented intelligent disassembly sequence planner. Kongar and Gupta (2006b), Giudice and Fargione (2007), Duta et al. (2008a) and Hui et al. (2008) presented GA-based approaches for disassembly sequencing of EoL products.

c. Gonzalez and Adenso-Diaz (2006) proposed a scatter search-based methodology to deal with the optimum disassembly sequence problem for complex products with sequence-dependent disassembly costs by assuming that only one component can be released at each time.

d. Chung and Peng (2006) developed a GA to generate a feasible selective disassembly plan considering batch disassembly and tool accessibility. Shimizu et al. (2007) applied genetic programming as a resolution method to derive an optimal disassembly sequence.

e. Reveliotis (2007) presented a reinforcement-learning-based approach to provide (near-)

optimal disassembly sequences. Tripathi et al. (2009) presented a fuzzy disassembly sequencing problem formulation by considering the uncertainty inherent in quality of the returned products. They developed an Ant Colony Optimization (ACO)-based metaheuristic to determine the optimal disassembly sequence as well as the optimal depth of disassembly.

f. Kongar and Gupta (in press) employed a multi objective TS algorithm to generate near optimal/optimal disassembly sequences. In some studies, heuristic procedures were developed. Gungor and Gupta (1997) developed a methodology to evaluate different disassembly strategies. They also proposed a heuristic procedure to determine the near optimal disassembly sequences. Gungor and Gupta (1998) addressed the uncertainty related difficulties in disassembly sequence planning. They presented a methodology for disassembly sequence planning for products with defective parts in product recovery.

g. Kuo (2000) provided a disassembly sequence and cost analysis study for the electromechanical products during the design stage. He divided disassembly planning into four stages: geometric assembly representation, cut-vertex search analysis, disassembly precedence matrix analysis, and disassembly sequences and plan generation. The disassembly cost was categorized into three types: target disassembly, full disassembly, and optimal disassembly.

h. Gungor and Gupta (2001b) used a branch and bound algorithm for disassembly sequence plan generation. In Erdos et al. (2001), a heuristic is used to decompose the problem by discovering the subassemblies within the product structure. Then, shortest hyperpath calculation is applied to determine the optimal disassembly sequence.

i. Kang et al. (2003) proposed an algorithm based on mini-max regret criterion to solve the disassembly sequencing problem with interval profit values in the objective function. Mascle and Balasoiu (2003) proposed a wave propagationbased disassembly algorithm to select the disassembly sequence of a specific component of a product.

j. Lambert and Gupta (2008) presented a heuristic algorithm for detecting ‘‘good enough’’ solutions for disassembly sequencing problems in case of sequence-dependent costs. They applied both the heuristic algorithm and the iterative BILP method (Lambert, 2006) using disassembly precedence graph of a cell phone.

k. Sarin et al. (2006) proposed a precedence- constrained asymmetric traveling salesman problem formulation together with a three phase iterative solution procedure. Adenso-Diaz et al. (2008) proposed a GRASP and path-relinking- based heuristic methodology to solve a bi-criteria disassembly planning problem. Hsin-Hao et al. (2000) employed a neural network for disassembly sequence generation.

1.2.3.2 DISASSEMBLY ERGONOMICS

In Aerospace Industry products, the majority of disassembly tasks are performed by specialized and appropriately trained humans, mainly due to the complexity and adaptability (during execution) which robotic programming of tasks would require. As a result, the hands-on nature of disassembly tasks requires the consideration of ergonomic factors in the DfD of such products. However, the number of academic studies on the ergonomics of disassembly is quite small:

a. Kazmierczak et al. (2004) analyzed the current situation and future perspectives for the ergonomics of car disassembly in Sweden using several explorative methods such as site visits, interviews. In a follow-up paper, Kazmierczak et al. (2005) analyzed disassembly work in terms of time and physical work load requirements of constituent tasks.

b. Kazmierczak et al. (2007) combined human and flow simulations to predict the performance of alternative system configurations in terms of productivity and ergonomics for a serial-flow car disassembly line. In order to address the uncertainty due to manual operations in disassembly,

c. Tang et al. (2006) and Tang and Zhou (2008) defined the effect of several human factors (e.g., disassembly time, quality of disassembled components, and labor cost) as membership functions in their fuzzy attributed PN models.

d. Human involvement in disassembly was investigated by Bley et al. (2004) and Takata et al. (2001).

e. Kroll (1996) applied Maynard Operation Sequence Technique (MOST) to determine the difficulty scores of standard disassembly tasks.

f. Desai and Mital (2005) used Methods Time Measurement (MTM) to calculate the ease of disassembly scores for disassembly tasks.

1.2.4 DESIGN FOR DISASSEMBLY

As products become more complex, disassembling them also becomes challenging. Even though it is always possible to perform both nondestructive and semidestructive disassembly operations in a safe and clean way that would normally result in high recovery efficiency, the disassembly **time** and the associated **costs** can be substantial. It is for this reason that disassembly, even though desirable, in many products is practiced only to a limited extent. Enhancing the ease of disassembly and thus reducing disassembly time (and cost) is one of the objectives of the rational product design process of Design for Disassembly.

Three main topics have to be considered within this framework:

1. Appropriate materials composition:
   - Banned substances, such as Cd and asbestos, should be avoided.
   - Potentially hazardous substances should be avoided.
   - Substances that are difficult to recycle, such as composites, should be restricted.
2. Appropriate mechanical properties:
   - The product's structure should be transparent; the fasteners to be loosened to gain access to the product's interior or for separating it in modules should be clearly indicated and not be hidden.
   - The product should have a hierarchical and modular structure, which means that it is easily separable into its main functional units.
   - The fasteners should be accessible and, if forces have to be applied, this should be facilitated.
   - Connections should be reversible as much as possible.
   - The components, as much as possible, should be made of homogeneous materials.
   - The number of applied materials should be restricted, particularly with respect to plastics.
   - The number of fastener types should be restricted.
   - Operations, as much as possible, should be carried out with one tool only.
   - The number of disassembly directions should be restricted.
3. Appropriate availability of information:
   - A code should be applied on the plastic components, to indicate their materials composition.
   - Product data sheets, including data on materials composition, mass, and geometry of components, should be made available.

Many of the above-mentioned criteria also comply with criteria for the ease of assembly.

Several reports on disassembly processes in the literature are devoted to the estimation of time and cost. In most cases, a predefined disassembly sequence, arranged as a hierarchical tree structure is assumed. Typically, the hierarchical tree representation has a modular structure. The hierarchical tree structure is only appropriate for a product that has a distinct **modular** structure. If there is a demand for a particular component, the tree structure offers a unique way to get it. Evidently, a thorough analysis of disassembly processes by subdividing them into operations and tasks is the basis for sound cost metrics.

Two approaches for disassembly cost metrics are available in the literature, which include the **technical** approach and the **work measurement** approach. The technical approach is based on robotic disassembly whereas the work measurement approach is based on human work analysis.

Cost metrics that are based on the technical aspects of the disassembly process are due to Asiedu and Gu (1998), who also presented a review on life cycle costing. Their method includes a formula for the disassembly **time** based on the product structure. It is composed of time to remove components, time to release fasteners and time to release connections without discrete fasteners.

As already mentioned, robotic operations are not suitable for disassembly of aerospace products. In such cases, manual disassembly operations are necessary where costs are often based on direct labor charges.

Several modified work measurement methods have been developed especially for disassembly processes. Authors distinguish a **standardized base time**, which is based on the most efficient method for performing a task under average conditions. This is translated into a 1 to 10 dimensionless scale based on the difficulty of the task. The resulting value is increased with **penalties** based on factors such as **accessibility**, tool **positioning**, and **force** to be applied. Exchange of **tools** and additional **hand movements** are also incorporated. The set of values that are obtained by this are distilled into **one figure**. This is multiplied by a specific **factor** to reveal the disassembly time. In methods like this, the usefulness of the typology of disassembly operations is apparent, as it opens the way for collecting basic data on a restricted number of unit tasks.

Time metric is important in the optimization of both product and disassembly process design. In the approach of Kroll and his colleagues, who use a **disassembly evaluation chart**, the disassembly sequence is predefined. Their approach is primarily aimed at the **evaluation and optimization of the product design**. Alternative disassembly sequences can be evaluated on a one-by-one basis; however, they do not present a systematic optimization method. Although methods that are based only on work measurement can generate estimates for disassembly time, this is not the only component that contributes to the disassembly cost. To this end, Das et al. (2000) suggest an additional cost driver called the **disassembly effort index (DEI)**. Additional points toward costs are given for: (a) the use of specialized fixtures, (b) the need for instructions or skilled workers and (c) the need for safety measures, such as gloves or masks.

The DEI represents indirect costs, which have to be added to the direct labor costs according to some distributive code.

In practice, the disassembly time can vary considerably because of corruption of connections and other contaminations. These factors can be significant, particularly for those products that have been operated in aggressive environments, such as aircrafts, helicopters, Remotely Piloted Airplanes (RPAs). Corruption and contamination not only degrade the quality of components, they also contribute to more difficult and unsafe disassembly activities, which in turn may lead to even compromise the Flight Safety of the aerospace product if disassembly is performed during the useful life.

After the discussion above, Design for disassembly (DfD) could be defined as the consideration of the ease of disassembly in the design process. Thus, apart from the research for disassembly scheduling and sequencing, respective research was performed for the EoL of the products with regards to DfD, ease of disassembly and evaluating EoL disassembly operations, upfront, at the design phase of the product. The main researchers' work in this area:

a. Kroll and Hanft (1998) present a method for the evaluation of the ease of disassembly by using a spreadsheet- like chart and a catalog of task difficulty scores. The scores are determined based on the work-measurement analyses of standard disassembly tasks.

b. Veerakamolmal and Gupta (1999) introduce Design for Disassembly Index (DfDI) to measure the design efficiency. DfDI is calculated by using a disassembly tree which allows the identification of precedence relationships that define the structural constraints in terms of the order in which components can be retrieved.

c. Kroll and Carver (1999) try to develop time-based DfD metrics to be used for comparing alternative designs of the same product.

d. Das et al. (2000) estimate disassembly cost and effort by calculating a disassembly effort index comprising of seven factors: time, tools, fixture, access, instruct, hazard, and force requirements.

e. Chen (2001) uses axiomatic design to develop integrated design guidelines and an evaluation score for the ease of disassembly and recycling called Integrated Disassembly and Recycling Score (IDRS).

f. Ferrer (2001) proposes a framework for the determination of the disassembly and recovery process of a product by developing economic measures of recyclability, disassemblability and reusability.

g. Desai and Mital (2003) and Mital and Desai (2007) develop a methodology to enhance the disassemblability of products. They define disassemblability in terms of several factors such as exertion of manual force for disassembly, degree of precision required for effective tool placement, weight, size, material and shape of components being disassembled, use of hand tools, etc. Time-based numeric indices are assigned to each design factor. A higher score indicates anomalies in product design from the disassembly perspective.

h. Desai and Mital (2005) propose a quantitative DfD methodology by considering numerous ergonomic and conventional design attributes.

i. Villalba et al. (2004) use a recyclability index of materials to determine if it is economically feasible to disassemble a product.

j. Banda and Zeid (2006) present a computational methodology that enables designers to perform disassembly cost analysis in the design phase of a product.

k. Gungor (2006) uses Analytic Network Process (ANP) to evaluate alternative connection types from a DfD perspective.

l. Giudice and Kassem (2009) propose a DfD methodology for characterizing the disassembly depths of product components with respect to their need for removal and recovery at EoL.

m. As an alternative to the index-based approaches to DfD, Viswanathan and Allada (2001) emphasize the importance of product configuration in DfD. They propose a formal model, called the Configuration-Value (CV) model, to evaluate and analyze the effect of configuration on disassembly.

n. In a follow-up paper, Viswanathan and Allada (2006) develop a model for the combinatorial configuration design optimization problem. Design solutions proposed by the model are tested by using a hierarchical evolutionary programming-based algorithm.

o. Kwak et al. (2009) develop a novel concept, called ‘‘eco-architecture analysis’’ in which a product is represented as an assembly of EoL modules. Optimal EoL strategy is developed by determining the most desirable eco-architecture.

p. Chu et al. (2009) propose a CAD-based approach that can automatically generate a variant of 3D product structure by modifying the combination of parts, assembly method and assembly sequence. A Genetic Algorithm (GA)-based computing scheme is employed to determine an optimal product structure from the design alternatives generated by the approach.

1.2.5 EVALUATION OF DISASSEMBLEABILITY - DISASSEMBLY GUIDANCE CRITERIA

Disassemblability of a product is a function of several parameters such as exertion of manual force for disassembly, degree of precision required for effective tool placement, weight, size, material and shape of components being disassembled, use of hand tools, etc. At this point it is reminded that from the manufacturers’ / reclaimers’ perspective, the process may be clearly distinguished into two categories based on the method of disassembly:

a. Destructive disassembly or brute force approach, e.g. incineration, metal cutting, etc. Discussed in previous paragraphs.

b. Non-destructive disassembly or reverse-assembly. Discussed in previous paragraphs. Depending on the extent of disassembly, non-destructive disassembly can be further classified into:

   (1) Total disassembly: The entire product is disassembled into its constituent components. Discussed in previous paragraphs.

   (2) Selective disassembly: Reversible dismantling of complex products into less complex subassemblies or single parts. Discussed in previous paragraphs.

With the exception of a couple of independent researchers, little has been done to enable quantitative evaluation of a design from the disassembly perspective. Most algorithms focus on the theoretical part of the product disassembly process. Examples of these include optimization algorithms; algorithms based on economic analysis, CAD-based algorithms, etc. They fail to consider crucial factors of disassembly for aerospace products such as:

a. The magnitude of manual force required to effect disassembly.

b. The need for specialized manual tools in order to facilitate disassembly.

c. Accessibility issues to enhance quick and easy disassembly.

d. The need for the assumption of irregular working postures for a prolonged period of time.

This is where the ergonomic aspect of the disassembly process comes into picture. Special provisions need to be incorporated into the disassembly algorithms or criteria in order to account for these factors. Also, as already mentioned, the disassembly process of aerospace products is largely manual in nature. It is therefore imperative that a variety of ergonomic factors such as the ones mentioned above come into play in the mass disassembly of aerospace products. An effective disassembly algorithm or criteria model should consider the effect of such factors on the disassembly process as a whole.

1.2.6 DESIGN GUIDELINES FOR DESIGN FOR DISASSEMBLY

Several Life Cycle Analyses indicate that a large chunk of the entire cost associated with the product can be attributed to the product design process. It has further been proved that disassembly process optimization accounts for a meager 10–20% of all disassembly related gains, whereas the major chunk of disassembly related gains (80–90%) tends to be determined at the product design stage. Hence, it is in industry wide interest to develop methods and tools to incorporate environmental considerations into product design. DfD is therefore a key strategy within the larger area of Sustainable Product Design and development.

DfD initiatives lead to the correct identification of design specifications to minimize the complexity of the product structure by achieving numerous objectives such as minimizing the number of different parts, increasing the use of common materials, optimizing the spatial alignment between various components to facilitate disassembly without jeopardizing assemblability, functionality and structural soundness.

1.2.6.1 DEFINING AND EVALUATING DISASSEMBLABILITY

Disassemblability is defined as the degree of easy disassembly (Mok et al., 1997). The following factors affect disassemblability:

a. **Use of force**: Obvioulsy the objective is the need for minimal use of necessary force, which enables the disassembly process to be carried out quickly and without excessive manual labor.

b. **Mechanism of disassembly**: A simple mechanism is preferable.

c. **Use of tools**: Ideally, disassembly should take place without the use of tools. Examples of such processes would include simple push/pull processes or processes in which components become disengaged merely by the exertion of direct manual force. This factor is in agreement with factor a above.

d. **Repetition of parts**: Part repetition should be minimized to enable quick and easy identification of parts at each stage of disassembly.

e. **Recognizability of disassembly points**: Disassembly points are those joints which need to be disjointed so as to affect disassembly. Easy recognizability of such points is advisable especially in the case of complex product structures or products that incorporate snap fits, as well as in the case of products that accumulate internal dirt during their useful life.

f. **Product structure**: The simpler a product structure, the better it is from the disassembly point of view.

g. **Use of toxic materials**: Since most disassembly is still manual in nature it is advisable not to incorporate toxic materials in the design of parts since they may pose health hazards to the operator performing the disassembly.

From the DfD perspective, when a product is designed, a number of changes may be needed to be incorporated, which would render the product technically faulty or structurally unsound and in such a situation, would make product redesign necessary even during its useful life. It would be necessary to redesign components, standardize parts, materials and subassemblies, devise innovative joining methods, etc. This would be very costly and would create many negative impacts; it also became one of the most critical arguments made by researchers of DfD. System parameters classified by disassemblability factors have been collected, as illustrated below (Table 1-3).

Table 1-3: Disassembly System Parameters

Part parameters: STRUCTURAL ASPECTS			
Contact condition	Center of gravity	Weight	Joint point
Symmetry	Grippoint	Strength	Roughness
Interlocking	Joining element	Size	Rounding
Color	Material	Shape	Tolerance
Part parameters: ORGANIZATIONAL ASPECTS			
Product structure	Standardization	Variant	Number of parts
Process parameter: PRE-PROCESS			
Working space	Alignment mechanism	Degree of automation	
Disassembly information	Transport mechanism	Presence of hazards	
Inspection mechanism	Disassembly sequence		
Process parameters: IN-PROCESS			
Disassembly direction	Handling mechanism	Interference	Joining force

Source: Adapted from Mok et al. (1997)

Kroll and Carver (1999) attempted to develop time-based DfD metrics to be used when designing new products to simplify their disassembly for recycling. In their approach, the difficulty in product disassembly can be attributed to the following factors:

a. **Accessibility**: Measure of ease with which a part can be reached by hand or by a tool.

b. **Positioning**: The degree of precision required to place the tool or hand.

c. **Force**: Measure of effort required to perform the task.

d. **Base time**: The time required to do the basic task movements without difficulty.

Though disassembly evaluation metrics play a very important role in product DfD, **time** seems to be the only metric considered in open literature. For example, one factor that the open literature fails to address is the weight to be assigned to specialized tools if they are to be used. More important is the fact that usual methodologies rely heavily on specialized disassembly task analyses only. Similarly, the researchers have stopped at trying to compile a scoring system to estimate disassembly time of a disassembly operation. A systematic methodology to use such scores to enhance product design from the disassembly perspective has not been devised.

In response to that, an optimal disassembly strategy should optimize attributes such as use of manual labor, use of specialized tools, etc. Efforts therefore are needed to adapt knowledge from the theoretical realm to work in the practical realm. To this direction, researchers have managed to find only partial solutions. With this dissertation, an effort to establish scores and weight factors for disassembly, disassemblability and DfD has been implemented. The following paragraphs describe a DfD methodology based of quantitative analysis of design parameters affecting disassemblability. After proper adaptation, this methodology contributed to the creation of the DfD criteria model of this dissertation, for aerospace products.

1.2.6.2 EVALUATION OF DISASSEMBLEABILITY

The methodology presented in the following paragraphs, addresses additional considerations which have wide applicability in the disassembly of aerospace products. It assigns weightage to numerous factors such as size and shape of components being disassembled, weight, frequency of disassembly tasks, requirement of manpower, postural requirements and material handling requirements. A number of human factors in addition to design and economic factors merit consideration due to high labor intensiveness of the disassembly process. These factors directly affect the disassembly process and had hitherto been neglected in the formulation of disassembly algorithms and DfD methodologies.

Every disassembly operation is subdivided into basic elemental tasks. It has been observed that only a fraction of all the tasks in the entire disassembly operation are actually responsible for performing disassembly. For example, if we consider a simple unscrew operation, this may be subdivided into the following elemental tasks:

Operation: unscrew

a. Constrain the product to prevent motion during disassembly.
b. Reach for tool (power screwdriver).
c. Grasp the tool.
d. Position the tool (accessibility of fastener).
e. Align the tool for commencement of operation (accessibility of fastener).
f. Perform disassembly (unscrew operation: force exertions in case of manual unscrew operation).
g. Put away the tool.
h. Remove screws and place them in a bin.
i. Remove the component and put it in a bin.

Clearly, task numbers d, e and f actually affect disassembly. Task numbers a, b and c are preparatory tasks. Altering these tasks would have little or no effect on the efficiency of the disassembly process. Assuming all other conditions such as operator dexterity and speed of operation, weight and size of tool and workplace conditions to remain constant, the efficiency of the disassembly process can be directly attributed to task number d, e, f and i above, which are directly affected by the design configuration of the product. For example, some designs would allow easy access to components for disassembly while others may not. Accessibility of components and fasteners is a design attribute that enables effective positioning and alignment of a tool for disassembly purposes. Similarly, task number i can also be shown to be directly affected by product design. Component removal is influenced by design attributes such as size, shape, weight and material of the component. Large, unsymmetrical and heavy components as well as minute and sharp components are difficult to manipulate and handle and result in decrease in disassembly efficiency. Similarly, all the abovementioned tasks require the adoption of a particular posture during the disassembly process. If a large number of such operations are to be performed during the normal work shift (frequency of operations) and the worker is forced to adopt an unnatural posture resulting in the onset of static fatigue, the long-term effects can be devastating.

Meaningful disassembly evaluation criteria should therefore include all the above-mentioned factors since they are directly related to product design. Other factors that affect the disassembly process include weight and size of tool (large, heavy and unsymmetrical tools are unwieldy and difficult to operate) and any preparation operation such as cleaning and degreasing prior to disassembly.

The enhanced methodology consists of the following distinct elements:

a. A numeric disassemblability evaluation score.

b. Systematic application of DfD methodology.

The numeric disassemblability evaluation index is a function of several design parameters that directly or indirectly affect the process of product disassembly. Numerical scores are assigned to each of these parameters depending on the ease with which they can be attained. The following parameters have been addressed:

a. **Degree of accessibility of components and fasteners**: Easy access is a prerequisite for quick and efficient disassembly operation. The less accessible a component or fastener, the higher numerical score it receives.

b. **Amount of force (or torque) required for disengaging components (in case of snap fits) or unfastening fasteners**: The lesser the amount of force required, the better the design. The amount of effort required is directly proportional to the value of numerical score received.

c. **Positioning**: This attribute reflects the amount of precision required to place a tool for disassembly purposes. The greater the degree of accuracy required, the more the time. This leads to a higher numeric index being assigned.

d. **Requirements of tools**: An ideal disassembly operation constitutes reaching for an easily grasped object and removing it without the exertion of much force and without the use of any tools. However, in most cases, product disassembly entails the use of common tools such as a screwdriver, etc. Under special circumstances, special tools may also be required.

e. **Design factors such as weight, shape and size of components being disassembled**: This can be a crucial consideration in product disassembly especially since it involves the use of special fixtures and apparatus or simply more manpower e.g. for heavy or geometrically complex products.

The ascertainment of a **numeric disassembly score** consists of two distinct parts:

a. Assignment of discrete EoL options to each component.

b. Evaluation of numeric indices affecting disassemblability.

This is described in detail as follows:

1.2.6.3 ASSIGNMENT OF EoL OPTIONS TO COMPONENTS

Each component is assigned a discrete EoL option: reuse, remanufacturing and recycling. Incineration and land filling are not considered as EoL options since this methodology is being formed to enable non-destructive disassembly of product structures (Table 1-4) which is necessary in the useful life of the aerospace product as well. The following factors are considered while deciding EoL options for each component (Table 1-5).

Table 1-4: Comparison of EoL Options Based on Cost Considerations

EoL option	Definition	Associated costs of implementation
Reuse	Component is disassembled from the product structure and is used on an ‘‘as is’’ basis, without any technological up-gradation/downgradation or being subject to any design modifications (Aerospace Industry term: parting out)	• Disassembly costs • Cleaning costs • Assembly costs
Remanufacturing	Component is disassembled from the product structure and is subject to certain design changes which result in technological upgradation/ downgradation	• Disassembly costs • Cleaning costs • Redesign costs • Remanufacturing costs • Assembly costs
Recycling	Only the material of the component is used again to perform another function	• Disassembly costs • Cleaning costs • Recycling costs

		• Material processing costs • Manufacturing costs • Packaging costs • Assembly costs

Table 1-5: Attributes Affecting Decision of EoL Options

Attributes	
1.	The level of technological complexity of the component
2.	Functional importance of component
3.	Cost associated with manufacturing and assembling the component
4.	Level of manufacturing expertise associated with manufacturing and assembling the component
5.	Cost associated with taking the component apart and recycling it
6.	Component life
7.	Probability of component design undergoing fundamental changes in the near future that fundamentally affect its functionality, efficiency and/or performance

The logic in assigning EoL options to components early on during the evaluation process is to take advantage of the philosophy: "Vital few, trivial many".This means that components destined for reuse, being the most important are considered first for design changes. Design changes made to these components may in turn require changes to be made to other components as well. It is advisable to have more important components to be the focal point in design analysis.

1.2.6.4 NUMERIC EVALUATION OF DISASSEMBLABILITY

Each component is evaluated for each of the above-mentioned attributes directly affecting disassemblability. Each of the above factors is further subdivided into causal design parameters, alteration of which can result in significant improvement in disassemblability of the component. The scoring system as presented below is based on the MTM (motion time measurement) predetermined time system. The simplest disassembly task of removing an easily grasped object without the exertion of much force by hand, by a trained worker, under average conditions, has been considered as the basic disassembly task. A score of 73 TMUs (time measurement units) was assigned to this task, which corresponded to time duration of approximately 2 sec. Subsequent scores were assigned based on the detailed study of most commonly encountered disassembly operations. A similar scoring system was used together with an established maintainability index system, while the DfD criteria model of this dissertation was being built.

Table 1-6: Scoring System for Numeric Analysis of Disassemblability

Design attribute	Design feature	Design parameters	Score - Interpretation
DISASSEMBLY FORCE	Straight line motion without exertion of pressure	Push/pull operations with hand	0.5 Little effort required 1 Moderate effort required 3 Large amount of effort required
	Straight line and twisting motion without pressure	Twisting and push/pull operations with hand	1 Little effort required 2 Moderate effort required 4 Large amount of effort required
	Straight line motion with exertion of pressure	Inter-surface friction and/or wedging	2.5 Little effort required 3 Moderate effort required 5 Large amount of effort required
	Straight line and twisting motions with exertion of pressure	Inter-surface friction and/or wedging	3 Little effort required 3.5 Moderate effort required 5.5 Large amount of effort required
	Twisting motions with pressure exertion	Material stiffness	3 Little effort required 4.5 Moderate effort required 6.5 Large amount of effort required
MATERIAL HANDLING	Component Size	Component dimensions (very large or very small)	2 Easily grasped 3.5 Moderately difficult to grasp 4 Difficult to grasp
		Magnitude of weight	2 Light (o7.5 lb) 2.5 Moderately heavy (o17.5 lb) 3 Very heavy (o27.5 lb)
	Component Symmetry	Symmetric components are easy to handle	0.8 Light and symmetric 1.2 Light and semi-symmetric 1.4 Light and asymmetric 2 Moderately heavy, symmetric 2.2 Moderately heavy, semisymmetric 2.4 Moderately heavy, asymmetric 4.4 Heavy and symmetric 4.6 Heavy and semi-symmetric 5 Heavy and asymmetric
REQUIREMENT OF TOOLS FOR DISASSEMBLY	Exertion of force		1 No tools required 2 Common tools required 3 Specialized tools required
	Exertion of torque		1 No tools required 2 Common tools required 3 Specialized tools required
ACCESSIBILITY OF JOINTS/ GROOVES	Dimensions	Length, breadth, depth, radius, angle made with surface	1 Shallow and broad fastener recesses, large and readily visible slot/ recess in case of snapfits 1.6 Deep and narrow fastener recesses, obscure slot/recess in case of snapfits 2 Very deep and very narrow fastener recesses, slot for prying open snap fits difficult to locate
	Location	On plane surface	1 Groove location allows easy access
		On angular surface	1.6 Groove location is difficult to access. Some manipulation required
		In a slot	2 Groove location very difficult to access

POSITIONING	Level of accuracy required to position the tool	Symmetry	1.2	No accuracy required
			2	Some accuracy required
			5	High accuracy required
		Asymmetry	1.6	No accuracy required
			2.5	Some accuracy required
			5.5	High accuracy required

1.2.6.5 POSTURE ALLOWANCES

The disassemblability evaluation of medium size products, such as aircraft components, normally incorporates allowances for the need of specialized postural requirements, since disassembly is usually performed by one or two workers and the cost of specialized disassembly fixtures is high, especially if such fixtures are needed at the EoL of the product when design details may be unavailable. It is easily understood that the specialized postural requirements have significant impacts on the total cost of disassembly. Unnatural postures commonly encountered are listed in Table 1-7. In addition, product design characteristics leading to the need for the adoption of some such postures are also listed in Table 1-8.

Table 1-7: Correlation of Need for Unnatural Postures to Specific Design Anomalies

Posture	Design anomalies
Prolonged gripping of a tool	• Large number of fasteners • Need for large amount of disengaging force • Need for sustained exertion of disengaging force • Large number of disengaging points
Prolonged bending and twisting the neck	• Need to reach obscure components/fasteners (location) • Need to reach obscure components/fasteners (size) • Complex and twisted disassembly path • Need to perform a highly accurate disassembly operation on a sensitive component • Need to avoid hazardous components in the disassembly path

Table 1-8: Provision of Allowances for Adoption of Atypical Postures to Incorporate Ergonomic Considerations in Product Design

Posture	Score
Prolonged gripping	3
Prolonged arm extension forwards	3
Prolonged bending and twisting the neck	4
Prolonged bending and twisting the entire torso	4
Prolonged wrist flexion	3

Posture allowances were seriously considered in the DfD criteria model of this dissertation, but for the sake of keeping the model simple and applicable to all considered aerospace products, what was used, is the posture scoring system of an established maintainability index (BMI).

1.2.6.6 DESIGN DIAGNOSTICS

Once design attributes with high numeric scores have been identified for each component, causal effects need to be diagnosed. A detailed and in depth diagnosis of these effects results in the formation of alternative design configurations, which usually are better than the previous configurations. A few of the design diagnostics for the design attribute “Accessibility” are as outlined in Table 1-9 below.

Table 1-9: Design Modifications to Enhance Disassemblability from the Perspective of the Design Attribute: Accessibility

Design attribute	Design feature	Remedial measures	Component redesign required?
Accessibility	Deep fastener recesses	Redesign recess to facilitate tool access	Y
		Select a different fastening method	Y
	Narrow fastener recesses	Redesign recess to facilitate tool access	Y
		Select a different fastening method	Y
	Small fastener head	Increase fastener head size	N
		Select a different fastening method	Y
	Obscure fastener	Choose standard fastener sizes	N
		Increase fastener size	N
		Select a different fastening method	Y
	Deformed fastener	Improve fastener rigidity to withstand stresses during operation	N
	Deformed component	Improve component rigidity to withstand stresses during operation	Y
		Redesign weak component cross sections	Y
	Deformed bearing surface of component	Improve component rigidity to withstand stresses during operation	Y
	Need for cleaning before access	Redesign component/fastener interface	Y
		Change component material	Y
	Obscuring components	Redesign assembly sequence based on disassembly priority of components	N
	Insufficient clearance for effective tool manipulation	Redesign component recesses/slots	Y
		Redesign fasteners	N
		Select a different fastening method	Y

As is evident from the above diagnostics, a variety of alternative design configurations can be generated corresponding to each remedial measure. Each of these configurations may in turn be analyzed for cost effectiveness and in turn be tested for functionality, assemblability, manufacturability and structural rigidity under working conditions. The following Figure 1-2 is a hierarchical representation of the DfD algorithm based on the aforementioned considerations.

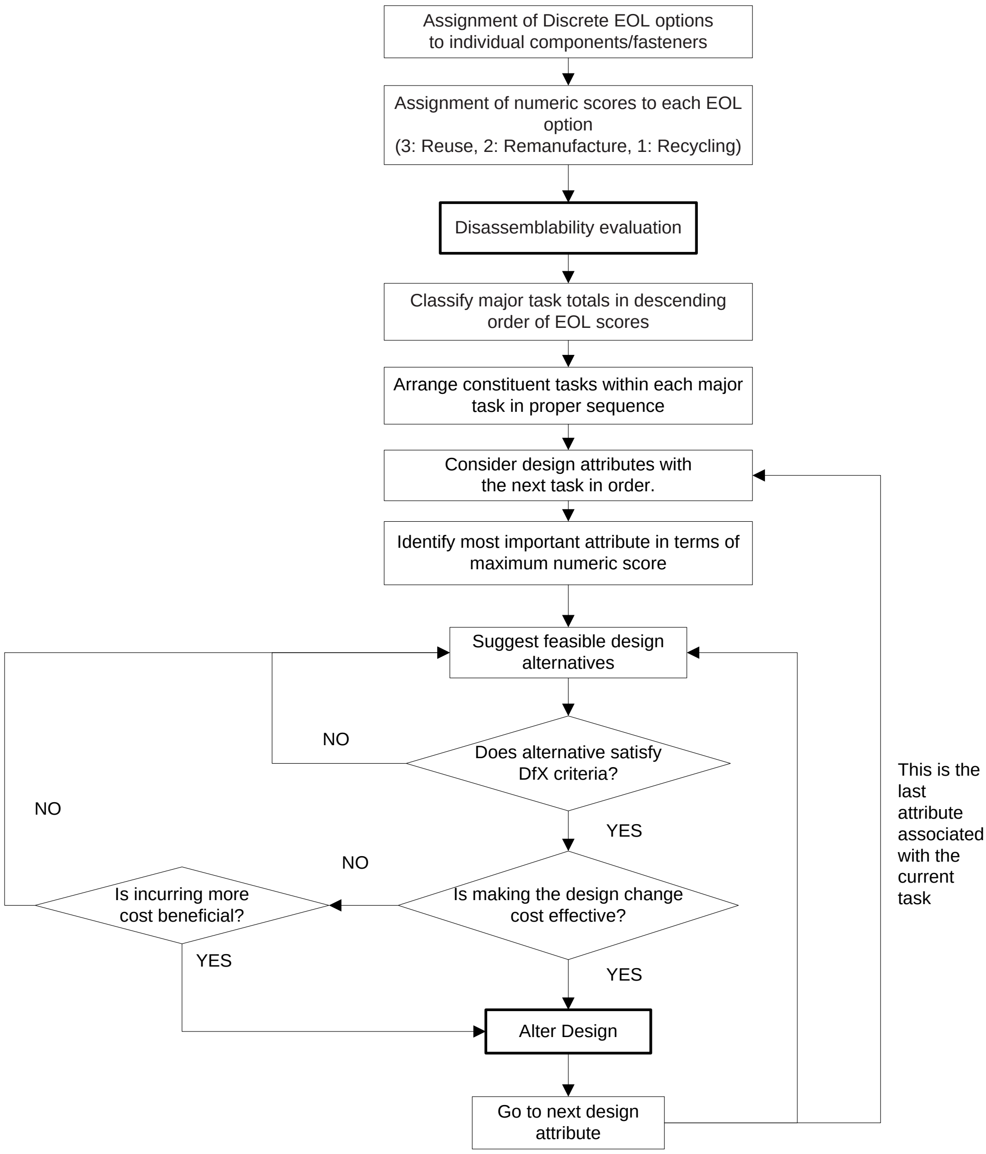


Figure 1-2: Hierarchical Reasoning of the DfD Algorithm.

An experiment conducted on an electric drill set to gauge the effectiveness of the above methodology in the objective Table 1-10 is only a random assortment of some disassembly tasks and tools. The tasks and tools listed do not necessarily correspond to one another. From the results of the experiment, it is clear that the total disassembly time equaled approximately 1.94 min.

Table 1-10: Sample List of Commonly Encountered Disassembly Tasks and Disassembly Tools

Task	Code	Tool	Code
Unscrew	Un	Power screwdriver	Ps
Pry open	Pr	Pry bar	Pr
Pull	Pu	Screwdriver	Sd
Invert	In	Adjustable wrench	Aw
Push	Ps	Allen key	Ak

1.2.6.7 COMPREHENSION OF DESIGN EVALUATION

As is evident from the numeric evaluation chart presented in the preceding section, the task involving removal of component 4 from the assembly comprises the highest score of the entire disassembly operation for components with the highest EoL value. This is followed by the task involving removal of component 9 and so on. The next step involves identifying the most important design anomaly in terms of maximum numeric score for the first task in the list. For example, in the case study performed in the preceding section, the task involving removal of component 4 would be the first task considered for scrutiny. The following design anomalies (those receiving the highest scores) are involved in performing the task:

a. Need for excessive force (design factor),

b. Component shape, size and weight (design factor),

c. Accuracy of tool positioning (design factor).

1.2.6.8 ADVANTAGES OF DESIGN METHODOLOGY

The described methodology offers several distinct advantages which are enumerated as follows:

a. The system of assigning numeric scores to varying degrees of difficulty of a particular criterion has been kept simple and straightforward. Each scoring criterion has been correlated to a list of possible design flaws. This enables quick and ready interpretation of numeric disassembly scores.

b. The scoring system can be readily adapted to suit any disassembly operation involving any kind of tool, and disassembly actions.

c. Since the methodology couples disassemblability evaluation with DfD criteria, numeric scores obtained from the former can be readily identified as design flaws, which can be corrected using appropriate DfD criteria.

d. Additional allowances for human factors such as assumption of unnatural postures while performing particular disassembly tasks can be readily correlated to a design flaw. For example, a highly repetitive task of accessing and positioning a tool in a narrow and deep recess requires much attention and entails visual fatigue.

2 DESIGN FOR DISASSEMBLY IN AEROSPACE INDUSTRY

2.1 INTRODUCTION - DEFINITIONS

Aerospace is a broad industry that consists of civilian and military aircraft, space vehicles, and missiles. Aerospace manufacturing and space research and technology provide large portions of the industrial employment across the industry. Additionally, aircraft suppliers provide parts and machinery for aircraft assembly and maintenance, including engines, interior components, avionics, and aircraft hardware such as landing gears. Suppliers are important for both the assembly and maintenance of aircrafts. The industry's customers normally include the military, commercial airlines, and general aviation.

Aerospace Engineering is the primary branch of engineering behind the design, construction and science of aircrafts and spacecrafts. It is broken into two major and overlapping branches: aeronautical engineering and astronautical engineering. Aerospace Engineering deals with the design, construction, and application of the science behind the forces and physical properties of aircraft, rockets, flying craft, and spacecraft. The field also covers their aerodynamic characteristics and behaviors, airfoil, control surfaces, lift, drag, and many other properties. Aerospace Engineering is not to be confused with the various other fields of engineering that go into designing these complex crafts. For example, the design of aircraft avionics, while certainly part of the system as a whole, would rather be considered as electrical engineering, or in some cases as computer engineering. The landing gear system on an aircraft may fall into the field of mechanical engineering, and so forth. It is typically a large combination of many disciplines that makes up aeronautical engineering. While aeronautical engineering was the original term, the broader "aerospace" has superseded it in usage, as flight technology advanced to include crafts operating in outer space. Aerospace Engineering, particularly the astronautics branch, is referred to colloquially as "rocket science".

Within the context of this dissertation, the aerospace products of interest are limited to the capable to fly (airworthy) products and not to their ground support equipment which is very generally and briefly addressed in the dissertation. To better understand the applicability of DfD in aerospace products, in the following paragraphs some useful and clarifying definitions are provided, so that the structural and functional complexity of the aerospace products as well as the considerations for their disassembly perspectives (procedural, physical, materialistic, human, environmental etc) become more obvious.

An **aircraft** is a vehicle that is able to fly by gaining support from the air, or, in general, the atmosphere of the planet. An aircraft counters the force of gravity by using either static lift or by using the dynamic lift of an airfoil, or in a few cases the downward thrust from jet engines. The human activity that surrounds aircraft is called **aviation**. Manned aircrafts are flown by one or two onboard pilots. Unmanned or Remotely Piloted aerial vehicles may be remotely controlled by humans or self-controlled by preflight programmed onboard computers.

An aircraft **part** is an article or component approved for installation on a certificated aircraft. Approval for these parts is derived from the jurisdictions of the countries that an aircraft is based. In the United States for example, the Federal Aviation Administration oversees the approval for these parts under Federal Aviation Regulation Part 21. Parts may be **life-limited parts**, which as a condition of their type certificate, may not exceed a specified time or number of operating cycles in service. Some high value aircraft parts can be repaired using various re-manufacturing processes such as machining, welding, plating, etc. As a result, disassembly takes places many times during the useful life of the product.

Most recently, the global business aviation community announced its commitment to climate change and has set ambitious targets for carbon emissions reduction. The industry's statement on climate change, commits to the following specific targets:

a. Carbon-neutral growth by 2020;

b. An improvement in fuel efficiency of an average of 2% per year from today until 2020;

c. A reduction in total CO2 emissions by 50% by 2050 relative to 2005.

Achievement of these objectives is pursued through expected advances in four areas: (a) technology, (b) infrastructure and operational improvements, (c) alternative fuels, and (d) market based measures. It should be noted however, that the efforts obviously address environmental savings during the useful life of the products and not at their EoL and beyond.

2.1.1 AIRCRAFT PRINCIPAL STRUCTURAL UNITS

The principal structural units of an aircraft consist of the **fuselage**, **engine mount**, **nacelle**, **wings**, **stabilizers**, **control surfaces**, and **landing gear**. Those principal units host numerous complex compontents, subassemblies and assemblies such as the engines, the fuel system, the hudraylic pressure systems, the environmental control system, the communication and avionics systems, the weapon systems (where applicable), the external stores/ loads (e.g. fuel tanks) the instrument and flight control systems etc.

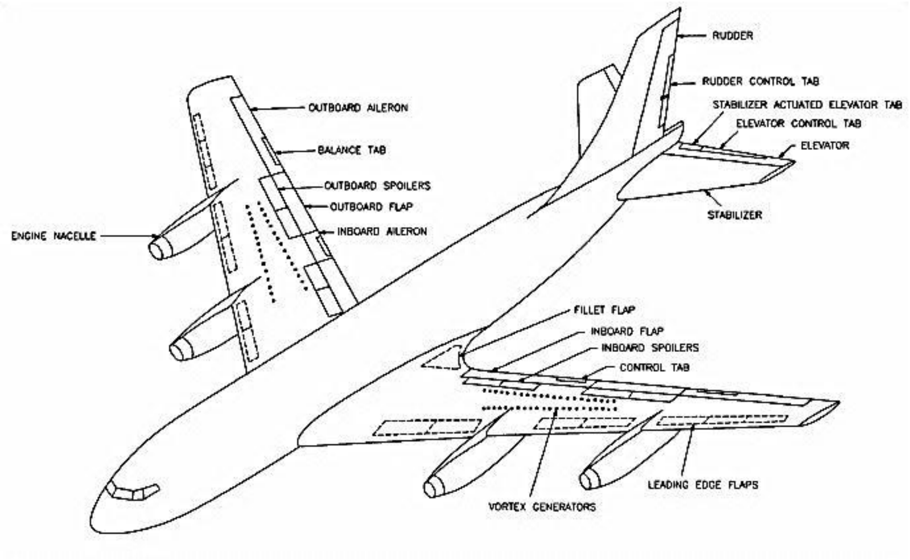


Figure 2-1: Commercial Airliner Aircraft Principle Structural Units

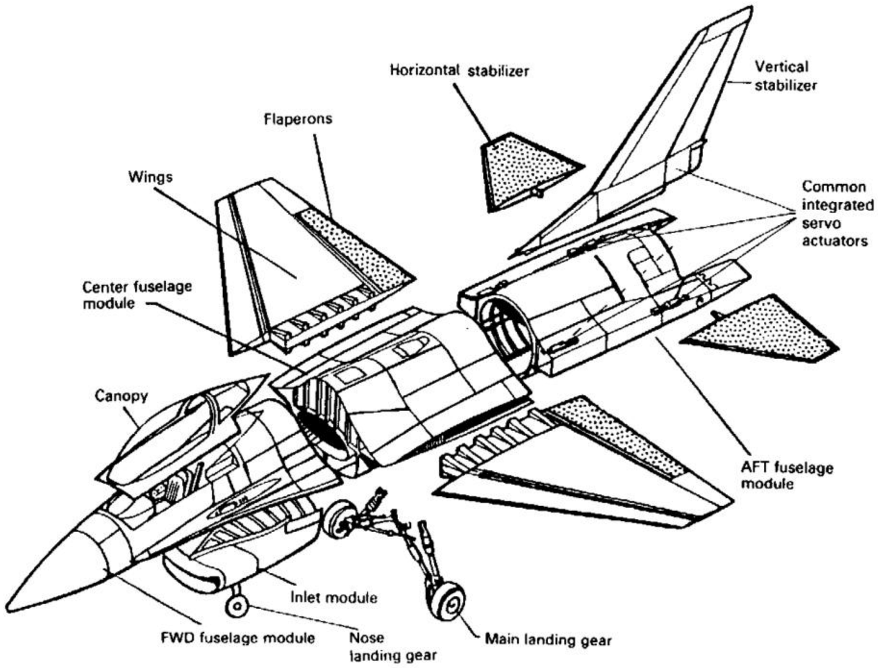


Figure 2-2: Military Fighter Aircraft Structural Breakdown

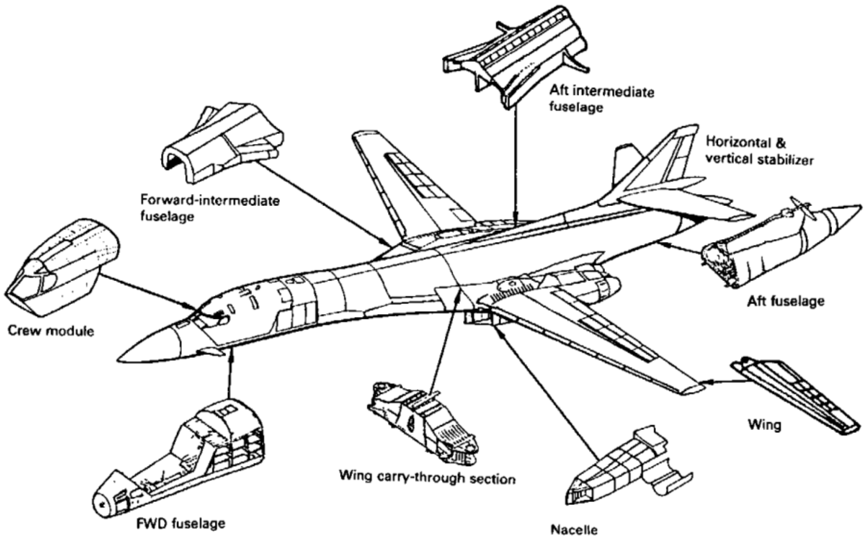


Figure 2-3: Military Bomber Aircraft Structural Breakdown

2.1.1.1 AIRFRAME - FUSELAGE

The airframe of an aircraft is its mechanical structure, typically considered to exclude the propulsion system. Airframe design is a field of engineering that combines aerodynamics, materials technology and manufacturing methods to achieve balances of performance, reliability and cost.

The fuselage is the main structure or body of an aircraft. It provides space for cargo, controls, accessories, passengers, and other equipment. In single- or multi-engine aircraft, its design may be such that it houses the power plant. Power plants may also be attached to the fuselage or suspended from the wing structure. The fuselage also serves to position control and stabilization surfaces in specific relationships to lifting surfaces, required for aircraft stability and maneuverability.The fuselages of modern aircraft typically rely on some form of stiffened shell design. This design may be divided into two classes: monocoque and semimonocoque. Different portions of the same fuselage may belong to either class, however, semimonocoque design is most common (see Figure 2-4).

a. **Monocoque Design.** Monocoque design relies on the strength of the skin (also known as the shell or covering) to carry the various loads. True monocoque construction does not use formers, frame assemblies, or bulkheads to give shape to the fuselage. Instead, the skin carries all fuselage stresses. Since no bracing members are present, the skin must be strong enough to keep the fuselage rigid. Thus, the biggest challenge in monocoque design is maintaining enough strength while keeping the weight within allowable limits. The advantage of a monocoque design is that it is relatively easy to manufacture. Despite this advantage, the **weight penalty** makes it impractical and inefficient to use monocoque construction except in relatively small areas of the fuselage that carry only limited loads. To overcome the strength-to-weight problem of monocoque design, a modification called semimonocoque design exists.

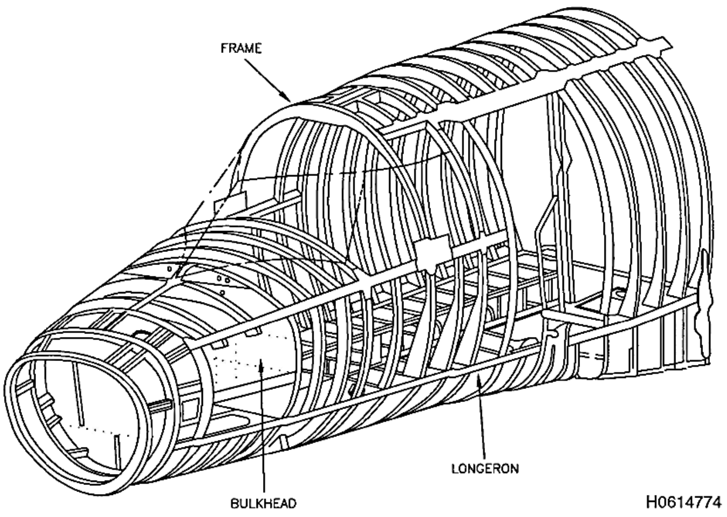


Figure 2-4: Semimonocoque Fuselage Design

b. **Semimonocoque Design.** Semimonocoque design may use any combination of longerons, stringers, bulkheads, and frames to reinforce the skin and maintain the cross-sectional shape of the fuselage. The skin, which is fastened to all of these members, helps resist shear load and, together with the longitudinal members, the tension and bending loads. Longerons resist the majority of fuselage bending loads. Stringers help resist fuselage bending and stabilize the skin in compression. Bulkheads are used where concentrated loads are introduced into the fuselage, such as those at wing, landing gear, and tail surface attach points. Frames are used primarily to maintain the shape of the fuselage and improve the stability of the stringers in compression.

2.1.1.2 FUSELAGE CONSTRUCTION

Today's modern aircrafts are constructed from various materials. The most common material being used for fuselage construction is aluminum alloy. Common fuselage materials, such as aluminum 7075 and 2024, are about three times lighter than steel. Following heat treatment, these alloys are approximately equal in strength to mild steel. For some uses (e.g., surface covering), the alloy is made in sheets with a thin covering of pure aluminum on both sides. In this form, it is commonly known by the trade name Alclad. The pure aluminum cladding on both sides serves as a protective coating to the base metal. Extrusions are generally of aluminum 2024; however, aluminum 2014 is being used for extrusions with web thickness greater than 1/8 inch. In addition to aluminum, stainless steel, titanium, and various composite materials are also used in fuselage structure.

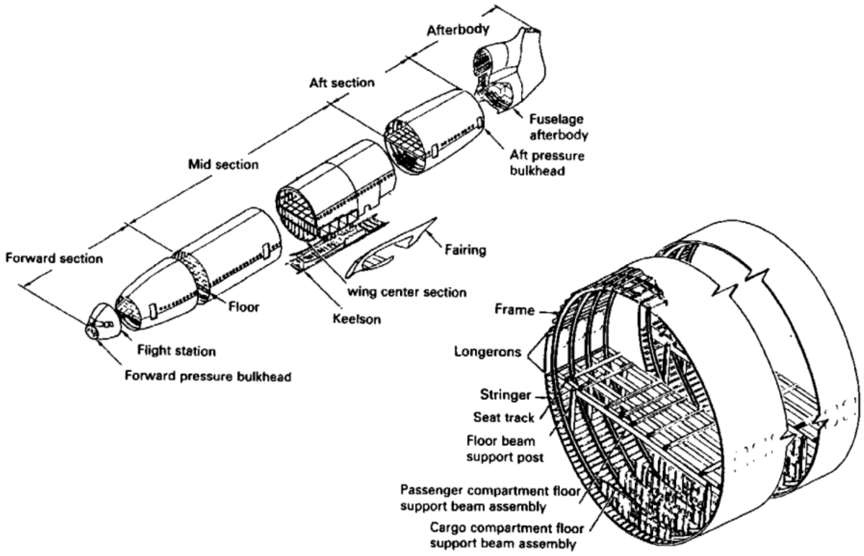


Figure 2-5: Section of Commercial Airliner Fuselage

2.1.1.3 ENGINE MOUNT

A primary consideration in the design of engine mounts and support fittings is to render the engine and its equipment accessible for inspection and maintenance. These mounts and support fittings are typically made of some type of corrosion-resistant steel with an ultimate strength of 180 to 200 thousands PSI. The exact location of the engine mounts and their attachments are specific to the aircraft they have been designed for, but the conditions to which they are subjected are similar:

a. Engine mounts and support fittings operate in a high- temperature environment. They are also susceptible to fatigue failure caused by high-vibration inertial loads and are as well susceptible to stress corrosion attack due to the harsh environment and the quality of the materials used. Therefore, the material properties and surface finish of engine mounts and support fittings must be of the highest quality to help prevent stress corrosion failures. In addition, protective coatings are used to shield the engine mounts from the environment. In conjunction with flight load, improper torquing of engine mount fasteners can cause fastener failure. This is a Safety-Of-Flight matter.

b. The nacelles of most aircrafts are of similar shape and general design. On multi-engine aircrafts, nacelles are streamlined enclosures designed to house and protect the engines. On single-engine aircraft, the nacelle becomes a streamlined extension of the fuselage. These structures vary principally with the size of the aircraft and the size and number of engines. In certain cases, nacelles are designed to transmit engine loads to the wing.

c. The structure and materials used in nacelle construction are similar to those used for the fuselage. The nacelle consists of skin, cowling, structural members, a firewall, and engine mounts. Skin and cowling cover the outside of the nacelle. Both are usually made of sheet aluminum alloy, stainless steel, magnesium, or titanium. Regardless of the material used, the skin is usually attached to the framework by rivets. The structural members include lengthwise members, such as longerons and stringers, and widthwise or vertical members, such as bulkheads, rings, and formers. The firewall, which separates the engine compartment from the rest of the aircraft, is usually made of stainless steel sheet metal. In some aircrafts, the firewall is made of titanium.

In general, powered aircrafts have one or more engines which usually are either lightweight piston engines or gas turbines. The fuel is usually kept in tanks around the vehicle. Most aircraft store the fuel predominantly in the wings, but may have additional fuel tanks elsewhere.

2.1.1.4 WING STRUCTURES

The wings of an aircraft produce lift. Many different styles and arrangements of wings have been used on heavier-than-air aircrafts, and some lighter-than-air crafts also have wings. Most early fixed-wing aircrafts were biplanes, having wings stacked one above the other. Most types nowadays are monoplanes, having one wing each side. Wings also vary greatly in their shape when viewed from above.

Variations in design and construction depend upon the manufacturer and mission performance requirements. Wing structure is based on one of three fundamental designs: monospar, multispar, or box beam. Wing structures of most modern aircrafts are of cantilever design and constructed of metal or advanced composite. With few exceptions, the skin is a part of the basic load-bearing wing structure and carries part of the stresses.

Generally, wing structures have two or more spars running the length of the wing and often through the fuselage. Ribs and bulkheads are placed chordwise, at frequent intervals between the spars, to maintain spar spacing and wing contour. Sheet aluminum or advanced composite skin covers the ribs and provides the airfoil surface. During flight, applied air loads are imposed directly on the wing skin. These loads are transmitted from the skin to the ribs and from the ribs to the spars. The spars support all distributed loads as well as concentrated weights from the fuselage and power plants. Similar to fuselages, the metal generally used for wing structures is heat-treated aluminum alloy. The spars and ribs are generally 2000 or 7000 series aluminum extrusions or forgings. The smooth outer covering is usually Alclad aluminum alloy and is attached with rivets or other fasteners. Improvements in the processing of fiber-reinforced and honeycomb composites have made it possible to combine a wide variety of materials for specific applications. These improvements have greatly increased the use of advanced composites in wing structures.

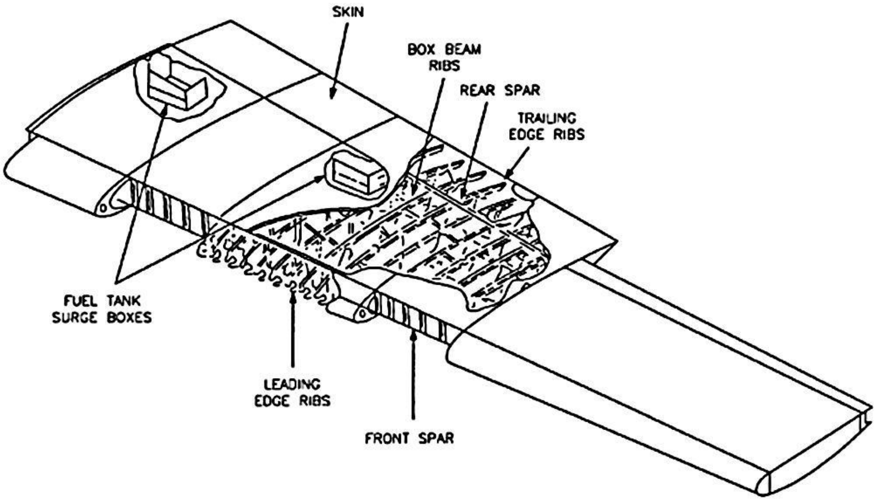


Figure 2-6: Aircraft Wing Design

Stabilizers (or tail surfaces) of conventional aircraft consist of vertical and horizontal airfoils located at the rear portion of the fuselage. These airfoils are generally referred to as the tail section or empennage. They consist of the horizontal stabilizer or stabilator, elevators, vertical fins, and rudders (Figure 2-6 and Figure 2-7). Empennage incorporating vertical and horizontal stabilizing surfaces which allow equilibrium of aerodynamic forces, stabilizes the flight dynamics of pitch and yaw, as well as housing control surfaces.

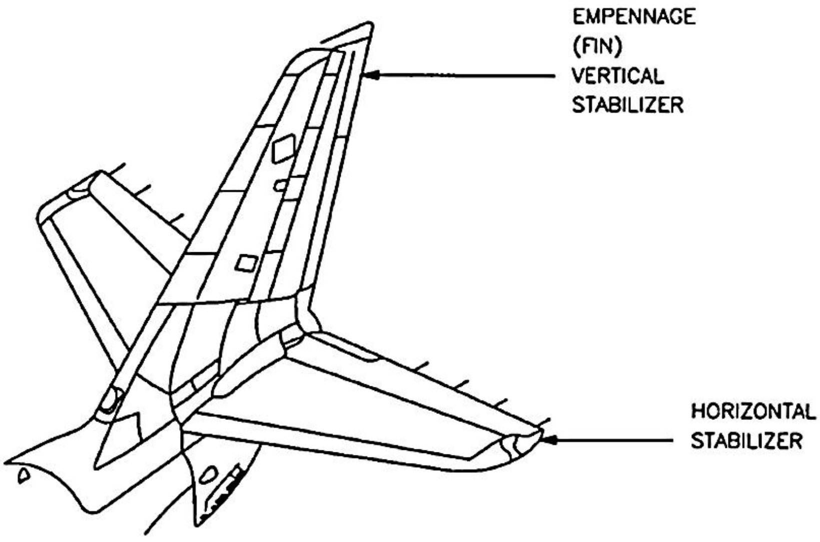


Figure 2-7: Typical Tail Structures

Construction features of tail surfaces are in many ways identical to those of wings. Tail surfaces are usually made of metal or advanced composite. The tail surface has a cantilever design, with the skin attached to a spar or spars and ribs. The stabilizer is generally constructed in a continuous section mounted on or through the fuselage, although it is sometimes built in left- hand

and right- hand sections. The stabilizer is similar to the fin in internal construction and serves as a support for the elevators.

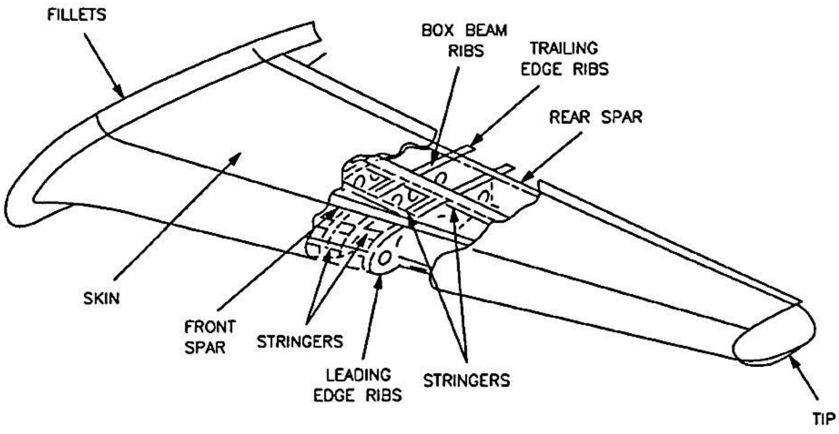


Figure 2-8: Typical Stabilizer Structures

2.1.1.5 MAIN CONTROL SURFACES

Flight control surfaces allow a pilot to control an aircraft's flight attitude. Development of an effective set of flight controls was a critical advance in the development of aircraft and literally it is what allowed flight. These surfaces are movable surfaces, usually made of an aluminum alloy structure built around a single spar member or torque tube. Ribs are attached to the spar at the leading edge and at the trailing edge. The leading edge or nose portion of the surface is covered with thin aluminum-alloy sheet back to the spar member and forms the front part of the structure.

Auxiliary control surfaces are relatively small airfoils attached to or recessed into the trailing edge of the main control surfaces. They consist of trim tabs, balancing tabs, and servo tabs. Flaps, speed brakes, slats, and spoilers are also considered auxiliary flight control surfaces.

Flaps are relatively large airfoils attached to the wing structure. Generally, the lower surface of the rear portion of the wing becomes the trailing edge flap. When closed, the trailing edge flap constitutes a section of the lower surface of the wing and usually swings downward to open. Some common types of trailing edge flaps systems are the plain, split, slotted and Fowler flap systems.

Aircraft requiring extra wing area to aid lift often use Fowler flaps. Like the split flap system, this system houses the flaps flush under the wings. Instead of using a stationary hinge line, however, Fowler flaps use worm-gear drives to move the leading edge of the flap rearward as it droops. In addition to increasing the camber of the wing, Fowler flaps increase wing area as the flaps are extended. Leading edge flaps are similar in operation to plain flaps. These flaps are hinged on the bottom side and, when actuated, the leading edge of the wing extends in a downward direction to increase the camber of the wing (see Figure 2-9 and Figure 2-10).

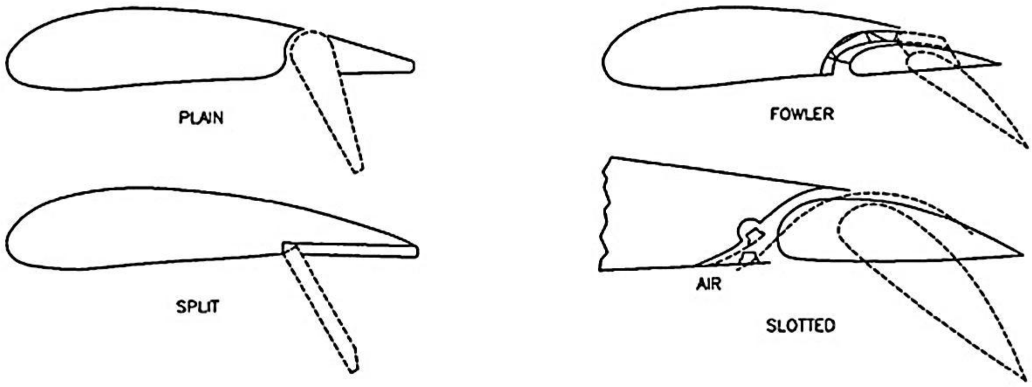


Figure 2-9: Types of Wing Flaps

Speed brakes are control surfaces which may be located on the upper or lower surface of each wing outer panel or may be located on the trailing edge of the wings as landing flaps are. Those found on the upper and lower surfaces of wing panels are either latticed or perforated. Each upper assembly is linked to its corresponding lower assembly to balance the air loads acting on each, with the result that comparatively little mechanical force is needed for operation. Trailing-edge speed brakes are located and operated in a similar manner as landing flaps. They are usually perforated and may be controlled electrically or hydraulically.

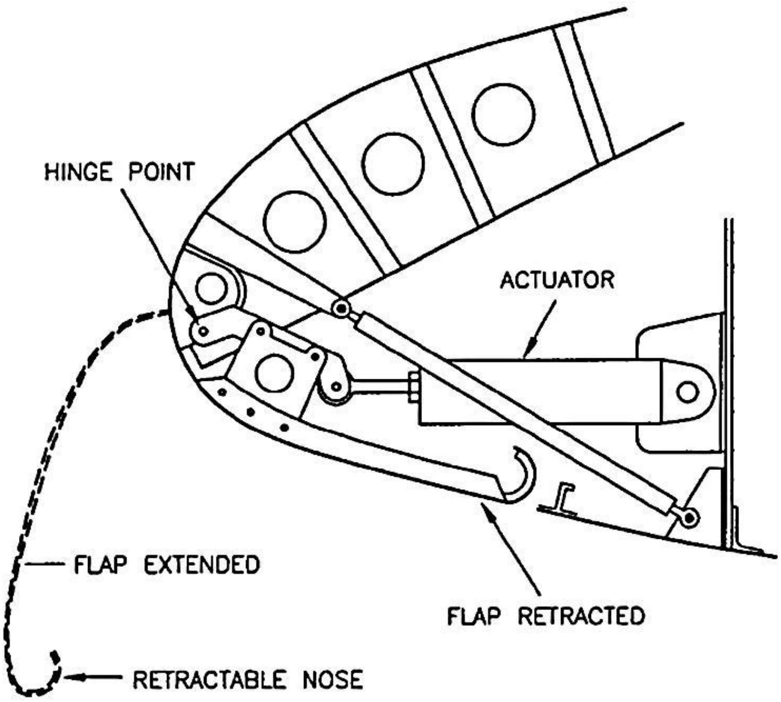


Figure 2-10: Leading Edge Flaps

Slats are movable airfoils attached to leading edges of wings. When open, a slot is created between the slat and the leading edge of the wing. At high angles of attack, this nozzle-shaped passage through the wing improves the airflow conditions. When the slat is closed, it resumes the original contour of the wing.

Spoilers generally are hinged portions of the upper surfaces of wings, similar to flaps except much smaller, which interrupt wing lifting characteristics and cause an increase in drag.

2.1.1.6 UNDERCARRIAGE (LANDING GEAR) STRUCTURE

The undercarriage or landing gear is the structure that supports an aircraft on the ground and allows it to taxi, to take off, and to land. In the typical undercarriage, wheels are used, but skids, floats, or a combination of these and other elements can be used, depending on the surface. Many aircraft have undercarriage that retracts into the wings and/or fuselage to decrease drag during flight. Flying boats are supported on water by their fuselage and hence have no undercarriage, except for amphibians, which have retractable undercarriage allowing them to take off from and alight on both land and water. The landing gear consists of that portion of landing gear that supports the aircraft when landing or taxiing. It may include any combination of the following:

a. Wheels
b. Skids
c. Skis
d. Struts
e. Brake and steering mechanisms
f. Retracting mechanisms and their controls
g. Warning devices
h. Fairings
i. Framing or structural members necessary to secure any of the above to the main structure

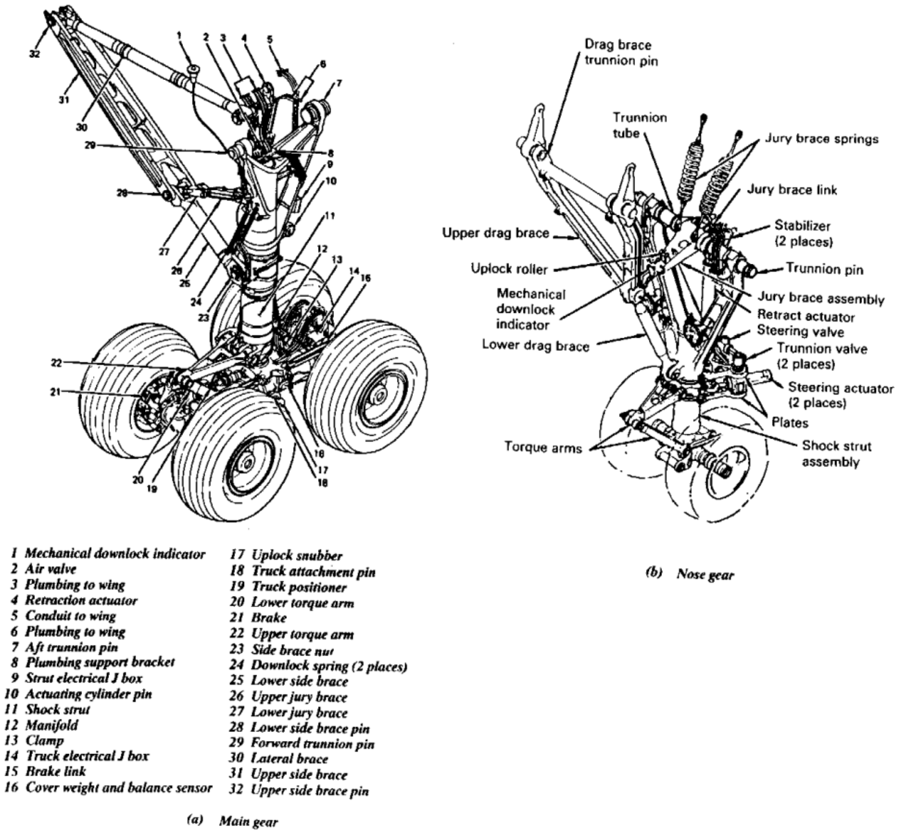


Figure 2-11: Main Landing Gear and Nose Landing Gear Assemblies of Commercial Airliner

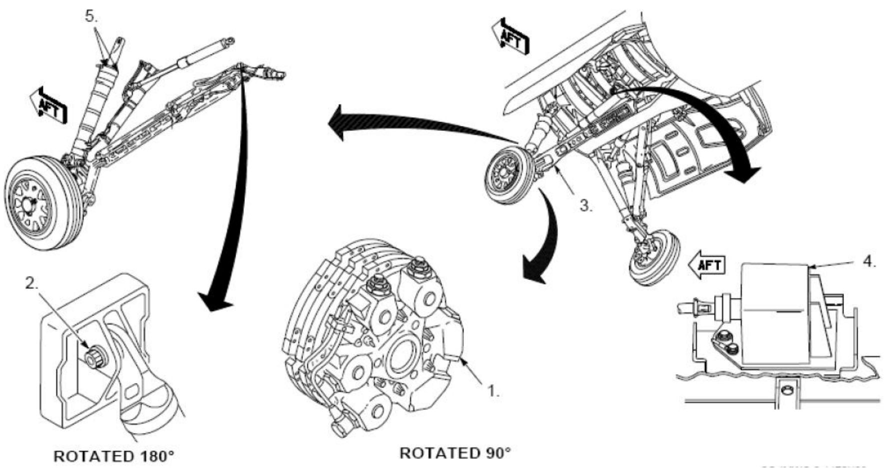


Figure 2-12: Main Landing Gear Aspects of Fighter Aircraft

Auxiliary landing gear systems have been incorporated on some aircraft to improve landing or ground handling characteristics. These systems may be found in various arrangements and are usually aircraft specific. They may consist of tail wheel installations, wing tip gears, or any other necessary fairing, bracing, or structural reinforcement.

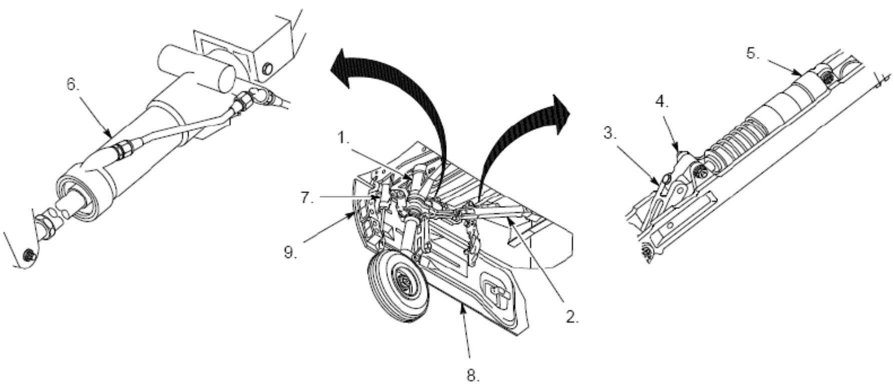


Figure 2-13: Nose Landing Gear Aspects of Fighter Aircraft

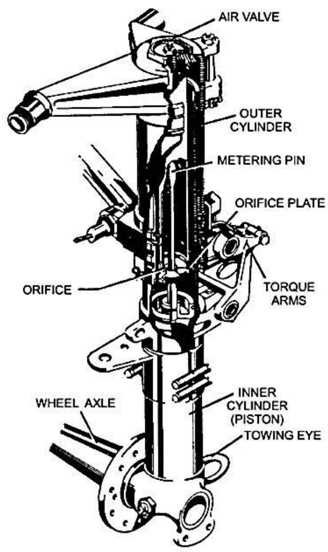


Figure 2-14: Internal Construction of a Shock Strut

2.1.1.7 OTHER COMPONENTS

Other structural and aerodynamic components are often present, like canards which are wings situated near the nose of the vehicle (notably on fighter jets), air refueling booms and other un-usual components such as external drop tanks.

After the above discussion, the following figures show the components' general arrangement aa (Figure 2-15) and hierarchy (Figure 2-16) on an aircraft.

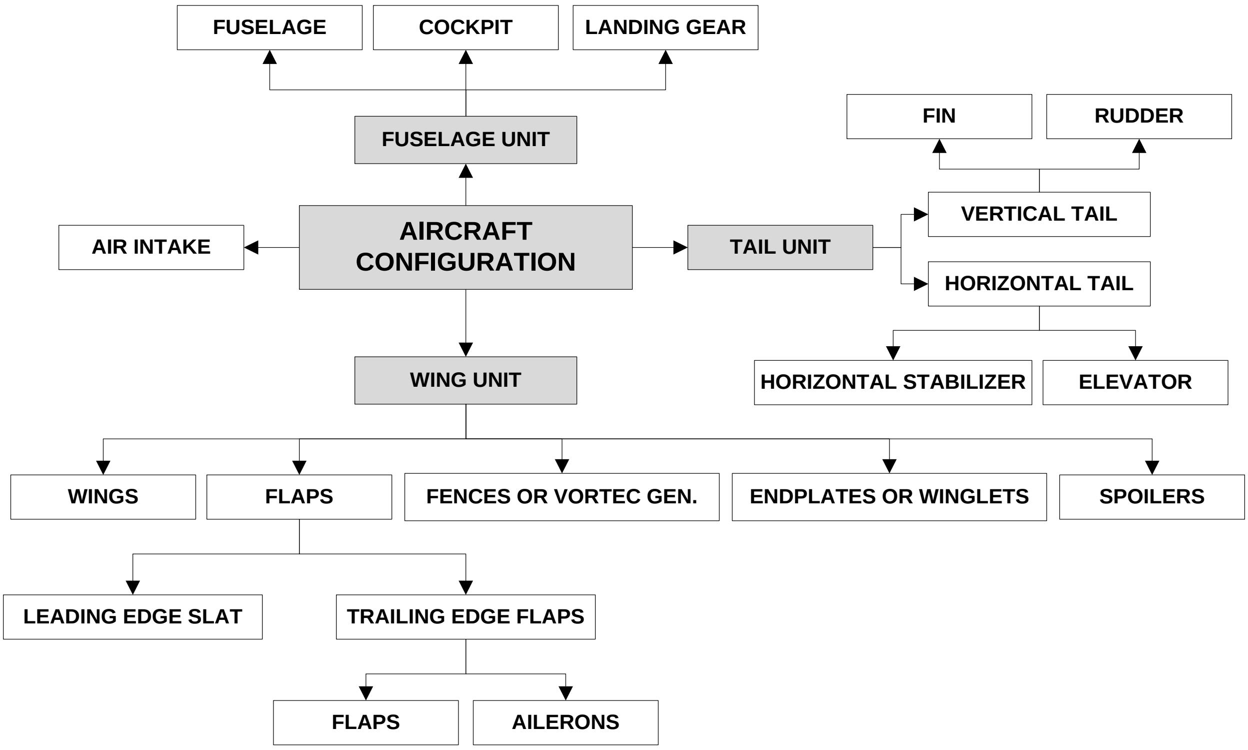


Figure 2-15: Components of Aircraft Configuration

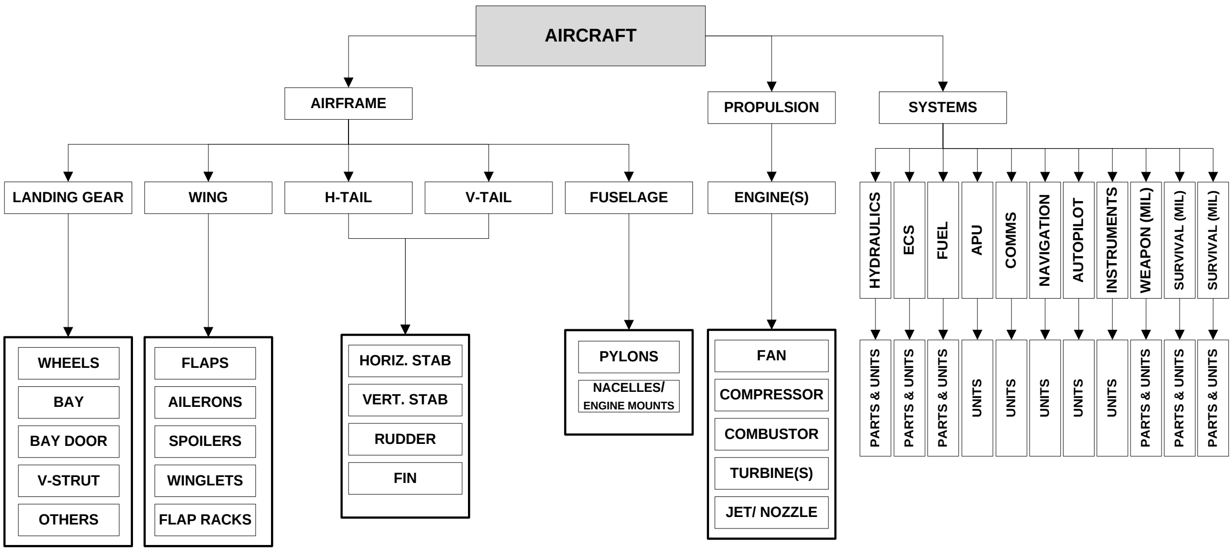


Figure 2-16: Breakdown of the Aircraft into Major System Components

2.2 DfD CATEGORIZATION OF AEROSPACE PRODUCTS

Before entering detailed discussion on DfD considerations in Aerospace Industry, a categorization (from a DfD perspective) of Aerospace Industry products was performed. Predominant DfD considerations per platforms category were identified and summarized, as shown in the following tables and have been coordinated during the ref. (7) meeting.

Once again, it is reminded that in the areas of aerospace electronics, this dissertation addresses DfD only down to the level (disassembly depth) of the Avionics “box” unit, which may be removed from the aerospace product (spacecraft, aircraft, helicopter, Remotely Piloted Airplane (RPA) etc) to be reused or send in some specialized installation for further recovery of materials. The next lower disassembly levels that go down to the internal or embedded electronic boards, chassis, microchips and any other electronic or optoelectronic compontents, are “out of scope” of this dissertation and therefore not studied.

2.2.1 CIVIL AVIATION

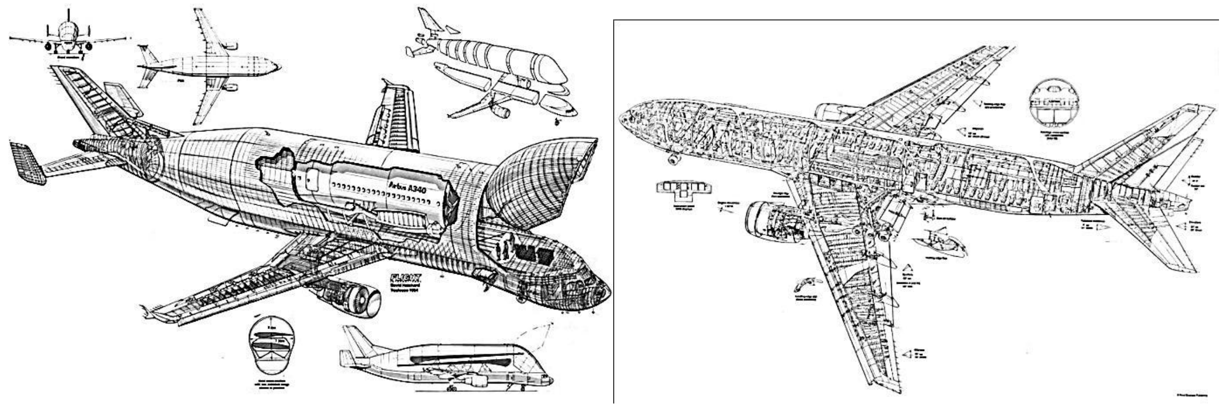


Figure 2-17: Commercial Airlines Aircrafts - Commercial Cargo Aircrafts

COMMERCIAL AIRLINES AIRCRAFTS - COMMERCIAL CARGO AIRCRAFTS			
Key Factors	**DfD Applicability and Interest**	**Non-Destructive Disassembly**	**Destructive Disassembly/ dismantle (recycling/ disposal):**
- Big Population of platforms. - Big size of platforms. - A lot of COTS (Commercial Off-The-Shelf) equipment installled internally. - Aluminum alloys and composite materials. - Profitable use of plat-	- Highest, great area for DfD (flight deck, fuselage, cabin, landing gear assemblies, big assemblies etc) due to the population and size of platforms. - Where non-flight critical COTS equipment used, usual DfD criteria are recommended.	- Applicable to COTS equipment and reusable assemblies- components- parts (e.g. engines, landing gear assemblies, wings, tail pieces, fuselage).	- Applicable to COTS non-reusable parts. - For removing hazardous materials: asbestos, hydraulic fluids, lubricant oils, depleted uranium - For recovering: aluminium alloys (needs only 5% of energy input as compared to new production, while CO2 out-

form.	- For Flight Critical and Flight Safety Equipment, DfD criteria can only be advisory and should be implemented only if possible with zero compromise to flight safety characteristics.		put is only 4%).

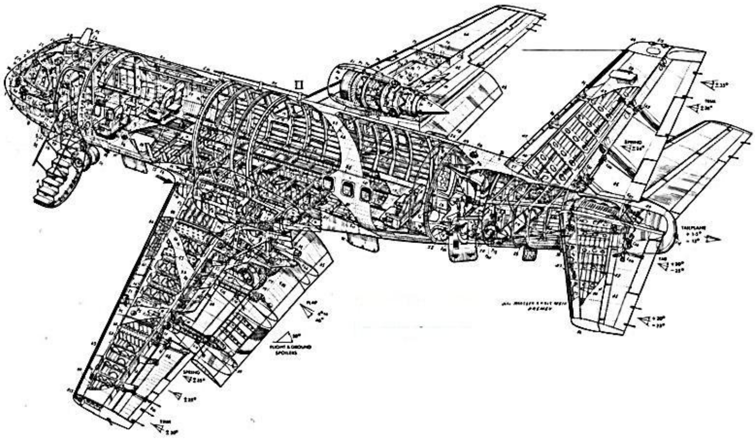


Figure 2-18: Regional Airlines Aircrafts

REGIONAL AIRLINES AIRCRAFTS			
Key Factors	**DfD Applicability and Interest**	**Non-Destructive Disassembly**	**Destructive Disassembly/ dismantle (recycling/ disposal):**
- Limited Population of platforms. - Use of COTS equipment internally - Use of aluminum alloys and composite materials - Profitable use of platform	- High, due to profitable use of platforms to satisfy regional in-country transportation needs. - Same 2nd and 3rd statements as for commercial airlines aircrafts apply.	- Same statements as for commercial airlines aircrafts apply.	- Same statements as for commercial airlines aircrafts apply.

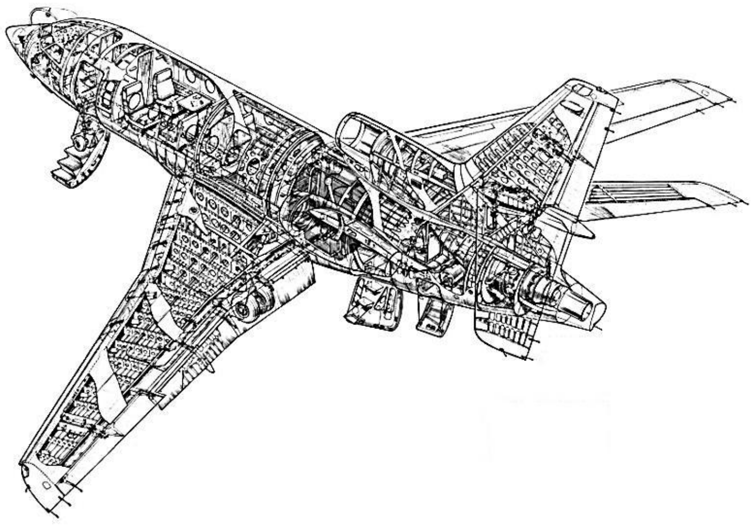


Figure 2-19: Business Aircrafts

BUSINESS AIRCRAFTS			
Key Factors	**DfD Applicability and Interest**	**Non-Destructive Disassembly**	**Destructive Disassembly/ dismantle (recycling/ disposal):**
- Medium Population of platforms - Use of COTS equipment internally - Use of aluminum alloys and composite materials - Limited use of hazardous materials - Private use of platform	- Medium, due to the population of platforms. - Same 2nd and 3rd statements as for commercial airlines aircrafts apply.	- Same statements as for commercial airlines aircrafts apply.	- Same statements as for commercial airlines aircrafts apply.

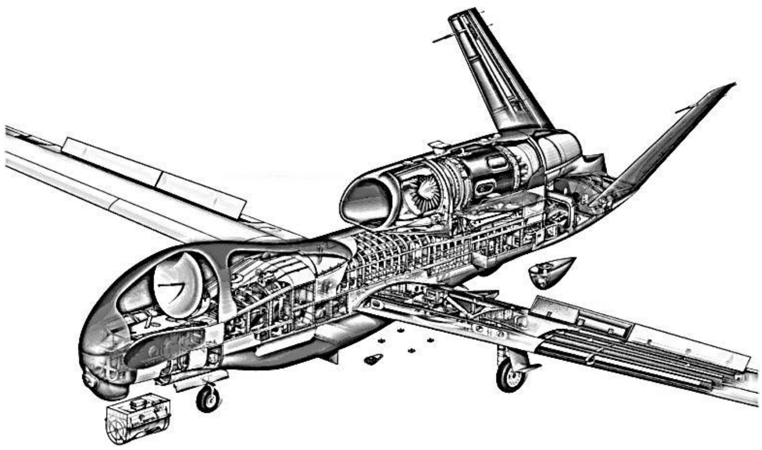


Figure 2-20: UAVs – RPAs (Unmanned Aerial Vehicles – Remotely Piloted Airplanes)

UAVs – RPAs (UNMANNED AERIAL VEHICLES – REMOTELY PILOTED AIRPLANES)			
Key Factors	**DfD Applicability and Interest**	**Non-Destructive Disassembly**	**Destructive Disassembly/ dismantle (recycling/ disposal):**
- Increasing Population of platforms. - Medium to small size of platforms.	- High, good area for DfD (fuselage, landing gear assemblies, big assemblies etc) due to the increasing population and use of platforms (military, law enforcement, coastal services etc). - Same 2nd and 3rd statements as for commercial airlines aircrafts apply.	- Same statements as for commercial airlines aircrafts apply.	- Same statements as for commercial airlines aircrafts apply.

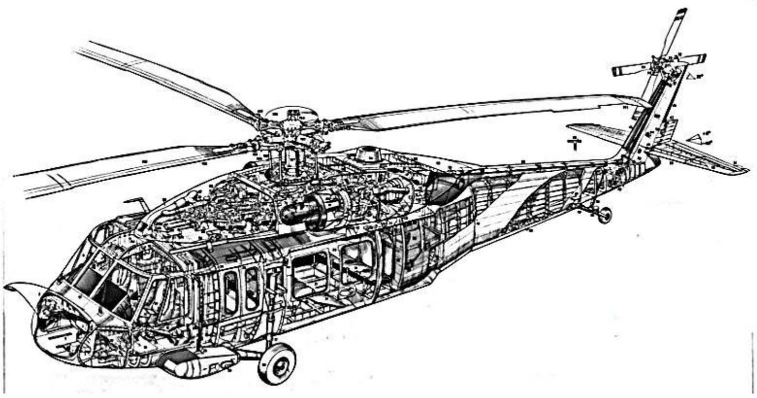


Figure 2-21: Helicopters

HELICOPTERS			
Key Factors	**DfD Applicability and Interest**	**Non-Destructive Disassembly**	**Destructive Disassembly/ dismantle (recycling/ disposal):**
- Big Population of platforms. - Medium to small size of platforms.	- High, good area for DfD (flight deck, fuselage, cabin, landing gear assemblies, big assemblies etc) due to the population of platforms.	- Same statements as for commercial airlines aircrafts apply.	- Same statements as for commercial airlines aircrafts apply.

	- Same 2nd and 3rd statements as for commercial airlines aircrafts apply.		

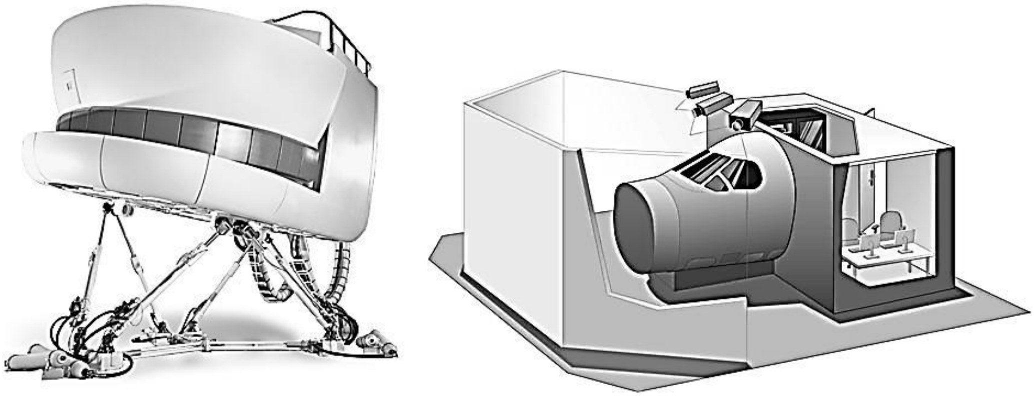


Figure 2-22: Examples of Full Flight Simulator (FFS) - Flight Training Devices (FTD)

FLIGHT TRAINING EQUIPMENT ON GROUND (FFS, FTD, etc)			
Key Factors	**DfD Applicability and Interest**	**Non-Destructive Disassembly**	**Destructive Disassembly/ dismantle (recycling/ disposal):**
- Medium Population of platforms. - Medium to small size of platforms.	- Highest, great area for DfD (flight deck, fuselage, cabin, landing gear assemblies, big assemblies etc) due to the fact that those systems not physically fly, therefore no Flight Critical equipment exists.	- Applicable to COTS equipment and reusable assemblies- components-parts (e.g. motion system, flight deck replica and instrumentation, visual system assemblies).	- For non-reusable equipment and any equipment with low to zero retail interest.

2.2.2 MILITARY ONLY AVIATION

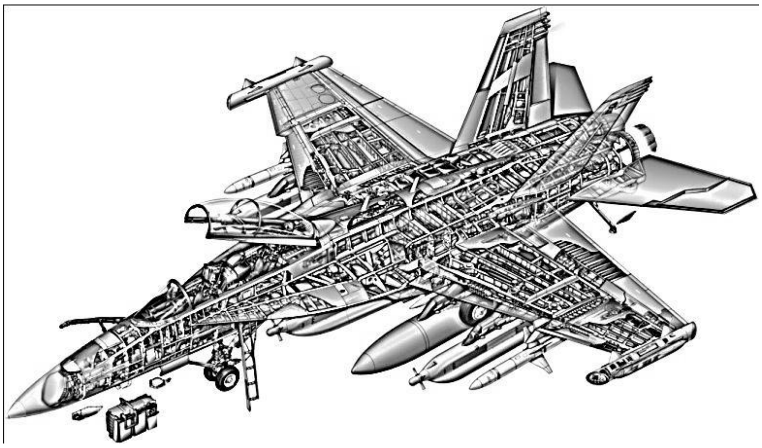


Figure 2-23: Fighter Aircrafts

FIGHTER AIRCRAFTS			
Key Factors	**DfD Applicability and Interest**	**Non-Destructive Disassembly**	**Destructive Disassembly/ dismantle (recycling/ disposal):**
- Big population of platforms. - Very high or top-notch technologies coexist in small sized platforms. - Very stringent conditions of operation (aerodynamic, environmental, thermal, electromagnetic etc). - Normally no COTS equipment installed. - High demands for platform combat readiness, extreme reliability, maximum availability, maintainability, quick turnarounds, adequate spare parts, low life cycle cost. - Flight Safety prevails and is mandatory. - Human Factors and Engineering extensively	- Highest DfD interest for purposes of maintainability and availability during useful life, as well as for getting reusable parts through disassembly to be used as spares or to be installed on other aircrafts.	- Applicable to reusable assemblies- components-parts (e.g. engines, landing gear assemblies, wings, tail pieces, fuselage). - The lower the MTBF or Life Cycle of the equipment, the higher the need for DfD. - Several assemblies which contain hazardous materials like hydrazine, require non-destructive disassembly.	- Applicable to non-reusable parts. - For removing hazardous materials: asbestos, hydrolic fluids, lubricant oils, depleted uranium - For recovering: aluminium alloys (needs only 5% of energy input as compared to new production, while CO2 output is only 4%).

applied. - Size limitations and geometrical peculiarity for involved equipement. - Modularity - Very “tight” Design limitations to meet physical, functional and operational requirements, with high accuracy and reliability.			

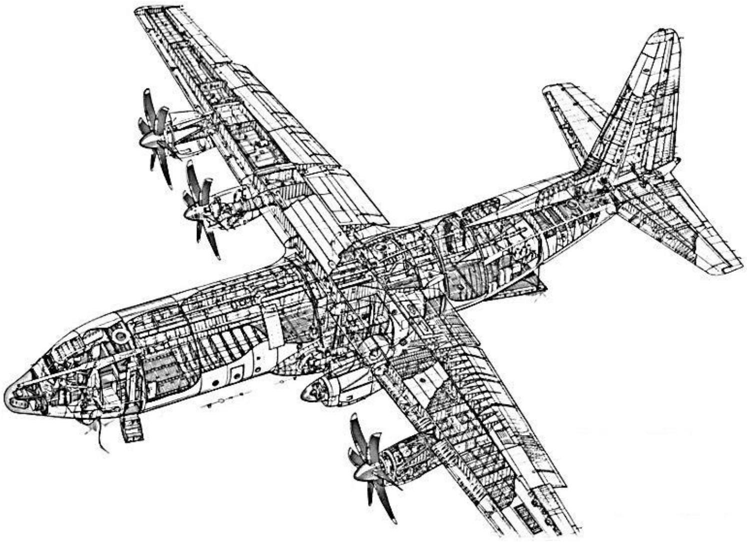


Figure 2-24: Transport (Widebody) Military Aircrafts

TRANSPORT (WIDEBODY) MILITARY AIRCRAFTS			
Key Factors	**DfD Applicability and Interest**	**Non-Destructive Disassembly**	**Destructive Disassembly/ dismantle (recycling/ disposal):**
- Medium population of platforms. - Normally few COTS equipment installed. - High demands for platform availability, maintainability, quick turn-arounds, adequate spare parts, low life cycle cost.	- Highest interest for DfD for purposes of maintainability and availability during useful life, as well as for getting reusable parts through disassembly to be used as spares or to be installed on other aircrafts.	- Applicable to reusable assemblies- components-parts (e.g. engines, landing gear assemblies, wings, tail pieces, fuselage). - The lower the MTBF or Life Cycle of the equipment, the higher the	- Applicable to non-reusable parts. - For removing hazardous materials: asbestos, hydrolic fluids, lubricant oils, depleted uranium - For recovering: aluminium alloys (needs only 5% of energy input as

- Flight Safety prevails and is mandatory. - Human Factors and Engineering are applied. - Modularity is preferable - More “tight” Design limitations than for commercial aircrafts		need for DfD.	compared to new production, while CO2 output is only 4%).

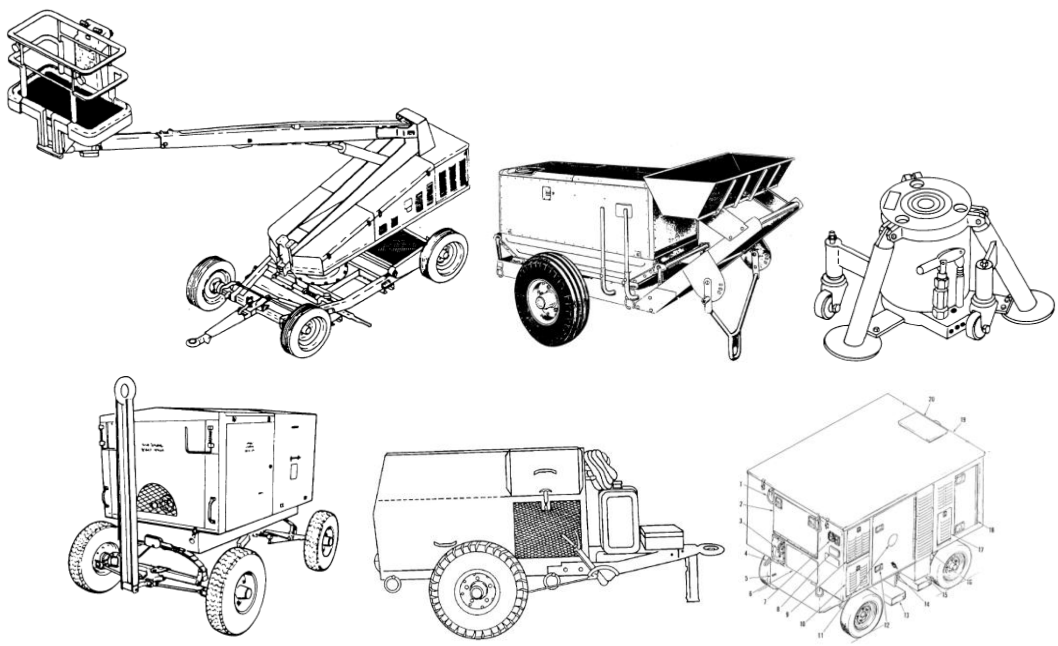


Figure 2-25: Flight Line Equipment – Ground Support Equipment

FLIGHT LINE EQUIPMENT – ILEVEL –DLEVEL SUPPORT EQUIPMENT			
Key Factors	**DfD Applicability and Interest**	**Non-Destructive Disassembly**	**Destructive Disassembly/ dismantle (recycling/ disposal):**
- Medium population - Tow vehicles, Ammunition and ordnance Lifters, Flight Line Test Equipment, Power generators, Hudraulic System Support Equipment (e.g. F-16 Denisson, Test Stand etc)	- Great area for DfD for purposes of maintainability and availability during useful life, as well as for getting reusable parts through disassembly. - Not further addressed in this dissertation.	- Applicable to reusable assemblies- components-parts. - The lower the MTBF or Life Cycle of the equipment, the higher the need for DfD.	- Applicable to non-reusable parts with the purpose to get scrap metals.

- Design restrictions focus on endurance of equipment			
MAINTAINANCE SHOPS' GROUND SUPPORT EQUIPMENT			
- Big population - Test Benches, peculiar test devices	- High, good area for DfD due to the use of COTS equipment and the need for high availability of the equipment. - Not further addressed in this dissertation.	- Applicable to reusable assemblies- components-parts. - The lower the MTBF or Life Cycle of the equipment, the higher the need for DfD.	- Applicable to non-reusable parts with the purpose to get scrap.

2.2.3 *SPACE INDUSTRY PRODUCTS*

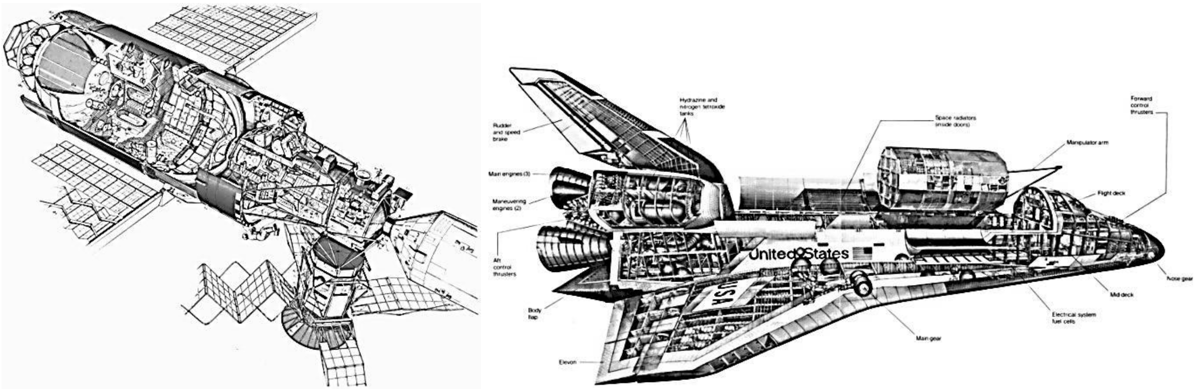


Figure 2-26: Space shuttles - Satellites- Rockets

SPACE SHUTTLES - ROCKETS - SATELLITES			
Key Factors	**DfD Applicability and Interest**	**Non-Destructive Disassembly**	**Destructive Disassembly/ dismantle (recycling/ disposal):**
- Very limited population per platform type. - Design requirements differ by far from other aircrafts' requirements. - Not researched under this dissertation. General considerations were made.	- DfD interest only for maintainability reasons. - Area for possible future work (e.g. disassembly and maintainance in space environment).	- It is assumed to be applicable for all reusable parts (assumption).	- It is assumed to be applicable for the purpose to get precious metal scrap.

The tables above make obvious that there are many and several areas where DfD can be studied and applied; however for the purposes of this dissertation, primary focus was centered on the airborne platforms and in particular, on the commercial airliner aircrafts and military aircrafts.

2.3 DESIGN IN AEROSPACE INDUSTRY

In the areas of Aerospace Indrustry, the design process is a blend of classical procedures and evolving philosophical principles and practices in the ever-changing and challenging environments of customer expectations, new technologies and constraining economics. Design of aerospace systems is much more challenging today due to global competition, shifting design emphasis from performance to cost and operations. Total design must deal with at least six factors: quality, operations, reliability, cost, performance, and usefulness. The process of design is therefore a series of trades between conflicting requirements imposed on a competitive aerospace product. The complexity of this interaction is depicted in the example of Figure 2-27 for a liquid propulsion system illustrating many of the tightly coupled interactions.

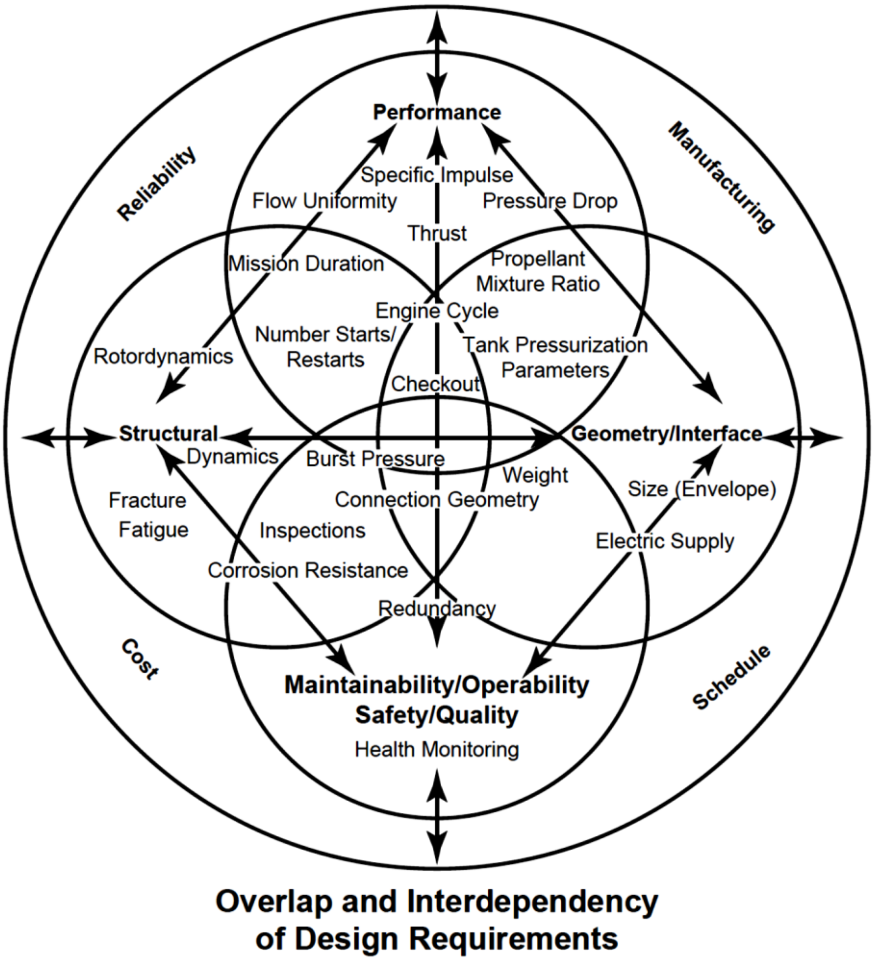


Figure 2-27: Example of Interacting Design Requirements for a Liquid Propulsion System

Their influences are woven through the various systems and disciplines, analyses and interactions (Figure 2-27) throughout all design phases of the systems engineering process, and particularly noted in the design cycle section. Many authors have greatly influenced design methods of which Pye in “The Nature of Design” and Pugh in “Total Design” are outstanding examples.

During the development of a new aircraft concept, the optimization of the design to provide the desired capabilities at a minimum cost is of paramount importance. Aircraft are incredibly expensive compared to almost any other human-made single item. A new four-seat aircraft costs an order of magnitude more than a normal four-seat automobile. A large commercial airliner costs roughly half a million dollars per passenger seat, or, looked at from another perspective, approximates the cost of a major new high-rise office building.

The development of Computer-Aided Design (CAD) improved the actual design layout process in all phases of aircraft design, especially with regards to the interface between design and fabrication, through better product definition and through computer numerical control (CNC) machining directly from the CAD digital products. Newer modern aircrafts including the military aircrafts B-2, F-22, F-35, Eurofighter Typhoon, SAAB Gripen, Dassault Raphale, and Beech Premier have all benefited in both cost and quality from the application of CAD and CNC. This however does not apply for the disassembly of their assemblies, components and parts.

Optimization methods, present another area in which improvements to the design process can provide substantial savings in cost, independent of the application of new technologies. An improved design process that would identify excess capabilities - characteristics early and allow the designers to drive them out would directly save cost. Another way that an improved design process can reduce aircraft cost is in the early identification of the best possible balance between the disparate desires of the various design disciplines. For example, the aerodynamics department generally prefers a thinner wing to reduce drag, whereas the structures department prefers a thicker one to reduce weight. Identification of the best balance must be done in the context of the aircraft’s roles and missions, and has the potential for a substantial overall cost savings. Obviously, if DfD is considered in those early design efforts, then the overall savings will further considerably improve, due to the reuse, remanufacture or the recycling of products and materials.

Aircraft design is multidisciplinary and comlex by its nature. In aircraft conceptual design, optimizations have always included aerodynamics, structures, propulsion, controls, systems, and a host of other disciplines. However, emerging MDO (Multidisciplinary Design Optimization) techniques provide a more-formalized structure to the design optimization process and allow better management of the large number of trades necessary to find the optimum design. To this extend, DfD can have a role of high value, which however has to remain advisory and not obligatory.

Aircraft design can be broken into three major phases, namely Conceptual Design, Preliminary Design, and Detail Design (

Figure 2-28). Each phase has different tasks and objectives, and the design process in each phase is quite unique from other phases. The tools to be employed differ and even the people involved are usually different (at least in big companies like Boeing).

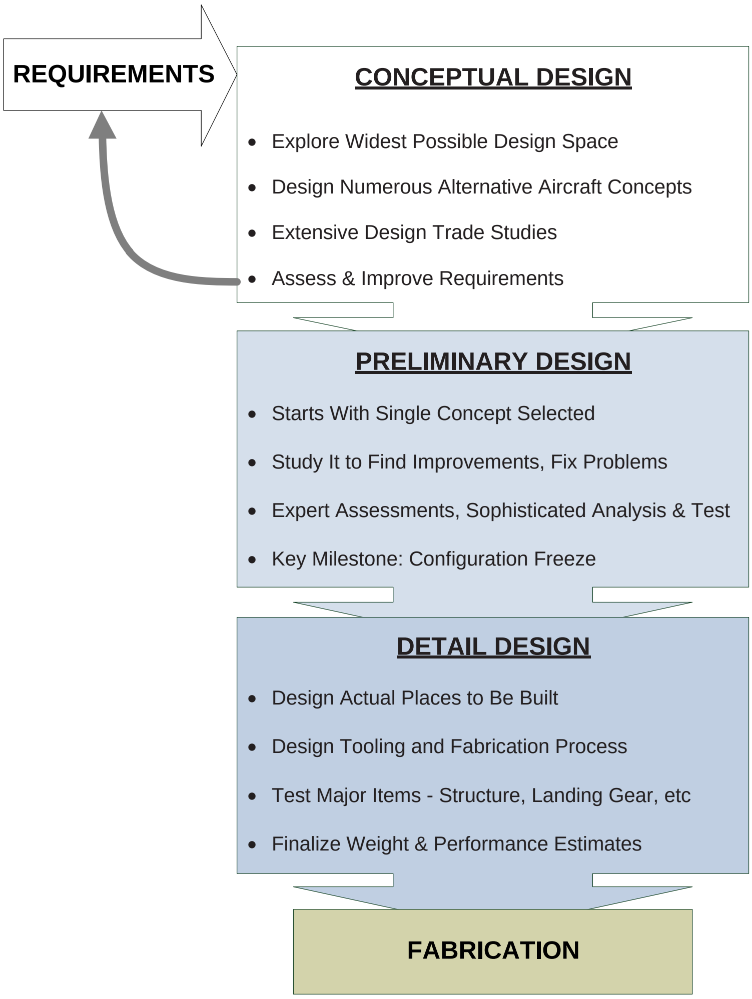


Figure 2-28: The three Phases of Aircraft Design

In Conceptual Design, the basic questions of configuration arrangement, size, weight, and performance are answered. Numerous alternative design concepts are prepared in response to the design requirements, and numerous variations on those concepts are also studied. All design options are “fair game”, and the design space extends as far as the designers’ imaginations. In Conceptual Design also, the design requirements are used to guide and evaluate the development of the overall aircraft configuration arrangement. A mathematical process called “sizing” is used to calculate what the aircraft take-off gross weight, empty weight, and fuel weight must be for the design to reach the range as specified in the design requirements. This calculated weight is used as the starting point in making a design arrangement drawing, determining the overall size, wing and tail area, required fuel tank volume, and many other aspects of the design. Calculated aircraft weight is commonly used as the Measure Of Merit (MOM) in aircraft design optimizations, so the implementation of a reliable procedure for calculating it is critical to any optimization result. If cost is used as the MOM, the calculated weight is a key input to the cost calculation so again, this sizing calculation is critical. This design arrangement includes wing and tail overall geometry (areas, sweeps, etc.), fuselage shape and internal locations of crew, payload, passengers, and equipment, engine installation, landing gear, and other design features. The level of detail in configuration design is not very deep, but the interactions among all the different components are so crucial that it requires years of experience to create a good conceptual design.

This initial layout is analyzed to determine if it will perform the design mission. Aerodynamics, weights, and installed propulsion characteristics are analyzed and subsequently used to do a detailed sizing calculation. Furthermore, the performance capabilities of the design are calculated and compared to the design requirements.

A key aspect of Conceptual Design is that it is a very fluid process, and the design layout is always being changed, both to incorporate new things learned about the design and to evaluate potential improvements to the design. Trade studies and an ever-increasing level of analysis sophistication cause the design to evolve on almost a week-by-week basis, and changes can be made in every aspect of the design including wing geometry, tail arrangement, and even the number of engines. Furthermore, during Conceptual Design a number of alternative designs are studied to determine which design approach is preferred (generic example per Figure 2-29), based also on optimization methods which focus on the overall design characteristics rather than details of the concept. This provides room for several DfD considerations to contribute into the design of the platform.

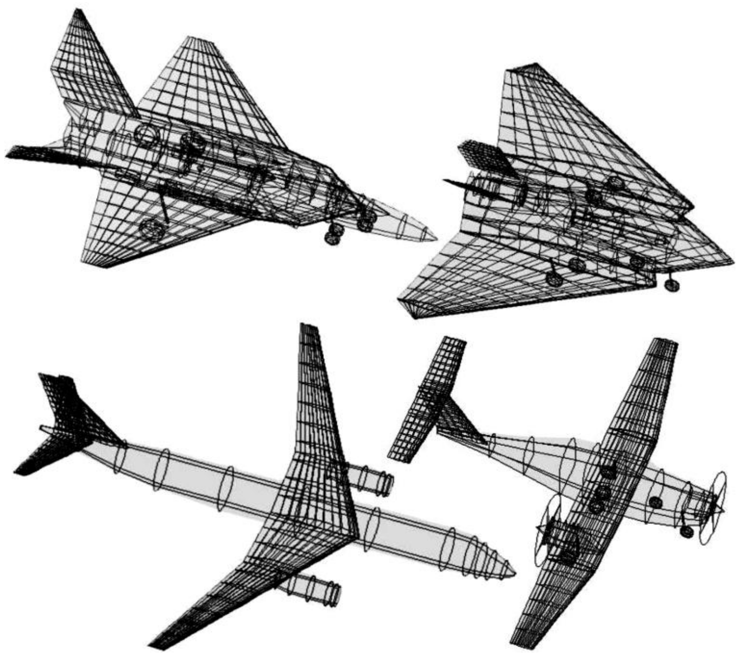


Figure 2-29: Validation Models: Four Aircraft Concepts

During early Preliminary Design, optimization continues on top-level parameters such as thrust to weight ratio, wing loading, wing aspect ratio and sweep, and fuselage fineness ratio, but then, as the design progresses and major revisions become less likely, optimization proceeds towards finer design aspects such as the exact airfoil shapes and the distribution of twist and camber, or the best shape for the fuselage to promote laminar flow. This is often done by defining shape functions - geometric equations which control the shape and are themselves controlled by parametric inputs. Alternatively, aerodynamic optimization can be done by specifying desired pressure distributions and searching for a shape that will produce it. By this phase of the design process, the top-level parameters mentioned above are locked in and will not be further changed or optimized unless major problems are uncovered. Also during Preliminary Design, specialists who are experts in the various design disciplines and aircraft subsystems are given the overall design concept and asked to evaluate it and to refine the design in their area of expertise. They commonly find areas in which they request design modifications, requiring further iterations and refinements of the design concept. Following such revisions, the design optimizations must be redone because any change to the design layout will likely affect the inputs, and hence the outputs of an optimization. At this phase DfD can play a significant role as physical characteristics and shape functions - geometric equations and relations of the whole platform and its components are defined.

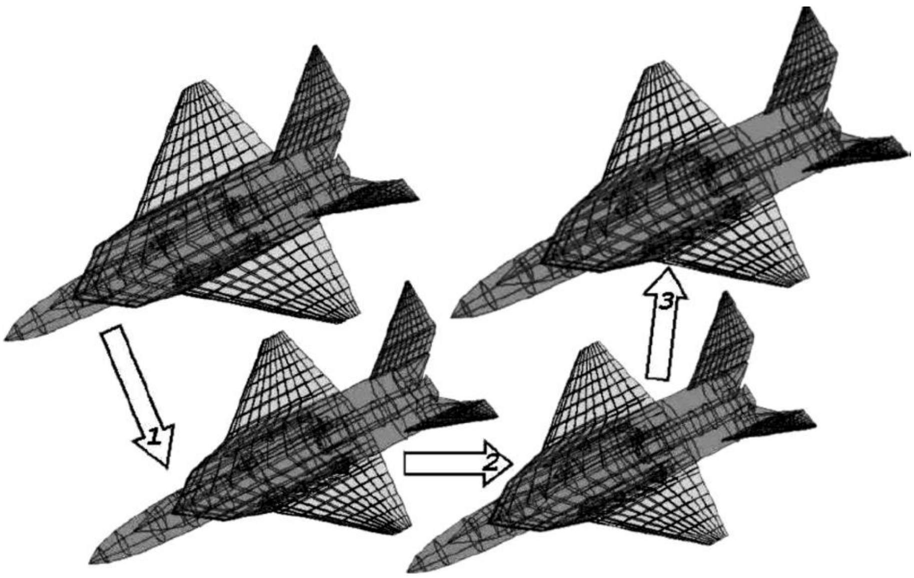


Figure 2-30: Example of Preliminary Design Optimization

Optimization in Detail Design tends to be subsystem or part specific, not system-wide. Design procedures for structural parts, equipment, wiring, and other areas typically include the minimization of weight of those items, but not tradeoffs with other parts or systems. Such tradeoffs should have been accomplished during Conceptual and Preliminary Design. As the design progresses through conceptual, preliminary, and detail design, the level of detail of the design steadily increases. This is illustrated in Figure 2-31 for a typical piece of aircraft geometry, the front wing spar. The top of Figure 2-31 depicts the design of a front wing spar in the amount of detail typical of conceptual design, usually nothing more than a straight line in top view at the desired location of the spar. The spar is assumed to be approximately the depth of the wing.

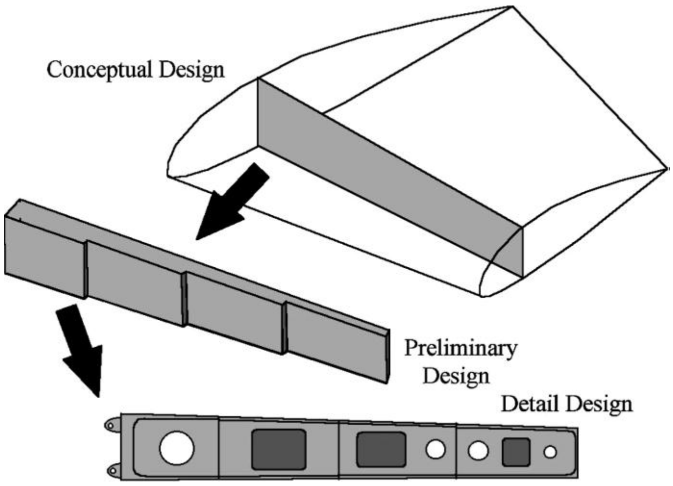


Figure 2-31: Wing Spar as Defined in Conceptual, Preliminary, and Detail Design

2.4 CONSIDERATIONS FOR DESIGN OF AEROSPACE PRODUCTS

Design engineering is fundamental to every aerospace project. The role of the design engineer is the creation, synthesis, iteration, optimization and presentation of design solutions. It is the primary discipline that creates and transforms ideas into a product definition that satisfies customer as well as business requirements.

The Systems Engineering Concepts which are involved include the following basic steps:

a. Understand Customer's Need. Every product starts with a need. In the end, the value of the design is always measured against the customer's needs

b. Develop Concept of Operations. The requirements of all operational phases must be considered for a design to be successful.

c. Review Product Requirements for Completeness. Typical requirement categories include (a) performance, (b) lifetime / duty cycle, (c) affordability, (d) reliability, (e) human factors, (f) field support / logistics, and (g) deployment / disposal. If the product requirements are not complete, appropriate assumptions should be made and then validated with the customer.

d. Use Trade Study Methods to Develop the Product Design. Further systems engineering techniques can help complete the product design. Trade study methodology is an effective way to choose among design alternatives and develop the product design. Essential elements of a trade study include:

(1) Identify design alternatives.

(2) Develop evaluation criteria and weighting factors.

(3) Analyze design alternatives and select final design concept. The design alternative with the highest score and acceptable sensitivities is the preferred solution.

A Systems Engineering approach is recommended for any aerospace design project. In summary, design engineering is the creative process by which ideas from one or many contributors are converted to documents that define a product that can be profitably manufactured and that meets the design, performance, and functional specifications required. Design engineering seeks an optimal whole, rather than attempting to perfect each individual part within a system, thus obtaining a balanced, well designed product that fulfills the requirements and satisfies customer and business needs.

In Aerospace Industry also, depending on the environmental conditions of the product mission, several stringent technical criteria for selection of materials usually apply to address respective considerations like the following ones included in space vehicles literature:

a. Temperature	Material properties shall be compatible with the thermal environment to which they are exposed.
b. Thermal cycling	Materials subject to thermal cycling shall be assessed for their ability to withstand induced thermal stress and shall be tested according to approved procedures
c. Vacuum	1. Materials selection shall be made in accordance with approved data sources. 2. Outgassing tests shall be carried out according to approved procedures.
d. Offgassing, toxicity, bacterial and fungus growth	Spacecraft/ aircraft and associated equipment shall be manufactured from materials and by processes that shall not cause an unacceptable hazard to personnel or hardware, whether on the ground or in space.
e. Flammability	The materials flammability resistance shall be evaluated for the most hazardous environment envisaged for their use.
f. Radiation	Materials used on the spacecraft/ aircraft external surfaces shall be assessed to determine their resistance to the radiation dosage expected during the mission (e.g. stealth coating on military aircrafts).

g. Electrical charge and discharge	External surfaces of the aircraft / spacecraft shall be sufficiently conductive, interconnected and grounded to the spacecraft structure to avoid the build-up of differential charges.
h. Lightning strike	Provision shall be made in the design to ensure that the safety and functionality of the vehicle are not compromised by the occurrence of a lightning strike during launch or return.
i. Corrosion	For all materials that come into contact with atmospheric gases, cleaning fluids or other chemicals, it shall be demonstrated that the degradation of properties during their anticipated service-life is acceptable in terms of the performance and integrity requirements.
j. Stress-corrosion	1. Materials used for structural and load-bearing applications (subject to tensile stress) shall be chosen in conformance with approved data sources, (e.g. Table 1 of ECSS-Q-70-36A). 2. Any material not covered by standard shall be tested according to approved procedures.
k. Fluid compatibility	1. Materials within the system exposed to liquid oxygen (LOX), gaseous oxygen (GOX) or other reactive fluids, both directly and as a result of single point failures shall be compatible with that fluid in their application. 2. The possibility of hydrogen embrittlement occurring during component manufacture or use must be assessed. An appropriate material evaluation must be undertaken, including the assessment of adequate protection and control.
l. Galvanic compatibility	When bimetallic contacts are used, the choice of the pair of metallic materials used shall be taken into account. This also includes metal-to-conductive fibre-reinforced materials contacts.
m. Atomic oxygen	1. All materials considered for use on the external surfaces of spacecraft intended for use in Low Earth Orbit (LEO) altitudes (between 200 km and 700 km) shall be evaluated for their resistance to atomic oxygen (ATOX).

	2. Test procedures shall be subject to the approval of the customer.
n. Micrometeoroids and debris	The effect of impacts by micrometeoroids and debris on materials shall be reviewed and assessed on a case-by-case basis and that their use shall comply with safety evaluation and assessment results concerning design and application criteria or details.
o. Moisture absorption and desorption	Precautions shall be taken to avoid moisture absorption during manufacture and storage of CFRP-type materials.
p. Mechanical contact surface effects (cold welding, fretting, wear)	For all solid surfaces in moving contact with other solid surfaces, it shall be demonstrated that the degradation of surface properties over the complete mission is acceptable from a performance point of view.
q. Life	Materials shall be selected to ensure sufficient life with respect to the intended application.

The table above makes obvious that the materials selection for an aerospace product focuses on the performance and functional endurance of the product in severe environments and conditions.

2.4.1 AIRWORTHINESS – SAFETY OF FLIGHT

The design of an aircraft is a synthesis of different disciplines like aerodynamics, flight mechanics and aeronautical structures. Furthermore, to allow an aircraft to be operational in normal air traffic, it is necessary to demonstrate that its design and construction are in compliance with the applicable requirements; the verification of such compliance is entrusted to the competent authorities.

Airworthiness introduces aerospace engineers into this world consisting, on the one hand, of designers, manufacturers and operators, and on the other, of airworthiness authorities, in two disciplines that should work in unison, because they should aim at a common goal: Flight Safety. In the last decades, airworthiness has gained the highest attention of designers and manufacturers of aerospace products and constitutes a paramount goal of their design.

Airworthiness is the property of a particular air system configuration to safely attain, sustain, and terminate flight in accordance with the approved usage and limits.

Airworthiness certification is a repeatable process implemented to verify that a specific air vehicle system can be, or has been, safely maintained and operated within its described flight envelope. The two necessary conditions for issuance and maintenance of an airworthiness certificate are (a) the aircraft must conform to its type design as documented on its type certificate, and (b) the aircraft and therefore all its assemblies, components and parts must be in a condition for safe operation. Civil and Military regulations of Airworthiness establish numerous categorized criteria which have to be met before certification of the aerospace product is given. Those criteria are primarily established in civil aviation authorities' documentation (e.g. FAA 14.CFR.xxxx documents) and in respective military aviation documents e.g. MIL-HDBK-516B.

The airworthiness criteria do not directly address DfD criteria or DfD requirements, however, in many indirect ways they indeed promote DfD for the aerospace products. The reason for this, stems from the fact that the aerospace products have to be designed in such a multidisciplinary way, that during their useful life, many cycles of: (a) disassembly, (b) servicing or maintainance, (c) reassembly and (d) operational tests have to be successfully executed, whereas after each cycle, the aerospace product has to be verified that it retains its airworthy and safe-to-fly operational state.

2.4.2 RELIABILITY - MAINTAINABILITY - HUMAN ENGINEERING / HUMAN FACTORS

The alarmingly high operating and support costs of aerospace systems and equipmentand the necessary subsequent repairs, are the prime reasons for emphasizing maintainability. Maintainability refers to the measures taken during the development, design, and installation of a manufactured product that reduce required maintenance, manhours, tools, logistic cost, skill levels, and facilities, and ensure that the product meets the requirements for its intended use.

Probably the most effective maintainability effort has been in the commercial aircraft industry, where aircraft availability has become an important index of an airline's ability to satisfy the needs of its market. The main aim of maintainability efforts is to improve dispatch availability or reliability through factors such as: interchangeability, accessibility, maintenance frequency, simplicity, visibility, testability, state-of-the-art technological advances.

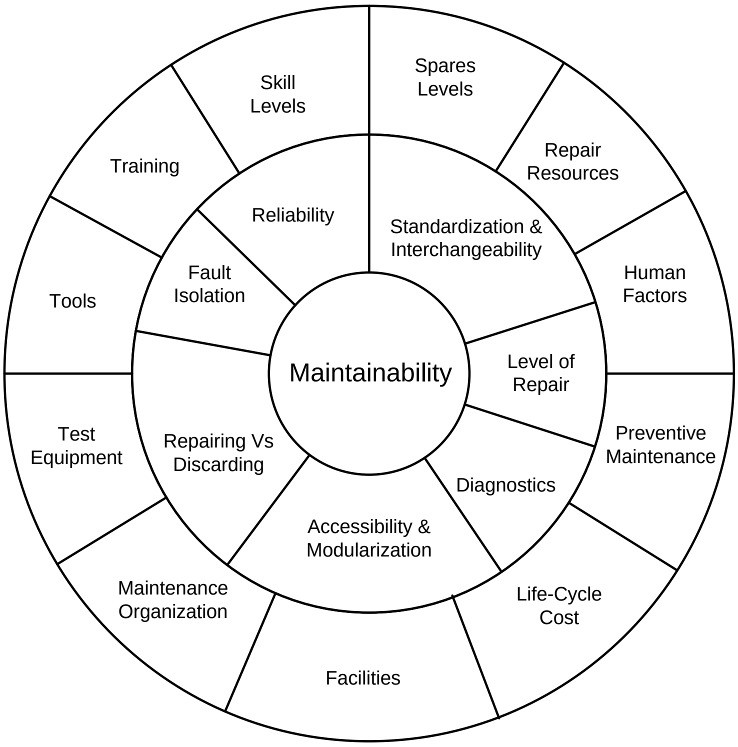


Figure 2-32: The Maintainability Universe: Inherent and Secondary Design Features

Maintenance and maintainability are closely interrelated; many people find it difficult to make a clear distinction between them. Maintenance refers to the measures taken by the users of a product to keep it in operable condition or repair it to operable condition. Maintainability refers to the measures taken during the design and development of a product to include features that will increase ease of maintenance and will ensure that when used in the field or in space, the aerospace product will have minimum downtime and life-cycle support costs.

2.4.2.1 MAINTAINABILITY TERMS AND DEFINITIONS

Some of the terms and definitions used in maintainability work are:

a. **Repairability**. The probability that a failed product will be repaired to its operational state within a given active repair time.

b. **Serviceability**. The degree of difficulty (or of ease) with which a product can be restored to its operable state.

c. **Maintainability**. As already discussed, this refers to the aspects of a product that increase its serviceability and repairability, increase the cost effectiveness of maintenance, and ensure that the product meets the requirements for its intended use.

d. **Downtime**. The total time during which the product is not in an adequate operating state.

e. **Availability**. The probability that a product is available for use when needed.

f. **Active Repair Time**. The segment of downtime during which, repair staff is working to effect a repair.

g. **Logistic Time**. The segment of downtime occupied by the wait for a needed part or tool.

h. **Design Adequacy**. The probability that the product will complete its intended mission successfully when it is used according to its design specifications.

The most frequently addressed maintainability design factors are: accessibility; test points; controls; labeling and coding; displays; manuals, checklists, charts and aids; test equipment; tools; connectors; cases, covers and doors; mounting and fasteners; handles; and safety factors. Other factors are standardization, modular design, interchangeability, ease of removal and replacement, indication and location of failures, illumination, lubrication, test adapters and test hookups, servicing equipment, adjustments and calibrations, installation, functional packaging, fuses and circuit breakers, cabling and wiring, weight, training requirements, skill requirements, required number of personnel, and work environment. Most of those factors affect the aerospace products' ease of disassembly and were thoroughly considered into the proposed DfD criteria model of this dissertation. The most important factors are presented in following paragraphs.

2.4.2.1.1 STANDARDIZATION

This important design feature restricts to a minimum, the variety of parts and components that a product or system will need. It can also be described as the attainment of maximum practical uniformity in a product's design. Some of the primary goals of standardization include maximizing the use of common parts in different products; minimizing the number of different types of parts, components, assemblies, and other items; maximizing the use of interchangeable and standard or off-the-shelf parts and components; minimizing the number of different models and makes of equipment in use.

2.4.2.1.2 INTERCHANGEABILITY

There are two types of interchangeability, functional interchangeability and physical interchangeability. In functional interchangeability, two specified items serve the same function. In physical interchangeability, two items can be mounted, connected, and used effectively in the same locations and in the same manner. Checklists for effectively incorporating interchangeability into equipment and product design contain questions which accelerate the disassembly process, especially when disassembly is frequently needed during the useful life of the product, such as:

a. Is there total interchangeability wherever possible?

b. Does interchangeability exist for items with high failure rates?

c. Are differences in mounting, size, and shape being avoided unless these differences serve a functional purpose?

d. Are identical parts or components used wherever feasible in similar products or systems?

e. Are items such as parts, connectors, and cables standardized throughout the equipment in question?

f. Are items such as screws and bolts the same size for all covers and cases?

2.4.2.1.3 MODULARIZATION

Modularization is the division of a system or product into physically and functionally distinct units, to allow removal and replacement. Some of the guidelines for designing modularized products:

a. Divide the equipment into many modular units.

b. Make modules and parts as uniform in size and shape as possible.

c. Match the functional design of the equipment with division of the equipment into removable and replaceable units.

d. Aim to design all equipment so that a single person can replace any malfunctioning component.

e. Design control levers and linkages to permit easy disconnection from components, so that disconnecting/ replacing components is a simpler process.

f. Take an integrated approach to design - that is, consider the problems of component design, materials, and modularization simultaneously.

g. Strive to make each module capable of being inspected independently.

h. Place emphasis on modularization for forward levels of maintenance.

i. Aim to make each modular unit small and light enough that a single person can handle and carry it without any difficulty.

Some of the many advantages associated with modularization, which reduce the total disassembly costs, are the lower skill levels and fewer tools needed for replacement of modules, the easier isolation and replacement of faulty items, the more efficient maintenance and the decrease of equipment downtime.

2.4.2.1.4 SIMPLIFICATION

Simplification is probably the most difficult element of maintainability to achieve, but the most important. Simplification should be the constant goal of design. A good designer incorporates important functions of a product into the design itself and uses as few components as sound design practices will allow. Reducing the number of components does not always promote ease of disassembly, however, when combined with other elements of maintainability, it can offer considerable reductions to the disassembly costs (time, labor, skills, tools, minimize errors etc).

2.4.2.1.5 ACCESSIBILITY

Accessibility is the relative ease with which a part or piece of equipment can be reached for service, replacement, or repair, which always involve disassembly. The factors that affect accessibility include:

a. The item's location and environment.

b. Maintenance tasks to be carried out through the access opening.

c. Types of tools and accessories needed to perform the required tasks.

d. Clothing worn by the technical staff.

e. Visual needs of staff carrying out the tasks.

f. Specified time requirements for performing the tasks.

g. Work clearances necessary for performing the tasks.

h. Danger associated with use of the access opening.

i. Distance to be reached to access each item.

j. Packaging of items behind the access opening.

k. Mounting of items behind the access opening.

l. Frequency with which the access opening is entered.

The way a piece of equipment is installed governs in part the location of its maintenance access openings. The access openings should occupy a face of the piece of equipment that will be accessible in the usual installation. Some guidelines for designing and placing access openings contribute to the ease of disassembly:

a. Ensure that access openings will be accessible under normal installation of the equipment.

b. Place access openings for maximum convenience in conducting the anticipated maintenance tasks.

c. Ensure that the location of access openings permits direct access to the parts that will require maintenance.

d. Ensure that the access openings occupy the same face as associated features such as control, test point, and displays.

e. Ensure that the access openings are a safe distance from high voltage points or hazardous moving parts.

f. Ensure that the lower edge of a restricted access opening is no less than 24 inches or its top edge no greater than 60 inches from the floor or work platform.

g. Ensure that the location of accesses is in conformance with height of work stands and carts that will be frequently used.

h. Ensure that heavy units can be pulled out instead of lifted out.

The access openings must be at the proper size to allow a repair person to perform tasks effectively. The factors that should determine the size of access openings include the size and shape of the internal objects to which access is required; the necessity of removing and replacing the objects through the openings; once access is gained, the movements of the human body required for actions such as turning, pushing, and pulling; and the size required for a repair person to enter partially or fully through the access opening. The last two factors are determined, respectively, by dynamic and static body measurements.

Other disassembly-related guidelines to consider in the design of access openings are:

a. Label each access opening with a unique number, letter, or other identifier.

b. In the case of small openings, indicate the position in which components or connectors should be inserted through the opening.

c. Use safety interlocks on openings that lead to high voltage points.

d. Round the edges of access openings.

e. Identify on each access opening the items accessible through it.

f. Furnish large access doors with a device to hold them securely open, because such doors might fall shut and cause damage or injury.

g. Provide efficient inspection apertures on items such as gear boxes and housings.

h. Make the access opening that leads to heavy items large enough to allow two-handed operation. Provide sufficient visibility to ensure safety for maintenance operations that involve hazard from nearby electrical circuits.

i. When access openings are located near hazardous components, design the access door so that, at its opening an internal light automatically indicates the danger points.

j. Locate access openings to protect workers from contact with sharp edges, hot or moving parts, or other potential hazards.

2.4.2.1.6 IDENTIFICATION

If the worker is unable to readily identify parts, test points, or controls, maintenance tasks become more difficult, take longer to perform, and are more likely to be performed incorrectly. Identification does not directly promote ease of disassembly, however, when combined with other elements of maintainability, can offer considerable reductions to the disassembly costs (time, labor etc).

2.4.2.2 GENERAL MAINTAINABILITY DESIGN GUIDELINES AND COMMON ERRORS

The Figure 2-33 below shows some of the important general design guidelines that maintainability professionals have developed.

Maintainability is more dependent upon the action of the operating and maintenance personnel, and to a greater extent involves the interactions between people and machines. In that respectt, Human Factors engineering applies knowledge about human capabilities, strength, and size to equipment design. Failure to effectively consider such factors can lead to serious problems, because of which, equipment designers must minimize to the extent possible, the likelihood of human error, and the consequences of potential errors. For instance, they should reduce the number of disassembly tasks required, design equipment so that the available personnel can easily accomplish the required tasks in the given environment (e.g. hangar, field, space) and try to build in features that will make it impossible to perform required disassembly tasks incorrectly.

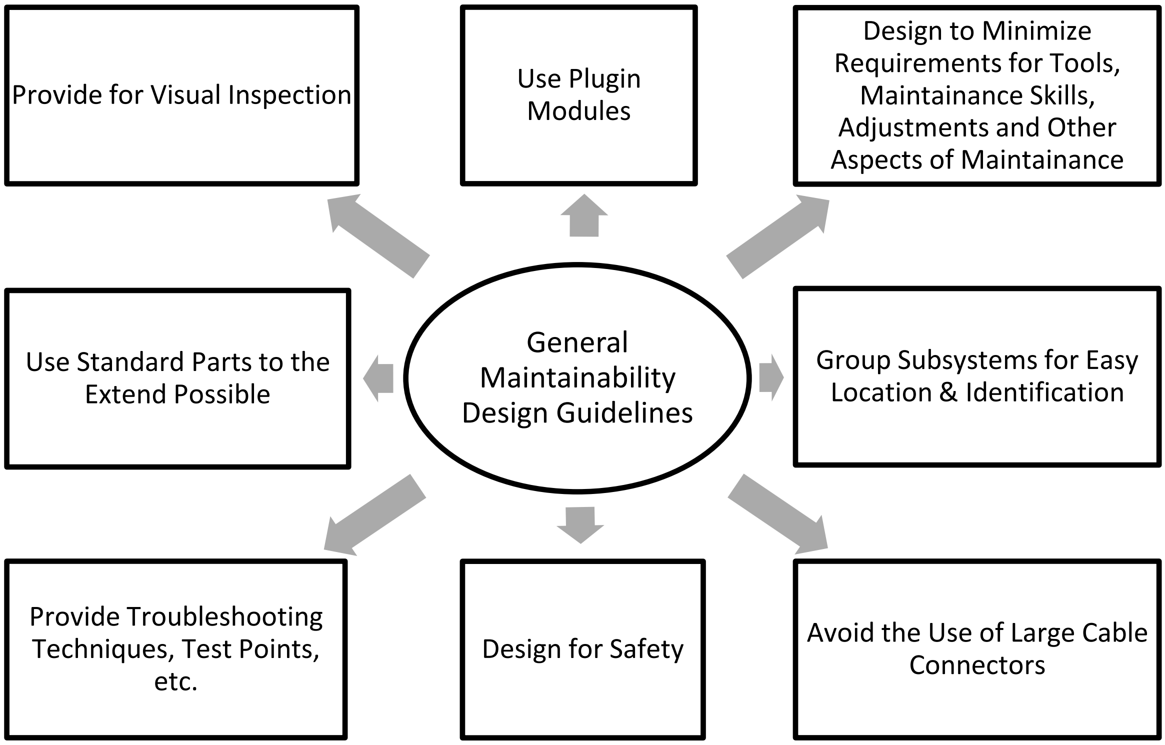


Figure 2-33: Some of the Important General Maintainability Design Guidelines.

Maintainability requirements, and the resulting maintenance actions, must be supported by system design of any aerospace product. It is mandatory that a system maintainability concept be formulated prior to detailed design of such a product. Physical features and pertinent questions that affect maintainability follow:

1. **Accessibility**. Can the item be reached easily for repair or adjustment?
2. **Visibility**. Can the item being worked on be seen?
3. **Testability**. Can system faults be detected readily and isolated to the faulty replaceable assembly level?
4. **Complexity**. How many subsystems are in the system? How many parts are used? Are the parts standard or special purpose?
5. **Interchangeability**. Can the failed or malfunctioning or retiring unit be readily replaced with an identical unit with no requirement for alteration and calibration?
6. **Identification and Labeling**. Are components uniquely identified? Are the labels permanent, or are they easily erased or obliterated by operation or maintenance actions? Are labels positioned to be easily read?
7. **Simplicity**. Is the design as simple as possible? Are standard parts and tools used? Are functions and parts consolidated?

In many cases the equipment uses too many parts, has too close operating tolerances, is too expensive to build, and is difficult and expensive to maintain. The resolution of these factors, to develop a simple design, is the result of compromises and trade-offs among the user, designer, and maintainability engineer but never at the expense of system availability or effectiveness.

2.4.2.3 HUMAN FACTORS

Over the years considerable new developments have taken place in the areas of human factors, reliability, and error. Human factors, reliability, and error have become major disciplines in the aerospace industrial sector. Thus, nowadays it is common to come across human factors specialists (who cover human reliability and error as well) working alongside design engineers during the design and development of engineering systems, for use in areas of aviation. These specialists use various human factors, reliability, and error-related concepts to produce effective systems with respect to humans who take the burdain of disassembling the complex aerospace products.

Disassembly of aerospace products is primarily executed by humans in a manual fashion. The main reasons for this fact include both advantages and disadvantages of humans against machines, (advantages prevail and dictate manual disassembly, but disadvantages also need to be seriously considered in the aerospace products' DfD) are presented here in the form of comparison between humans and machines to perform the disassembly tasks:

a. Humans have excellent memory (machines to have the same capability are remarkably costly).

b. Humans have relatively easy maintenance needs (machines' maintenance problems become serious with the increase in complexity).

c. Humans are subjected to social environments of all kinds (machines are independent of social environments of all types).

d. Humans' performance efficiency is affected by anxiety (machines are quite independent of this shortcoming).

e. Humans are very flexible with respect to task performance (machines are relatively inflexible).

f. Humans have high tolerance for factors such as ambiguity, vagueness, and uncertainty (machines are quite limited in tolerance in regard to factors such as these).

g. Humans are limited to a certain degree in channel capacity (machines have unlimited channel capacities).

h. Humans are poor monitors of events that do not occur frequently (machines possess options to be designed to reliably detect infrequently occurring events.

i. Humans are subjected to stress because of interpersonal or other difficulties (machines are completely free of such difficulties).

j. Humans are unsuitable for performing tasks such as amplification, data coding, or transformation (machines are extremely useful for performing tasks such as these).

k. Humans have rather restricted short-term memory for factual matters (machines can have unlimited short-term memory but its affordability is a limiting factor).

l. Humans are subjected to factors such as motion sickness, disorientation, and Coriolis effects (machines are completely free of such effects).

m. Humans are often subjected to departure from following an optimum strategy (machines always follow the design strategy).

n. Humans are subjected to deterioration in performance because of boredom and fatigue (machines are not affected by factors such as these, but their performance is subjected to deterioration because of wear or lack of calibration).

o. Humans are very capable of making inductive decisions under novel conditions (machines possess very little or no induction capabilities at all).

p. Humans possess many useful sensors: touch, sight, taste, hearing, and smell. A clear understanding of their sensory capacities can be quite useful in reducing the occurrence of human errors in engineering maintenance. Thus, some of the human sensory-related capacities are described below.

Table 2-1: Human Sensory-related Capacities

No.	Typical Human Behavior	Corresponding Design Consideration
1.	Humans often tend to hurry	Develop design such that it properly takes into consideration the element of human hurry
2.	Humans get easily confused with unfamiliar items/things	Avoid designing totally unfamiliar items/ things
3.	Humans often use their sense of touch for exploring or testing the unknown	Give careful attention to this factor during design, particularly to the product/item handling aspect
4.	Humans frequently regard manufactured items as being safe	Design products such that they become impossible to be used incorrectly
5.	Humans have become accustomed to certain color meanings	During design strictly observe existing color coding standards

6.	Humans normally expect to turn on the electrical power, the switches have to move upward, or to the right, etc.	Design such switches as per human expectations
7.	Humans always expect that faucets/handles will rotate counter-clockwise for increasing the flow of gas, steam, or liquid	Design such items as per human expectations

2.5 DISASSEMBLY IN RECYCLING OF AEROSPACE PRODUCTS

As with any product, an aircraft depreciates in value with time. The reduction in value arises from a number of factors including the increased costs of maintenance, of repair and of upgrading to comply with legislation. At some stage, maintenance, repair and upgrading become uneconomic and at this point the owner will consider taking the aircraft out of service. In many cases the retired airframe will contain valuable components and parts that can be returned to service via the second hand parts market. The second hand market is tightly controlled and parts returning to service must be accompanied by appropriate documentation. Failure to comply with national and international safety requirements can result in very significant fines.

The process of dismantling an aircraft at its End-Of-Life as an integrated airframe is referred to as “parting-out”. An aircraft may be parted-out while still fully certified (e.g. for airworthiness) and potentially still generating revenue, because the component parts of the aircraft become more valuable than the aircraft in flying condition. The parting-out process is undertaken in phases as useful and reusable parts are progressively removed. The body owning the airframe at the parting-out stage may require that the engines, undercarriage, in-flight entertainment systems and some of the avionics are returned for future use. Following removal of these parts back to the owner, other useful parts are removed, catalogued and sold to specialist second-hand parts dealers. All parts are inspected and certified with appropriate documentation, as usable, repairable or unfit for service. Second-hand parts suppliers tend to focus on particular aircraft types or makes.

Having removed all valuable components, the remaining fuselage is broken up into small pieces and processed by a metal recovery company. The point at which sub-systems and materials cease to be “valuable” to the parting-out agency is dependent on the cost of removing them, the overhead associated with securing appropriate paperwork, and particularly the infrastructure and technology available to extract value. The legislative environment also affects the value (positive or negative) of the reduced airframe.

As aircraft manufacturers increase the composite content of commercial aircraft, so the recycling of the shredded residue becomes increasingly difficult. When these airframes are retired, it is likely that the already difficult landfill regulations, especially in Europe, will put a high cost – or total ban - on disposal by this route. Further, should OEM take-back requirements such as those being introduced in the automotive sector in Europe in 2007 be extended to other products such as airframes, OEMs currently possess little know-how or experience in what to steps take. In general, OEMs in the aerospace sector have high levels of awareness of this scenario and are being proactive in seeking global solutions to end of airplane life issues. Airbus is evaluating the management of dismantling sites through its PAMELA pilot-project that aims to demonstrate that up to 95% of the aircraft and its components can be recycled. Boeing has established a voluntary association, known as AFRA, to achieve a similar aim; but in this case through recommended end-of-life organisations and the distribution of best practice.

Science and technology plays a major role in determining the end of life value of an aircraft. Where value can be increased, an economic driver is created to increase the fraction of recovered, re-used or recycled materials. The infrastructure in Europe and the US is already in place to reuse/recycle more of the airframe if cost-effective dismantling and separation technologies were available, such as efficient separation of metallic materials including differentiation between aluminium alloys; carbon fibre extraction and re-use; avoidance of Pb, Cr and Cd in aircraft manufacture; robust smart tags; and more recyclable cabin interiors.

Over the next 15 years thousands of airliner aircrafts are expected to be retired, with their material content measured in tens of millions of dollars. With some 200 commercial aircraft reaching the end of their lives every year, storage fields are becoming increasingly crowded, but the huge potential asset value represented by the ranks of retired jets is attracting interest.

Aircraft disposal is the subject of two projects led by Airbus and Boeing companies and mentioned before (PAMELA, AFRA). The European manufacturer is leading research to develop procedures for the environmentally responsible decommissioning of airliners, while its US rival has formed a coalition to develop industry standards for the disassembly of aircraft, salvaging of parts and recycling of material.

2.5.1 AIRBUS - PAMELA PROJECT - TARMAC AEROSAVE

The Process for Advanced Management of End of Life Aircraft (PAMELA) Project, initiated in 2006, was an enterprise set up by Airbus at Tarbes Airport in Southern France, with the aim of recycling aircraft parts. The project was brought about by the EU’s end-of-life directive and received funding from the EU. Airbus later partnered with the waste management company SITA, Sogerma Services and EADS CCR. The ultimate goal was protecting the environment; instead of letting old passenger aircraft deteriorate in airport perimeters or in "boneyards", aircraft will be decommissioned and recycled, using disposing requirements set out by PAMELA.

PAMELA-LIFE successfully demonstrated a business step change: as much as 85 per cent of each aircraft’s components could be safely and effectively reused, recovered or recycled. As the world’s first such full-scale demonstration project, it also identified a generic methodology for handling all end-of-life aircraft, along with a set of best practices. When the project finished, the participants established the Tarmac Aerosave company, which draws on the lessons learned from PAMELA to undertake commercial dismantling of end-of-life aircraft. With this experience, Airbus and its Tarmac Aerosave joint venture use a proven method for dismantling and recycling the entire product range of Airbus aircraft in an environmentally and financially viable way. Tarmac Aerosave is also able to perform CFM56 Series Engine Recycling.

Airbus gained valuable experience from Tarmac Aerosave, which is used as a source of information concerning aircraft ageing and improvements in dismantling techniques. This data is used as feedback for the different functions in Airbus, from aircraft early design to end-of-life management – including re-use of final valuation materials. One key achievement of the PAMELA-LIFE project and of the Tarmac Aerosave industrial undertaking is a business shift from “cradle to grave” to “cradle to cradle” – mitigating the risks of future raw material scarcity.

Airbus estimated that 6,000 aircraft will finish active service between until 2025, a rate of over 200 aircraft per year, and that between 85% and 95% of their components can easily be recycled, reused, or otherwise recovered. Initially funded 53% by industry and 47% by the EU’s LIFE (L’Instrument Financier pour l’Environment) programme, the PAMELA project developped aircraft disposal procedures that comply with the environmental and health rules enshrined in the European Aviation Safety Agency’s Part 145 standards for maintenance operations and organisations.

Figure 2-34: PAMELA Project Test Aircraft for Disassembling and Dismantling

Since the first A300B2 entered service more than 35 years ago, Airbus had taken orders for more than 6,000 aircraft from 200 customers, and is preparing to help dispose of them. The PAMELA project was a demonstration that set up innovative and environmentally friendly, safe practices for management of the end-of-life of aircraft, to recycle 85-95% of the aircraft parts, according to Airbus.

Airbus leveraged PAMELA to go further and produce recommendations for future aircraft design processes like DfD; as well as create new standards for decommissioning, storage, disassembling and dismantling, and recycling or elimination of aircraft parts. According to Airbus, PAMELA should also provided valuable recommendations to better introduce environmental considerations at the earliest design stage of the aircraft.

The PAMELA partners used a General electric CF6-50C2-powered Airbus A300B2-200, registered TC-FLF, as the test vehicle for disassembling and dismantling. The aircraft entered service in 1982 and accumulated 53,489 flight hours before being retired. Dismantling involved the removal of materials considered hazardous and polluting, including hydraulic fluid and residual fuel, while disassembling involved the identification of equipment or parts that are in good condition or can be repaired for reuse. According to Aibus, the possibility of the components being reused depends on the type and the age of the aircraft and its related parts, and can be managed according to applicable regulations and standards.

Airbus's partners are waste management firm SITA, maintenance company EADS Sogerma Services, the EADS Corporate Research Centre in France and the regional government of Hautes-Pyrenees. SITA manages dismantling operations such as the cutting, sorting and recovery of metals, which will be recycled on the secondary raw materials market or re-integrated into the production cycle. The company has developed processes to separate composite, copper and plastic constituents and to remove electrical wiring insulation.

The partners have set up a special centre for PAMELA at Tarbes airport in south-west France, within the Hautes-Pyrenees prefecture. There, the engine pylons, landing gear, avionics boxes, flight controls, batteries and hydraulic pumps are removed and the airframe divided into manageable sections. However, Airbus did not predict a rapid expansion of the aircraft recycling industry in Europe, saying: The lessons learned will have to be considered before any possible further industrial development. Project work includes an economic and market analysis of aircraft disposal, in which the scarcity of some extracted raw materials would certainly play a key role in the business analysis.

2.5.2 BOEING – AFRA ASSOCIATION

Several years ago Boeing conducted a field survey of approximately 50 companies involved in older fleet management and aircraft scrapping. A realization from that process was that a group of companies quickly distinguished themselves in terms of experience, capabilities and technologies, and Boeing began to focus its attention in that direction. Since that time 19 companies, including Boeing, have come together to establish a common industry working group, (Aircraft Fleet Recycling Association), AFRA was officially announced on April 17, 2006. It formalized its charter and elected a board of directors and executive director in June 2006 in Châteauroux, France

Introduced by Boeing, the Aircraft Fleet Recycling Association (AFRA) aims to provide owners of aircraft with an integrated fleet management process. Boeing wants to reclaim composite material and recycle fibres to flow that into high value reuse, not low value. High value includes the use of recycled carbonfibre for aircraft parts such as tray tables, while low value includes the incorporation of reclaimed fibre in material for road construction.

For the close future, AFRA's primary objectives are to develop a code of conduct for retired aircraft management, establish next-generation standards and practices within a year of the code's launch, and then expand those standards through AFRA. Later on, the industry group will focus on recycling technologies for the improved recovery of aluminium and precious metals and the recycling of carbonfibre. In particular:

a. The AFRA charter contains the following goals and objectives for the organization:

   (1) Develop a code of conduct for retired aircraft management.

   (2) Establish next-generation standards and industry best practices for aircraft recycling and reclaimed materials management.

   (3) Work to promulgate these practices through broader industry associations.

   (4) Continue cooperation between all AFRA members in technical and commercial matters.

b. The Boeing objectives for aircraft recycling are as follows:

   (1) Promote Boeing's industry leadership and endorsement of AFRA's recycling initiatives,

   (2) Demonstrate through its participation in AFRA that the organization has a long-term commitment to build and expand its offering to industry,

   (3) Offer airline customers end-of-life and maintenance options that will:

      (a) Re-sell planes that are fit to return to service

      (b) Offer safe parts recovery, scrapping and recycling of planes that are not fit for service,

      (c) Greatly improve materials recovery from retired planes and manufacturing scrap.

The AFRA coalition has two locations: Chateauroux Air Centre in central France, south of Paris, and Evergreen Air Center in Marana, northwest of Tucson, Arizona. Chateauroux airport offers a 4.900 m^2 (16.000 ft^2) hangar and a one-stop shop for the storage, maintenance, painting, parting out and scrapping of aircraft. On site are maintenance company Europe Aviation and scrapping specialist Bartin Recycling Group, both AFRA members.

Boeing anticipates that as many as 7.200 commercial aircraft will be retired from active service in the next 20 years and all should be available for recycling. Recycling, rather than land-filling, is better for both business and the environment. Boeing supports efforts to develop commercially feasible and environmentally sound guidance and best practices for aircraft recycling. AFRA's first guidance subject, Management of Used Aircraft Parts and Assemblies, contains voluntary best practices for the removal of parts from an End-Of-Life aircraft, covering parts management prior to their entering the distribution network which is covered by FAA Advisory Circular 00-56A.

Beyond the newer challenge to reclaim carbon fiber from composite scrap, AFRA recycling considerations include:

a. aluminum sorting by alloy,

b. aircraft electronics recycling,

c. effective disposal of other aircraft components such as hazardous waste, solid waste, airplane fluids,

d. conservative use of labor and energy to accomplish the overall objective of reducing the impact of a retired aircraft on the environment.

AFRA's approach is to integrate such new and emerging technologies into older aircraft management and new materials recycling industries. Various current members are improving the technologies that address composite recycling, aluminum separation by alloy type, and electronics recycling. However, AFRA does not endorse or recommend any specific technologies or companies.

Regarding composites, Boeing is actively working with its global partners to find applicable best practice guidelines for the 787 program. Among the newest members of the Boeing family of airliners, it is an all-new, mid-sized airplane with long range capabilities. The 787 is being made primarily of carbon fiber composite material comprising 50% of the 787's structural weight. This represents a breakthrough from today's airliners that are primarily composed of aluminum. Looking forward, Boeing is working with companies around the world towards a goal of maximizing the use of recyclable materials on the 787. Although the first retirements of the 787 are likely 30-40 years away, it is important that the foundation of that recycling activity begin today to support 777 series aircraft retirements (20% by weight composites) as well as other aerospace products.

Fiber composite materials comprise 50% of the 787's structural weight. This represents a breakthrough from today's airliners that are primarily composed of aluminum. Looking forward, Boeing is working with companies around the world towards a goal of maximizing the use of recyclable materials on the 787. Although the first retirements of the 787 are likely 30-40 years away, Boeing believes is important that the foundation of that recycling activity begin today to support 777 retirements (20% by weight composites) as well as other aerospace products.

This activity greatly involves the recycling of composites which is still evolving. Normally it is a two-step procedure that involves; first, a mechanical process that separates composites from other aircraft materials during an aircraft's retirement and second, a recycling process that recovers fibers of sufficient quality that they can be re-introduced as a materials source in aerospace manufacturing.

For example, Milled Carbon Ltd company uses a pyrolytic (incineration that chemically decomposes materials by heating them in a near oxygen-free atmosphere) continuous flow process to burn off all the resin and additives, freeing the fiber reinforcement. It does not need to pretreat the material before pyrolizing and has the ability to process the recyclate further by chopping or milling for various applications. Adherent Technologies uses a low-temperature catalytic conversion batch process to recycle complex mixtures of thermoplastic and crosslinked thermoset polymers. It reclaims not only fibers but also thermoplastic and thermoset polymeric waste in the form of reusable hydrocarbon fractions (chemical building blocks). The various materials are separated by designated support unit operations during the process. Both processes are proprietary and owned by their respective developers.

Shredded composite scrap from damaged F/A-18 fighter aircraft's horizontal stabilizers (end-of-service, scrapped aircraft parts) was sent to both Milled Carbon and Adherent. The reclaimed AS-4 fibers were sent back to Boeing and subsequently forwarded blind to N. Carolina State University for testing. The control was virgin AS-4 (35 msi modulus / 3501-6 graphite epoxy). Spectroscopic analysis showed that both processes left a metals residue on the fibers. Both processes were "optimized", which removed this residue from a second run of the scrap.

Fiber from both Adherent and Milled Carbon has been successfully compounded into injection molding and bulk molding compounds for evaluation. Performance characteristics exceeded those of glass reinforced materials and in the case of injection molding were competitive with off the shelf virgin carbon fiber filled compounds.

Recycled F18 fighter aircraft's carbon fiber has also been directly incorporated into fiber preforms for a compression molding demonstration. Materials Innovation Technologies of Fletcher North Carolina was able to successfully fabricate preforms directly from as provided fiber after chopping and had them molded into a production configuration automotive component, a Corvette C6 fender, fabricated from recycled carbon fiber which is approximately 20% lighter than the production fiberglass component even without engineering for improved stiffness.

The first commercial U.S. composite recycling facility designed, built, owned and operated by Milled Carbon's U.S. entity, Recycled Carbon Fibers, Inc, is running since 2008. A priority is its ability to also service facilities like the Aerospace Maintenance And Regeneration Group's (AMARG) Center. The Tucson, AZ, Center is the prime USAF site involved in military aircraft recycling and disposal, including aircrafts of Boeing and other manufacturers.

Airplane graveyards throughout the American Southwest will welcome an influx of retired planes in the coming decades, but these boneyards may increasingly serve more as stopovers than final destinations, since recycling is set to expand as the airline industry seeks to become more sustainable and as costs rise for raw metals and manmade ingredients such as carbon fiber. From a materials' technology standpoint, components of dead aircraft can be broken down and begin a new journey, eventually landing in consumer products including furniture, cell phone casings, and food cans.

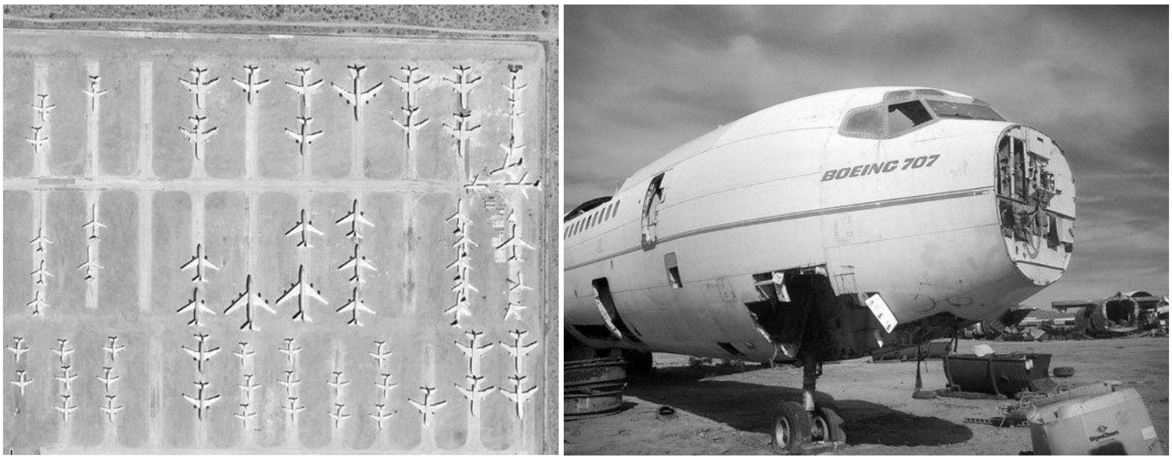


Figure 2-35: Aircraft Scrap Yards

This bird's eye view of a scrap yard in Victorville, California (Figure 2-35), can be seen online via Google Maps. The arid desert climate keeps the craft well-preserved.

From the shell to the seats to the wheels, about 80% of a plane can be reused, according to Boeing. It may take about a month to dismantle an aircraft. Mechanics break down engines, controls, pumps, batteries, wings, the fuselage, and other parts, sending many intact to dealers of used aircraft parts (Figure 2-36). Scrap brokers buy metals, metal alloys, plastics, and composite materials that are further separated and shredded. Items containing toxic chemicals, such as varnishes or hydraulic fluids, must be (and are) disposed of separately.

Most of the fuselage and wings from jets are made of aluminum, which can be sold for scrap and used later in automotive parts including wheels and transmissions. However, currently more aluminum is recovered from obsolete automobiles than from aircraft, because the complex composition of aerospace aluminum alloys can be difficult to recover and reuse.

Figure 2-36: Dismantling of Aircrafts

Steel, found in the landing gear of airplanes is also relatively easy to recover. The metal can be separated with a magnet. Scrap dealers sell steel from boneyards to companies that make anything, from new aircraft to food cans to bridges. Each ton of scrap steel used saves 2.500 pounds of iron ore, 1.400 pounds of coal, and 120 pounds of limestone, according to the Steel Recycling Institute. About 70 million tons of steel are recycled in the United States per year.

Figure 2-37: Recycling Steel and Composites from Aircrafts

The Figure 2-37 shows a bale of steel scrap on its way to be mixed in a furnace with coal, iron ore, and limestone to make fresh steel goods. Recycling composite aircraft materials like those in the Figure 2-37 is trickier than working with raw metals. Composites using lightweight and durable carbon fiber are found more and more in newer aircraft, and make up half of each Boeing 787. The Aircraft Fleet Recycling Association aims to recycle 5 tons of carbon fiber per day.

However, the process of separating carbon fiber from plastic and metal composites is still being perfected. Using heat to break down the materials through pyrolysis may be the most promising method, according to recycling companies. Researchers are also exploring the use of microwaves and radio frequency to extract the material.

Recycled carbon fiber is being tested for use in tires, paint, industrial injection molds, and sporting goods such as skateboards. Companies are also looking into using it in airplane baggage bins and galley carts, within car brakes, and even spinning it into yarn.

Figure 2-38: Furniture Created by Recycled Aircraft Parts (Example)

Outside of the industrial market for scrap materials, a small but growing number of designers are recycling mothballed aircraft to create high-end furniture. In the Los Angeles area, Moto Art sells wing desks and tables to advertising and design firms as well as Hollywood stars. The $12.000 desk shown in Figure 2-38 is made from a Lockheed C-130, which had been used for military cargo and medical operations and in humanitarian missions since the 1950s. In addition to making trendy home furnishings, aircraft can be turned into homes.

2.5.3 WINGNET – A UK INITIATIVE

Like all products, civil aircraft eventually come to the end of their useful working lives. The reasons for this may include, increasing maintenance costs, legislation demands for expensive technology upgrades, difficulties in obtaining replacement parts, increasing content of time or service expired parts. A typical depreciation in value of an airframe is shown in Figure 2-39.

Figure 2-39 shows that a wide-bodied airliner built in 1980 had almost no value in 2007 even though it may be in flying condition. A similar trend is seen for all aircraft types, irrespective of manufacturer. Consequently there is a point when the operating airline will take the decision that an aircraft is no longer worth retaining in service. This point will depend on market conditions and can be affected by fuel costs, depressed air travel during times of conflict, terrorism, or other concerns such as those seen due to the transmission of Severe Acute Respiratory Syndrome (SARS).

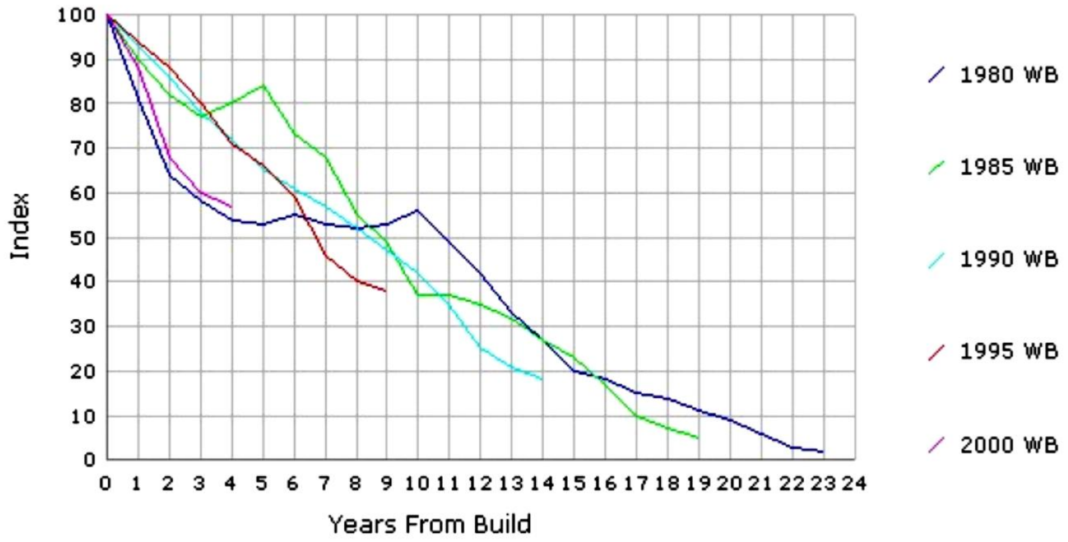


Figure 2-39: Wide Bodies (WB) Aircraft Value as a Function of Age (Wide Bodied Aircraft)

WINGNet (Waste reduction IN aircraft-related Groups) is a network funded by the UK Engineering and Physical Sciences Research Council (EPSRC). WINGNet is focused on the development of the technologies and infrastructure required to meet the challenges in the sustainable use and reuse of aircraft materials. The WINGNet scope of activities was formulated in consultation with the UK Aerospace Industry to identify critical materials science research required to improve the UK's performance in sustainable use of materials. This report constitutes one of the WINGNet outputs and is intended for a non-expert in sustainable use materials working in the aerospace sector. WINGNet objectives:

a. To examine and highlight fundamental materials science and techniques relevant to the development of new materials, recycling, remanufacture of components and reuse of materials in the aerospace sector.

b. To identify technical opportunities for a series of high quality collaborative research proposals in the area of 'Sustainable Use of Materials'.

c. To improve the coordination within the UK aerospace sector on issues relating to the sustainable use of materials, involving key industries, academics, institutes, groups and trade bodies concerned with sustainable use of aerospace materials.

d. To establish the current state-of-the-art in the manufacture and remanufacture of components and the reuse of materials, and to develop research strategies where the current state-of-the-art is deemed to be lacking.

e. To bring together key personnel involved in the sustainable use of aircraft materials in an atmosphere conducive to open discussion.

f. To update on related research proposals and programmes facilitated by WINGNet.

g. To identify priorities for further research and activity.

While the End of Life Vehicles (ELVs) Directive 2000/53/EC places a significant burden on automotive vehicle manufacturers, with recycling and recovery targets of 85% and 95% respectively by 2015, no such directive applies to the civil Aerospace Industry. However, there is growing concern in the industry that a similar directive may be introduced. None of the world's civil aerospace suppliers are technically prepared to meet the requirements of such a directive. Nonetheless, it has become clear through WINGNet consultations that the sector wishes to be proactive in the development of disassembly or parting-out capabilities and technologies that will contribute to the development of a more sustainable Aerospace Industry in the UK. In the absence of legislative drivers, projects and expenditure in this area have to be justified on the basis of economic benefit. Therefore, there exists an opportunity for the UK to develop aerospace-related end of life technologies that will establish the UK as a world leader in economic end of life technologies and processes.

2.5.3.1 AEROPACE PRODUCT STEWARDSHIP

Product stewardship is a product focused approach to environmental protection, also known as extended product responsibility (EPR). Product stewardship calls on manufacturers, retailers, users, and disposers to share responsibility for reducing the environmental impacts of products. It also recognizes that product manufacturers can and must take on new responsibilities to reduce the environmental footprint of their products. The concept of product stewardship focuses only on the manufacture of a product and subsequently its use and disposal. Therefore consideration of any environmental impact is restricted to those areasIn the aerospace sector, the area of product stewardship was recently elevated in importance following a tipping incident involving a retired Ryanair Boeing 737-200.

In the UK and Europe, the key principles of product stewardship in aerospace have been put forward by the Advisory Council for Aeronautics Research in Europe in their October 2002 and 2004 documents and the Department for Transport's document on Sustainable Aviation (URN05/1251). These documents set the direction and priorities for achieving the goal of sustainable aviation. Product stewardship reduces the environmental impact of products by considering the entire lifecycle of a product and its components by:

a. Minimising the amount and type of material used in manufacture.

b. Reducing or eliminating the use of toxic materials.

c. Extending product life by future proofing the design.

d. Minimising maintenance, repair and overhaul.

e. Minimising fuel/energy consumed during the product's life.

f. Providing routes to reuse, recycle or responsibly dispose of waste products.

Product stewardship also has a role to play in design through:

a. The functionality of the product.

b. The materials used, their cost and environmental impact both in manufacture and disposal.

c. Designing in ease of repair and maintenance.

d. Extended product lifetime.

e. The energy used in manufacture of materials, components and sub-systems.

f. Transport costs and energy consumed.

Product stewardship in use effects:

a. Minimising maintenance, repair and overhaul, which in turn reduce disassembly frequency.

b. Minimising energy consumption during use.

Product stewardship at end of first life results in:

a. Extraction of valuable components and materials.

b. Ease of dismantling to economically extract components and materials.

c. Ability to upgrade.

The Figure 2-40 below shows a typical product stewardship process.

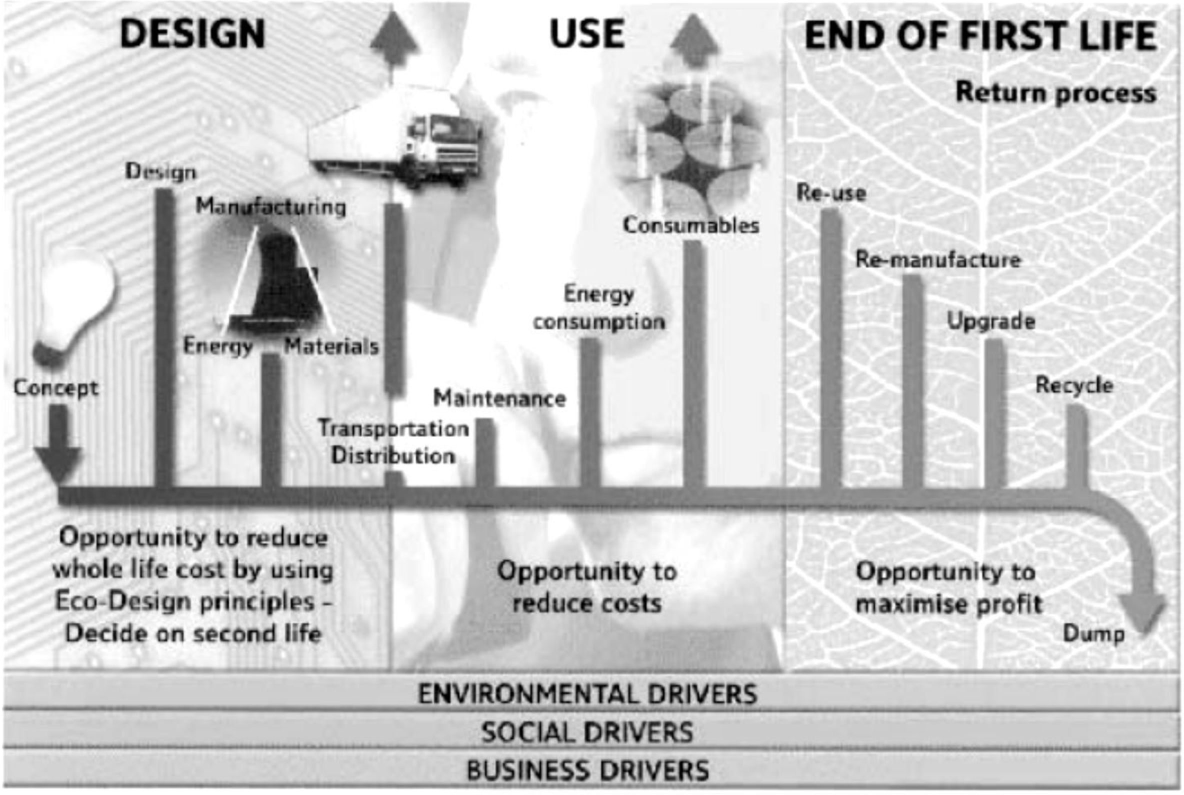


Figure 2-40: The Product Stewardship Process.

2.5.3.2 FUTURE ISSUES

New technologies, materials and manufacturing methods introduced into new products will increasingly reduce the environmental impact of products and assist in the responsible disposal of those products. In the automotive sector, there has been much discussion of adapting Design for Disassembly principles in order to ease recycling and disassembly. In the aerospace sector, this has not been regarded as a key customer requirement – not least because of the need to meet strict safety requirements for product robustness.

Nonetheless, as with any complex product, the difficulty of disposal and re-use increases with the number of different materials employed, and this is particularly the case for polymeric and composite materials increasingly used in all parts of the transport and aerospace sector. Therefore, rather than significant adoption of Design for Disassembly philosophies in the aerospace sector, it is more likely that there will be increasing emphasis placed on materials and structures research and development programmes. These programmes aim to rationalise the number of materials used. This rationalisation is certain to include targets to remove as many toxic and environmentally damaging materials as possible while maintaining the highest possible safety standards.

Shorter-term challenges are presented by the many thousands of older civil and military airframes still flying but approaching the end of their useful life. These airframes and their engines often comprise many disparate materials, the attitude to which in terms of their environmental impact and responsible disposal has changed dramatically since their manufacture. As these aircraft come to the end of their useful lives, techniques and technologies are needed to ensure that maximum value can be extracted and high environmental impact materials are responsibly disposed. In this respect, there is a pressing need to identify best-practice from the disparate parting-out chain and to seek consensus in applying this best practice across the sector.

The concept of life cycle thinking, from raw materials extraction, through manufacture, use and maintenance to final End of Life options facilitates an important shift in how Aerospace Industry has traditionally viewed itself and its operations. Life cycle analysis is a major topic in its own right, and its approaches are applicable across all industries including the aerospace sector. The ability to ensure that changes to design and/or operational procedures can reduce the total impact on the environment, as opposed to simply transferring the burden to another stage of the life cycle, is essential to life cycle thinking. This is easily understood since in the vast majority of cases, and particularly in aerospace, the environmental impact of the use phase is the largest.

2.5.3.3 PARTING-OUT OF RETIRED AIRFRAMES

The process of parting-out an airframe involves the dismantling of that airframe down to its component parts. The reasons why an operator may wish to do this is varied but can include:

a. Old aircraft being taken out of service to be replaced by newer models.

b. Removal of aircraft from revenue service because they no longer meet international operating regulations and it is too expensive to upgrade.

c. Aircraft damage sustained during operation is uneconomical to repair.

d. Scarcity of spare parts for that particular aircraft result in the sum of the individual parts having more value that the flying aircraft.

e. Cannibalisation of an aircraft to keep others airborne.

The International Society of Transport Aircraft Trading (ISTAT) defines “Parting-out Value” or “Salvage Value” as: the actual or estimated selling price of an aircraft, engine or major assembly based on the value of marketable parts and components that could be salvaged for re-use on other aircraft or engines.

Thus parting-out becomes advantageous, over storage, when disassembly for parts would most probably result in the highest cash yield for the asset “as-is” as compared with the market value of the asset as a whole. When considering storage, the on-going cost of that storage and required maintenance must be considered. The salvage or parting-out value should not be confused with scrap value, which is the actual or estimated market value of an aircraft, engine or major assembly based solely on its metal or other recyclable material content, with no saleable reusable parts or components remaining.

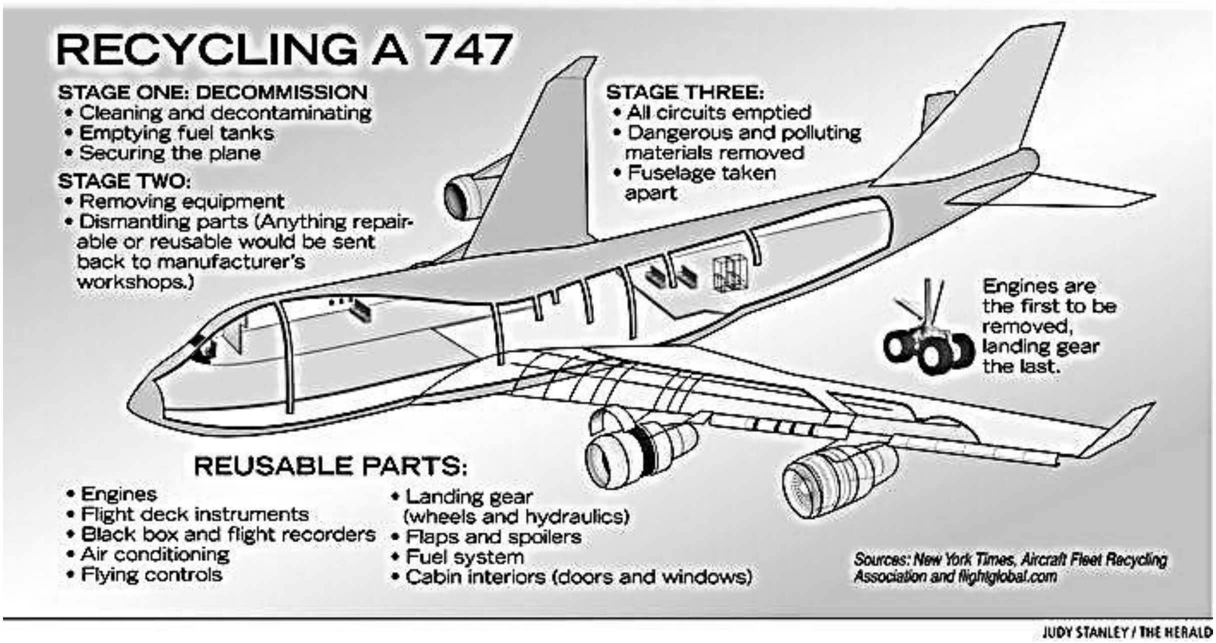


Figure 2-41: Recycling a Boeing 747 Airraft

At general paperwork level, any European based company or individual wishing to part-out an airframe with a view to salvaging, for aerospace use, parts and components must be registered under EASA (European Aviation Safety Authority) Form 145. In addition, parts returning to service must be accompanied by EASA Form One that specifies clearly the part, manufacture, part number, its service condition and a history of servicing or repair. Thus each part should be accompanied by a paper trail that itemises the history of that part. The responsibility for checking the conformity of a part rests with the owner. In Europe, parts suppliers are encouraged to become members of The European Aviation Suppliers Organisation that is run by its members.

2.5.3.4 PARTING-OUT OF AN AIRCRAFT

How an aircraft may be parted-out can be illustrated by considering a Boeing 757 that was parted-out by a leading UK based Specialist Company. In this case, the B757 (Figure 2-42) was worth more as parts than as a flying revenue generating aircraft because owing to the shortage of second-hand B757 parts for this aircraft type. This is not true for all makes and types of aircraft.

Prior to parting-out the aircraft had been operated by a leading tour company on revenue service. Having decided the aircraft was no longer required, the tour company returned it to the leasing agent who put it up for sale. It was purchased by a second-hand parts company, without its engines as these were retained by the leasing agent. The parts company issued a contract to dismantle the aircraft and to remove, in accordance with manufacturers' instructions, and catalogue reusable parts (rotable parts) on its behalf. Typically these parts will have included avionics, pumps and electric motors, hydraulics, in-flight entertainment systems, undercarriage and aerofoils.


Figure 2-42: Parting Out of a Boeing 757 at Lasham Airfield, Hampshire, UK

The aircraft was flown into Lasham airfield in Hampshire where the disassembly took place. The engines were removed and returned to the leasing agent as requested. After all rotables were removed, then the remaining carcass, comprising mainly the fuselage, wings, tail structure and internal fittings were transferred to the specialist dismantler for sale and disposal. Items such as the cabin doors and flight deck were salvaged and sold for training purposes. The remainder was sold as scrap to a metal smelter and the plastic cabin furniture was sent to landfill.

On completion of the parting-out/scrapping procedure, ASI returned the relevant paperwork to the leasing company and provided them with a certified disposal certificate confirming that the aircraft had been disposed of in accordance with legislation.

2.5.3.5 PARTS CONTROL

The competitive pricing of air travel increasingly puts pressure on airlines to cut the costs of maintenance and repair. The temptation to use “cheap parts” is growing in regions where regulation, inspection, enforcement and penalties for transgression are weak. Investigations have shown that “cheap parts” viz. parts and components that do not meet the manufacturers’ quality standards and are not approved by them, or parts that do not have the correct associated paperwork have been found in a considerable number of aircraft.

The second hand market for aerospace parts and components can be highly lucrative and there is a driver for unscrupulous businesses and individuals to sell unserviceable, damaged and time-expired parts. For example, in May 1998, the U.S. Department of Transportation’s Office of Inspector General announced that a company had pleaded guilty and agreed to pay a $3 million criminal fine and $2 million in restitution for falsifying records pertaining to the origin of parts removed from two Boeing 727 aircraft. In this case, more than 3.000 parts were removed from the aircraft and were transferred to a parts sales company. Equipment transfer tags identified that some parts were in serviceable condition under Federal Aviation Administration (FAA) regulations and could therefore be installed in commercial aircraft holding U.S. airworthiness certificates without further inspection or testing. The tagged parts included gyros, main landing gear assemblies, steering computers, navigational computers and other flight critical parts. These parts had in fact not undergone all the procedures required for tagging and re-entry into service.

Consequently it is imperative that the flow of used parts are controlled and documented and that unserviceable and time-expired parts are properly removed from the supply chain. These aims and objectives are fundamental to the AFRA and PAMELA projects, as already discussed.

In the military sector, parting-out of retired airframes may also bring various restrictions on the final destinations of components, equipment and sub-assemblies since even relatively old airframes may contain designs, materials, embedded know-how, systems, etc that are technologies controlled by sovereign governments. Even relatively small items of a dismantled airframe could provide useful information to an enemy. Evidently, part control is again of paramount importance.

2.5.3.6 THE PARTING-OUT CHAIN

Storage of an airframe in flying condition is expensive since the airframe will still be required to undergo regular safety and maintenance checks. These aircraft may remain in storage for a considerable time before being sold on to a new operator, and therefore the current owner can incur significant storage and maintenance charges. An alternative option for the owner is to consider parting-out the airframe. To help owners and operators make sound business decisions regarding continued storage, parting-out or scrapping, the owners need a good understanding of:

a. The current market value of the type being considered.

b. Market trends for the type.

c. The demand, and hence value, of the parts market for the type.

d. The costs involved in parting out versus the cost of storage and maintenance.

The relationships and interplay between the various players involved, once the parting-out option has been chosen, are shown in Figure 2-44. The key player in the parting-out process is the regulatory bodies as they are responsible for air safety and have a duty to ensure that the rules and regulations relating to the reuse of second hand parts are strictly controlled.

Parted-out or scrapped aircraft and parts must be documented according to CAA notice AN 96 that states: “The purpose of this Airworthiness Notice is to provide information and guidance to persons involved in the maintenance, sale, or disposal of aircraft parts. It provides information and guidance to prevent scrap aircraft parts and materials from being sold or acquired as serviceable parts and materials."

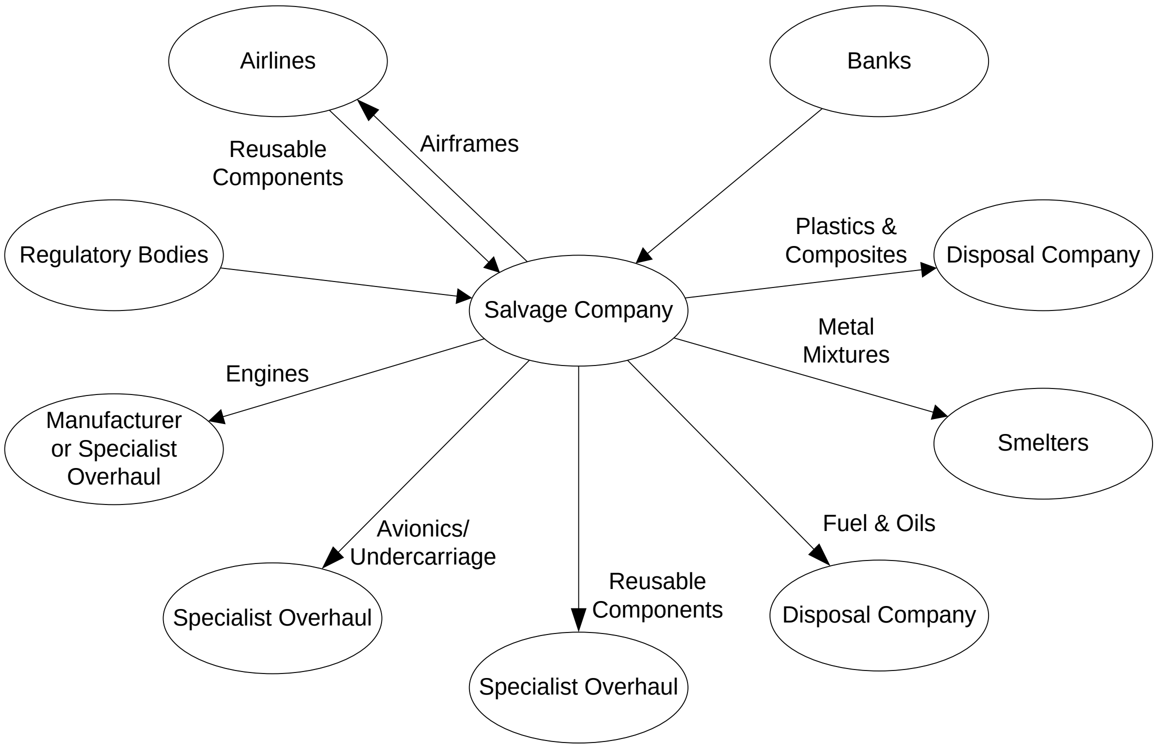
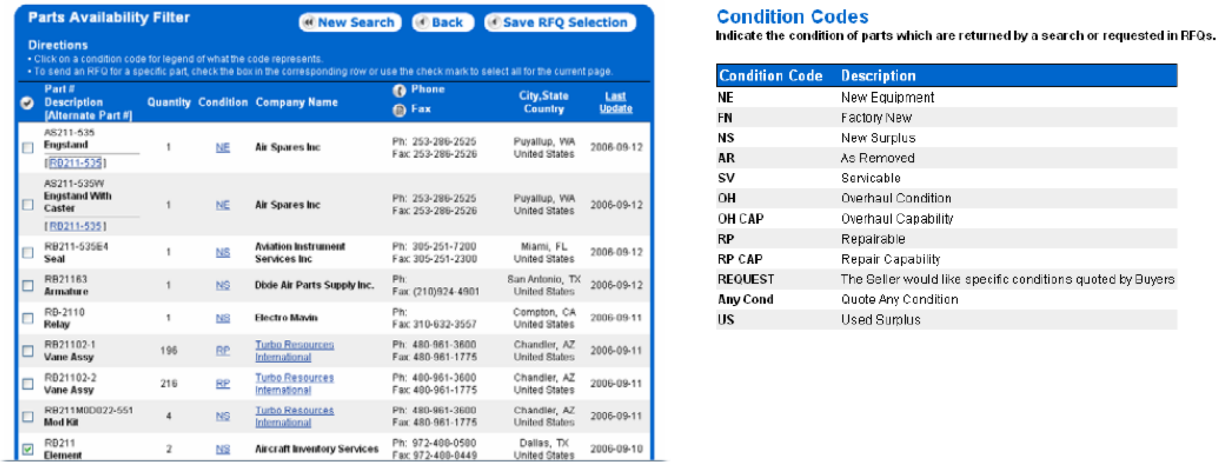


Figure 2-43: A Schematic Representation of the Parties Involved in the Aerospace Parting-Out Chain

Most often the salvage or parting-out company will be contracted by the airframe owner to undertake the parting-out. Only in a few cases will the parting-out company purchase an airframe themselves. The airframe owner will usually be an airline, leasing company, a bank or similar. As part of the parting-out contract, the airframe owner will usually specify those parts they require to be returned for future use, and these will often include the engines.

On removal, the rotable parts are catalogued, part numbers checked against the aircraft's logged inventory, and the parts inspected and recorded as being fit for immediate re-entry into service, in need of service or repair or unserviceable. If the part is unserviceable or irreparable, it is normally destroyed, or rendered unusable, to ensure it does not find its way back into service. Serviceable or repairable parts are sent onto a parts supplier. Some major parts may be sent to a specialist company that undertakes a major overhaul, such as the engines or the undercarriage. In the case of engines, they can be kept in storage for considerable lengths of time if properly sealed and stored. If not, then after 6 months of storage the engine will normally require recertification. Procedures for the storage of engines are provided by the manufacturers. Figure 2-44 shows a part availability report available on-line.

Materials such as residual fuel and oils are not permitted to re-enter the aviation sector and are usually disposed of by specialist companies or, in the case of fuel, used on-site as an energy source. Interior plastics and linings are usually sent for landfill and the aircraft carcass is chopped up and then taken to a metal smelter.



Parts Availability Filter

New Search | Back | Save RFQ Selection

Directions
• Click on a condition code for legend of what the code represents.
• To send an RFQ for a specific part, check the box in the corresponding row or use the check mark to select all for the current page.

Part # Description [Alternate Part #]	Quantity	Condition	Company Name	Phone / Fax	City, State Country	Last Update
AS211-535 Engstand [RB211-535]	1	NE	Air Spares Inc	Ph: 253-286-2525 Fax: 253-286-2526	Puyallup, WA United States	2006-09-12
AS211-535W Engstand With Caster [RB211-535]	1	NE	Air Spares Inc	Ph: 253-286-2525 Fax: 253-286-2526	Puyallup, WA United States	2006-09-12
RB211-535E4 Seal	1	NS	Aviation Instrument Services Inc	Ph: 305-251-7200 Fax: 305-251-2300	Miami, FL United States	2006-09-12
RB21163 Armature	1	NS	Dixie Air Parts Supply Inc.	Ph: Fax: (210)924-4901	San Antonio, TX United States	2006-09-12
RB-2110 Relay	1	NS	Electro Mavin	Ph: Fax: 310-632-3557	Compton, CA United States	2006-09-11
RB21102-1 Vane Assy	196	RP	Turbo Resources International	Ph: 480-961-3600 Fax: 480-961-1775	Chandler, AZ United States	2006-09-11
RB21102-2 Vane Assy	216	RP	Turbo Resources International	Ph: 480-961-3600 Fax: 480-961-1775	Chandler, AZ United States	2006-09-11
RB211M0D022-551 Mod Kit	4	NS	Turbo Resources International	Ph: 480-961-3600 Fax: 480-961-1775	Chandler, AZ United States	2006-09-11
RB211 Element	2	NS	Aircraft Inventory Services	Ph: 972-480-0580 Fax: 972-480-0449	Dallas, TX United States	2006-09-10

Condition Codes

Indicate the condition of parts which are returned by a search or requested in RFQs.

Condition Code	Description
NE	New Equipment
FN	Factory New
NS	New Surplus
AR	As Removed
SV	Servicable
OH	Overhaul Condition
OH CAP	Overhaul Capability
RP	Repairable
RP CAP	Repair Capability
REQUEST	The Seller would like specific conditions quoted by Buyers
Any Cond	Quote Any Condition
US	Used Surplus

Figure 2-44: Part Availability Report from Parts Logistics with Condition Key

2.5.3.7 PART SUPPLIERS

Part suppliers usually only cater for specific aircraft types or types or parts e.g. undercarriages. The list below, which is not exhaustive, gives an idea of this specialisation:

a. Boeing Parts Page (http://www.boeing.com/commercial/spares/part_page.html) provides an easy and efficient way to research, quote, order and track parts from Boeing Spares.

b. Avtrade (http://www.avtrade.co.uk/) Supports Boeing, Airbus and BAE Systems fleet types. Holds over 500,000 rotable and expendable line items. Full traceability is guaranteed on all components, and all rotables are supplied with current JAR/FAR release from approved workshops.

c. Bramlands Aviation Ltd (http://www.bramlands.com/) Supports SAAB 340 aircraft.

d. Aerospace Support Associates (http://www.asa.uk.com/) Offers a comprehensive spares service, are proficient in providing “kits” covering, engine change, B & C checks etc.

e. Aerotron (http://www.aerotron.co.uk/) A320, A330, MD80, DC10, Boeing 757, 767 and helicopters.

f. Burwood Aviation (http://www.burwoodaviation.co.uk/) Has established links with airlines and maintenance bases, e.g. Thomas Cook, Monarch, British Midland and KLM.

g. Ansett Aircraft Spares and Services (http://www.ansettspares.com/) Based at Heathrow but have sales and stores in California and Australia. Have large stocks of BAE expendables.

h. Inventory Locator Services (http://www.ilsmart.com/) ILS is a web based parts portal. Over 5 billion parts listed, 50,000 customer accesses the site each day.

i. Parts Logistics (http://www.partslogistics.com/) Parts Logistics, buy, sell, locate, and research aircraft parts, helicopter parts, electronic parts, marine parts, industrial parts, and defence related equipment. An example of a typical search report is provided in Figure 2-44, showing a description of the part, its part number, the condition of the part and the current owner.

2.5.4 FIVE DfD DRIVER TECHNOLOGY TRENDS AND CHALLENGES

The increase of interest in applications of DfD in the Aerospace Industry has lead to the identification of the following five (5) primary technological driver trends and challenges for aircraft DfD:

a. Composites and Composite Recycling.

b. Cabin Interiors.

c. Metal Separation Technologies.

d. Replacement Technologies for Toxic Metals and Coatings.

e. Materials Identification Tags.

2.5.4.1 COMPOSITES AND COMPOSITE RECYCLING

Aerospace composite recycling is increasingly important owing to the rapidly increasing use of these materials in the commercial aerospace sector. Future products from Airbus, Boeing, Embraer, etc, are announced to use up to 50% unladen weight of polymeric based composites in their primary structures. These types of materials currently pose very significant recycling and recovery challenges. One major airframe dismantler in Europe commented: “if asked to dispose of a 787 today we would have to dig a very large hole and bury it.” Evidently, the end of life problems concerned with composites are set to increase and new approaches and technologies to resolve composite end of life problems started to be developed. The increased use of composites is driven by weight reduction, reduction in the number of components, reduced maintenance costs and potential improvements in fatigue behaviour. It has been suggested that by 2020, the use of composites will give production aircraft of that date a fuel burn advantage of between 10% and 15% over their year 2000 counterparts. This advantage obviously makes all efforts to achieve better efficiencies in composite materials recycling a cost-effective target.

The land-filling of waste or end of life composites is no longer a commercially viable option as various European directives are forcing manufacturers and suppliers to accept responsibility for recycling EoL wastes. These directives include:

a. Council Directive, 1999/31/EC on landfill waste

b. Council Directive, 2000/76/EC on incineration of waste

c. Waste framework directive, 75/442/EEC

d. List of waste, (LoW) 94/3/EG

e. Hazardous waste directive, 91/689/EEC

f. Harmonisation of waste reduction programmes directive, 92/112/EEC

g. Shipment of waste directive, 120/97/EC

h. Municipal waste incineration directive, 89/369/EEC and 89/429/EEC

i. Harmonisation list of waste, com.dec.2000/532/EC

In Europe approximately 150.000 tonnes of new fibre reinforced plastics are used in a year.

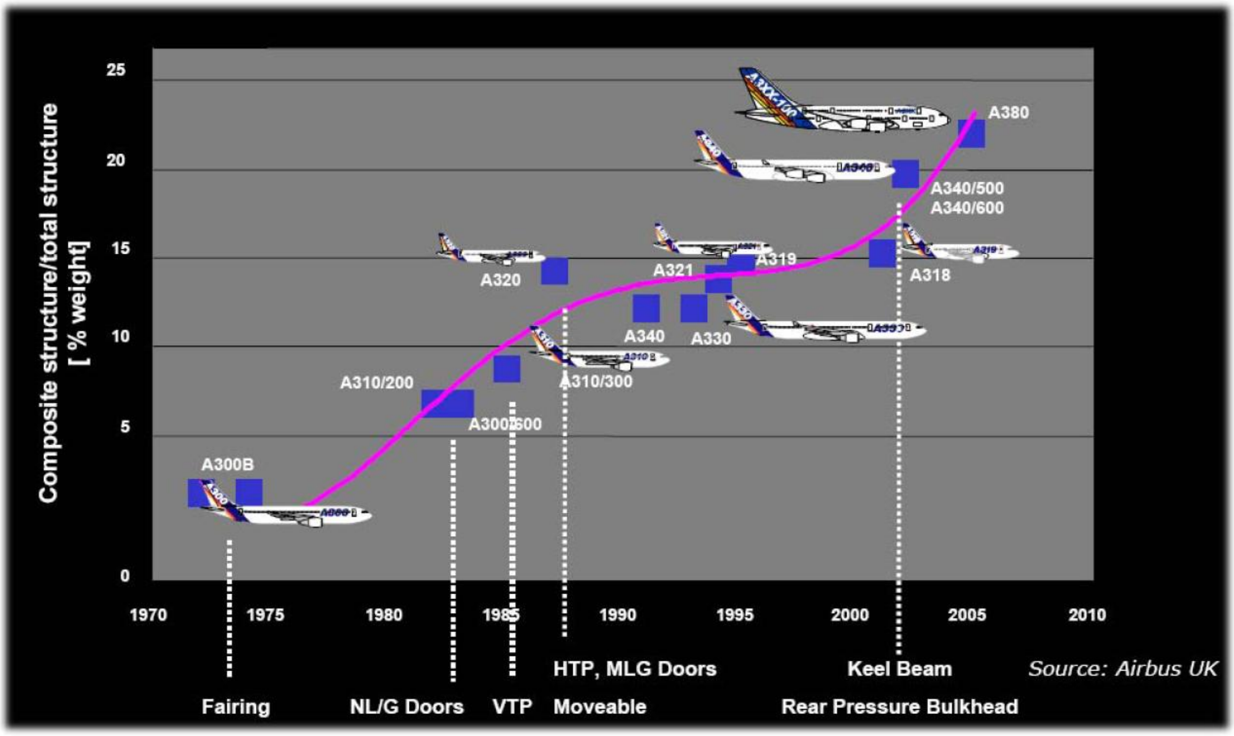


Figure 2-45: Increasing Use of Composites in Airbus Aircraft

The Figure 2-45 above, shows the increasing use of composites in Airbus aircraft with the early A300 model utilizing less than 5% while the new A380 comprising in excess of 20%. The upper fuselage section and horizontal tail section of the A380 super-jumbo is manufactured from the GLARE (a glass fibre and aluminium composite) material. One of the major reasons that GLARE was chosen is its resistance to fatigue crack growth and a density reduction of 10%

compared to conventional aluminium alloys. Carbon fibre reinforced plastic (CFRP) composite is also used widely, for example for the central wing box and in parts of the fuselage. The vertical fin box, rudder and elevators, the upper-deck floor beams and rear pressure bulkhead are also made from CFRP composite.

After an extensive flight test program, in April 2012 the Boeing 787 (also known as 7E7 Dreamliner) entered the commercial market with first official deliveries to Japan. It is a smaller aircraft than the A380 and is designed to carry approximately 300 passengers. The B787 materials design is based substantially on carbon fibres in an epoxy resin matrix for the fuselage and a composite wing. New production techniques have been developed and applied to produce the composite fuselage, including composite fuselage sections 6.7m long and nearly 6m wide, as shown in Figure 2-46.

The 787 forward fuselage composite barrel autoclave at Kawasaki, Nagoya, Japan. Source: James Wallace/Seattle Post-Intelligencer

A cured 787 fuselage barrel section

Figure 2-46: Some of the Composite Technology Developed for the Boeing 787 Fuselage

Approximately 50% of the unladen weight of the Boeing 787 comprises of composites, as shown in Figure 2-47; with its composite fuselage and wings, and with its advanced engines and systems, provides 16 percent better fuel economy and 16 percent lower carbon emissions, generates a 30 percent smaller noise footprint than the 747-400 and is expected to have the lowest seat-mile cost of any large commercial jetliner. Other civil aerospace uses of composites include the rapidly growing business jet market, such as the business jet shown in Figure 2-47.

Composite use in the Boeing 787 Honda Business Jet with Carbon Composite Fuselage

Figure 2-47: Usage of Composite Materials in Aircrafts

The business jet market is expected to require over the next 20 years up to 24.000 new jets, very light jets through business jetliners and all are expected to contain significant amounts of composites in their construction. For example the fuselage of the Honda business jet in Figure 2-47 is 100% carbon fibre reinforced composite.

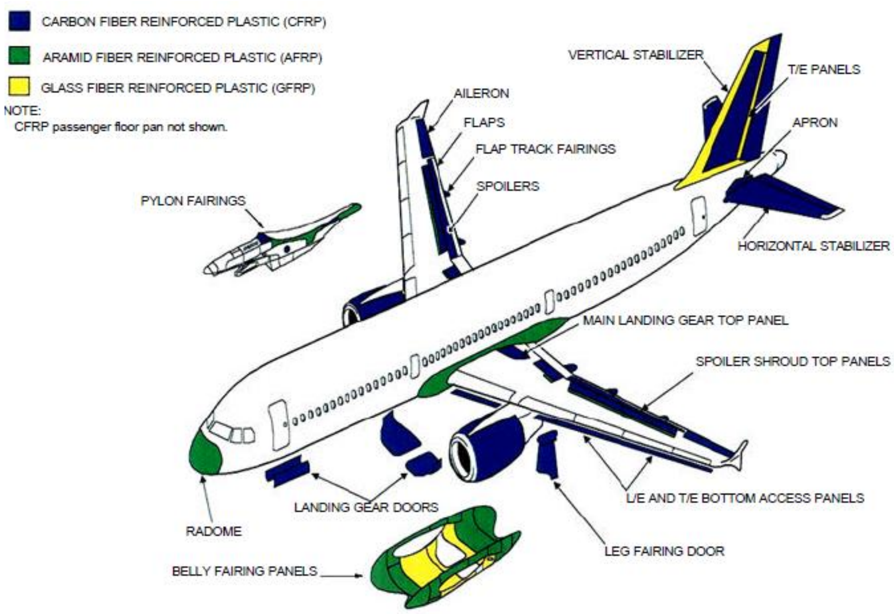


Figure 2-48: Aircraft Composite Materials and Component Location (Boeing 777-200)

Rotary aircraft, military aircraft (rotary, trainers, fighters, bombers and transports) and Remotely Piloted Airplanes of all types contain significant amounts of composites and the proportion of composites in these types is expected to continue to rise.

From a materials' technology standpoint, for many years, composites manufactured using thermosetting resins were considered to be non-recyclable, and some sectors of the plastics industry still consider this to be the case. Also, because disposal by land-fill was an easy and cheap option when the products were conceived, recycling did not need to figure highly in user and producer thinking. In the early 1990s, some companies in the thermosetting sector began to recognise that market pressures were demanding that these materials should be recycled or recovered rather than being land-filled upon completion of their life cycle. These factors, combined with user and public awareness, also with increased landfill charges, resulted in increasing efforts to find commercially viable routes to recycling composites using thermosetting resins.

There are now a number of European funded research projects looking to develop commercially viable routes to recovering carbon fibres from thermoset composites such as the work undertaken at INASMET Tecnalia in Spain. This work investigated three potential recycling techniques: (a) a nitric acid treatment to dissolve/remove the thermoset resin, (b) thermal pyrolysis and (c) an incineration process. The conclusion of this work was that, on environmental grounds, only the pyrolysis technique should be considered on the large scale, and that the quality of the recovered carbon fibre residue was sufficiently high that the fibres should be considered for re-use. A major airframe manufacturer has suggested that recovered carbon fibre from one particular pyrolysis process was of sufficient quality that it could potentially be used in other aerospace applications.

Studies on composite recycling have also taken place at Nottingham University, UK in collaboration with Milled Carbon Ltd. Milled Carbon have developed a pyrolytic process that can continuously recycle cured and uncured carbon fibre composite parts of up to 2 meters wide, 250 mm in height and thicknesses up to 25mm. The technique was also discussed in some previous paragraphs and is applicable to manufacturing off-cuts or unused rolls of pre-impregnated material, as well as formed parts.

An alternative process for the recovery of carbon fibre from composites uses a low temperature liquid process that digests the organic resin leaving the fibres intact, and is being developed by Adherent Technologies in the USA. This process involves the use of a highly acidic medium to digest the organic polymer matrix and was also discussed in some previous paragraphs .

Even if reusing recovered fibres or in aerospace applications is not possible, there are other potential uses in the automotive, construction and marine sectors. Currently carbon fibre containing composite manufacturing waste of end of life material places a disposal cost on the responsible organisation. Any technologies that could reduce this cost, or in the best case scenario, convert the financial drain associated with composite “waste” material into a valuable material resource, will find rapid commercial application. This would stimulate the recycling and re-use of composites independently of any legislative drivers. The economics of such an approach at the current time are particularly favourable since the rapid uptake of composites is leading to; high prices for newly produced carbon fibre and some restriction in availability.

2.5.4.2 CABIN INTERIORS

How to deal with cabin interiors at upgrade and EoL is a concern for both the airframe disposal companies and the operating airlines. Cabin furnishings are made up of a range of materials that are mostly plastic or composites based on polymers, and are often intimately inter-mixed. Currently the only option is to send these fittings to landfill, but as already stated, this is an increasingly expensive option.

Figure 2-49: The Cabin of a Boeing 757 During Parting-Out

As it is necessary to remove cabin components by hand, some degree of sorting can potentially be carried out at the time of removal, this is very different from the automotive sector. During any year, a major established airline with a fleet of 250 or so aircraft may have as many as 25 aircraft undergoing cabin upgrading or complete refurbishment. This represents several hundred tonnes of material.

What to do with retired the cabin interiors is also a problem for airlines when they schedule cabin improvements and upgrades. The cabin fittings for a Boeing 737 weigh about 5 tonnes and those for a Boeing 747 approximately 10 tonnes. Typically an airline such as British Airways will schedule a cabin maintenance programme after 4 to 5 years in service and a full cabin upgrade (complete replacement) every 10 years. For an airline with more than 250 aircraft, cabin disposal will become an increasingly important issue. Some of the challenges here include:

a. Efficient separation of organic materials from metallic and composite materials.

b. Identification of the different classes of material, metals and non-metals.

c. Developing efficient and commercially viable re-processing technologies.

d. Finding suitably high value markets for the recovered materials.

2.5.4.3 METAL SEPARATION TECHNOLOGIES

Having removed high value components and materials from an airframe the remainder is broken up into small pieces and sent to a metal smelter for processing. Because of the mixed nature of this feedstock its value is low. However, many of the alloys and materials comprising this feedstock have significant value if they could be readily separated into purer materials streams.

This can be achieved to some extent. EMR Ltd (European Metals Recycling Ltd) use standard technology to separate out ferrous and non-ferrous metals and then use a series of floatation chambers to separate out metals having significant density differences. Further metal differentiation is undertaken using laser-sorting technology.

However, in order for recovered metals such as aerospace grade aluminium alloys to regain entry into a high value supply chain, further automatic sorting into something approaching alloy types is needed. In addition, recovery of copper from the extensive cabling within an airframe would add value to the total materials recovered during the parting-out process.

2.5.4.4 REPLACEMENT TECHNOLOGIES FOR TOXIC METALS AND COATINGS

Current environmental legislation restricting the use of toxic metals in the manufacturing and automotive sectors is making the continued utilisation of metals such as lead, cadmium and hexavalent chromium increasingly problematic for other sectors. In the aerospace sector, attempts to find replacement technologies have not met with widespread success. Although the aerospace sector is largely exempt from some of these directives related to products on safety grounds, it is inevitable that eventually the aerospace sector will have to comply similarly; either through new targeted legislation, because of public pressure, or because since the aerospace sector represents typically <1% of the global market by value, the materials may cease to be widely available as the supply chain adopts other solutions. Of particular concern to the aerospace sector is any ban on the use of Hexavalent Cromium (Cr(VI)), Cadmium (Cd) and Lead (Pb) since underpinning understanding in and commercial confidence of alternatives does not exist. While considerable research into Cr(VI), Cd and Pb replacements has been conducted in a variety of commercial fields, these studies often do not have relevance for aerospace applications; where aerospace-related studies exist, they generally fail to provide sufficiently compelling performance to justify the costs of component re-qualification for airworthy use.

The ELV directive for the automotive sector came into effect on July 1st 2003 and one of its provisions restricts the content of Cr(VI) in corrosion preventing coatings from July 1st 2007 onwards to a maximum of 0.1% (w/w) per homogeneous material. The WEEE directive imposes responsibility on manufacturers for the disposal or recycling of their electrical or electronic equipment, although WEEE is currently only applicable to consumer goods. The US is introducing “RoHS-equivalency” (Restriction of Hazardous Substances equivalency) measures, for example in California where it is now prohibited to manufacture electrical/electronic goods that could not be sold in the EU. Unofficial notes of the RoHS Technical Adaptation Committee (TAC) proposed maximum concentration values of Pb = 0.1%, Cd = 0.01%, and Cr(VI) = 0.1% by weight in finished goods. Although the EU Commission’s Legal Services have suggested an RoHS exemption for Cr(VI), Cd and Pb (as well as others) in electrical equipment for the Aerospace Industry, the onus has been placed on the producer to supply all necessary independent scientific evidence to support a specific exemption application on safety grounds.

Hexavalent Cromium (Cr(VI)) containing processes are applied to the overwhelming majority of Al-based (aluminium based) aerospace components, including the airframe, wings and ancillary honeycomb panels, and are also used to protect electrical and electronic components. The three main uses of Cr(VI) are in Chromic Acid Anodising (CAA) processes, chromate conversion coating (CCC) processes, and as strontium chromate primer (SCP) in bonding applications. SCP replacement is currently the focus of research by major adhesive manufacturers. In 2005, Boeing stated that replacing Cr(VI) in the above processes is one of the key aims of their Pollution Prevention (P2) Group. The Joint Group on Pollution Prevention (JGPP, USA) recently initiated a Joint Test Protocol (JTP) on Cr(VI) avoidance for defence and aerospace platforms. In Europe, there have been a series a consortium based R&D projects addressing these same issues. All of the above projects have focussed on screening and evaluating existing technologies developed elsewhere rather than developing new processes.

Cadmium (Cd) coatings are routinely used on aircraft for the corrosion protection of vast numbers of fasteners, electrical components and electrical connectors. There is general consensus that there is no single replacement for Cd that fulfils all of its inherent properties/functions: barrier protection against corrosion; sacrificial protection on ferrous substrates; galvanic compatibility with Al and its alloys; good surface lubricity; low volume corrosion products; low electrical resistance; and a solderable surface.

Lead (Pb) is used extensively in Pb-based solders for electrical connections on printed circuit boards and printed wiring boards. Pb-free solder is the most commercially advanced of the toxic metal replacement problems investigated here, and commercial products are available. However, commercial Pb-free products have been developed for non-aerospace sectors and are of limited use in understanding / predicting lifetimes in the much harsher aerospace environment, where there are more severe combined effects of creep during thermal cycling, mixed frequency vibrations, higher and/or lower service temperatures and extreme temperature differences. A key concern of the aerospace sector (and all other sectors) is interconnections reliability. Fully numerical as well as empirical and semi-empirical approaches based on Coffin-Manson fatigue correlations are used generally to understand/predict solder joint lifetime but lack sophistication to account for the harsher aerospace environment. A particular concern is that as Pb-free is adopted everywhere in mass market electronics, there is no Pb-free drop in replacement for Pb containing solders for the harsher aerospace environment. The most popular tin-silver-copper (SnAgCu or SAC) alloys that are drop in replacements in domestic electronics suffer from slow stress relieve (slower creep) under wide temperature fluctuations in aerospace environments, hence thermal mismatch strains are retained, and leading to premature failure.

Therefore in the area of these three toxic metals, the sustainable materials community faces major tasks to identify new material solutions that offer the – probably unmatchable – performance of incumbent solutions. While the timetable for the emergence of such solutions is unclear and despite the lack of penetration of R&D to date, new ideas for toxic metal replacements should remain on the sustainable materials roadmap.

2.5.4.5 MATERIALS IDENTIFICATION TAGS

The development of embedded material identification tags would be highly beneficial to the aircraft scrapping sector. Although material tagging is not new, it is widely used in the polymer sector; there are potential issues when applied to safety critical components. In the case of turbine blades any, tagging would have to have no negative impact on the safe and reliable operation of the blade during use. Bar coding has been used in the steel industry however, here the codes are often on attached plates rather than on the material itself. This would not be possible in the case of a turbine blade, although it may well be applicable on other metallic components. Such a tagging scheme should allow materials to be separated into higher value feedstock streams.

2.5.5 DfD IN HELLENIC AEROSPACE INDUSTRY

In Greece the Aerospace Industry is represented at country level by the Hellenic Aerospace Industry (HAI S.A.), founded in 1975. HAI S.A. is the strongest public company in the defense and aerospace industries with significant technological potential in many sectors and strong presence in international markets. The company today, represents one of the leading providers of highly competitive and efficient services in the areas of:

a. Aircraft, engines, accessories and avionics maintenance (repair, overhaul, modifications, modernizations, upgrade, life extensions and logistics support).

b. Design, development, manufacturing, and after sales support of electronic, optoelectronic and telecommunication products.

c. Knowledge-centric integrated solutions in the field of Tactical Communication Networks, Command and Control Systems, Electronic Warfare and Security Systems.

d. Co-development and co-production of weapon systems.

e. Design and manufacturing of aircraft subassemblies and engine parts from metallic and composite materials.

f. Satellite systems and applications including the development of a satellite system network and the related telecommunications, observation and navigation applications.

g. Research and Development in the aeronautical sector.

h. Technical training which covers a wide spectrum of Aerospace Industry disciplines.

i. Composite materials parts, manufacturing for aircraft and helicopters (carbon fiber, fiberglass, etc).

j. Participation in European Satellite Programme for ESA (European Space Agency).

k. Partipation in the multinational nEUROn Program for the European Unmanned Combat Air Vehicle (remotely piloted airplane).

Some major Projects of HAI S.A. with strategic business partners are:

a. F-16 aircraft Air Inlets, Engine Access Cover (LM Aero)*

b. F-16 aircraft Aft Fuselage, F1 Fuel Tank, and Side Panels (LM Aero)*

c. C-130J aircraft Plug and Mid Panels (LM Aero)*

d. A300 and A310 aircraft Passenger Door Frames (Aerolia)*

e. A319/A320/A321 aircraft Cargo Door Frames (Aerolia)*

f. A330/340 aircraft Framework Lower Shell (Premium Aerotech)*

g. Boeing B787 aircraft Cargo Door Surround (Boeing)

h. C-27J Loading Ramp and Cargo Door (Alenia)*

i. Falcon 900EX aircraft Fuel Tanks (Dassault)*

j. Falcon 900 and 2000 aircraft Baggage and Emergency Doors (Dassault)

k. Eurofighter Supersonic Fuel Tank Parts (EADS Eurofighter)

l. T-6A Rib Assemblies (Hawker Beechcraft)

m. UH-60 Black Hawk Side Panels

n. CESAR Program for the design of a 15-seated aircraft

o. Design of “green regional aircraft”

p. Development of environmental-friendly materials and procedures (Eco Design) to manufacture aircrafts

(*) HAI S.A. is sole source supplier

Figure 2-50: Propulsion Systems Divison in HAI S.A.

HAI S.A. cooperates with about 240 Greek and 88 international companies in the market. The international affiliates include companies like Airbus France, Dassault, EADS, Lockheed Martin, Raytheon, SNECMA, Boeing, General Electric and for this reason, due to the need for high standardization and competitiveness, HAI has developed “center of excellence” efforts and activites to independently design new products.

After communication with senior HAI S.A. representatives, it was found that this industry has no DfD applications and policies for the products it designs.

Added to this, other top-notch technology industries in Greece activate in areas of aerospace electronics (out of scope of this dissertation) or execute sub-contractor work which does not include design of new products. Therefore, it can be noted that in Greece, the DfD for aerospace products is a new area for consideration.

2.6 DISASSEMBLY TECHNIQUES FOR AEROSPACE PRODUCTS

2.6.1 SCOPE OF DfD APPLICATION

When a fleet is modernized, disassembling an aircraft offers possibilities to acquire higher revenues than other options. The disassembly option should therefore always be part of any fleet management decision.

The technological life of an aircraft is unlimited, since as long as there are spare parts available, an aircraft can be kept airworthy. However the economical life of an aircraft is not unlimited. Maintenance cost will increase when an aircraft becomes older and new aircraft with newer technology have higher passenger comfort and lower utilization cost, such as fuel and maintenance cost. Thus, when an aircraft has reached the end of its economical life, it will be withdrawn from service. For an aircraft, which is (or will be) withdrawn from active service, a solution needs to be determined. In respect of that, two possible strategies for such an aircraft can be:

a. Selling the complete aircraft directly after the last flight or after a period of parking;

b. Disassembling the aircraft, selling or re-using the still valuable components and recycle the leftovers.

In the second strategy which relates to this dissertation, the revenues for that option must be firstly determined and then the disassembly must be executed together with other required activities in a quick, efficient and environmental friendly manner, sustaining the owner's corporate values towards the end. Therefore, the option of aircraft disassembly should be part of each fleet management decision, as an aircraft is not only a revenue generating asset but also a collection of valuable components and materials. Disassembling an aircraft can deliver higher revenues than selling the complete aircraft directly or after a period of parking. Making the decision between disassembly and selling the aircraft depends on many factors. Some elements that can influence this trade-off between selling and disassembling are:

a. **Parking:** Parking an aircraft is more expensive than one might think. Next to a parking fee the total cost of parking will consist of several other elements, like, the cost of the flight to the parking location, the cost of preparing the aircraft for long-term parking, the cost of the maintenance program during parking, the cost of ownership, which is the highest cost element.

b. **Corporate values:** A company's values are shown in many ways, like the way they operate their business, the way they behave towards the environment and the way their personnel behaves. The way their customers perceive the company, their corporate identity, highly depends on these values. A good End-Of-Life strategy will generate positive "green" publicity, whereas, a wrong End-Of-Life strategy can damage the company's identity, which is a much bigger negative effect than only less revenue for the specific aircraft. For example, a parked aircraft with their colours, bad maintenance on their old aircraft flying for another operator and bad disposal of an aircraft no longer in their possession but still with the company identity, will negatively impact the identity. On the other hand, disassembling an old aircraft will show that a company are modernising their fleet and this will probably generate special attention for their new aircraft. Disassembling old aircraft is also a good sign that a company takes global warming seriously, as not only they use the newest aircraft with the lowest CO_2 emission, but they also make sure that the problem maker, the old aircraft, is not creating any CO_2 on another location in the world.

c. **Current fleet:** Most airliners operate more than one aircraft per type and use the oldest aircrafts of the total fleet to get parts (cheaper than buying them from the market) and maintain the still operational aircrafts. In such a way they reduce cash-out and they use their own components whose historical and reliability data is known.

d. **Sales potential:** Disassembling one aircraft will also increase the sales potential of other aircrafts. Adding a batch of components in the complete sales option will increase the attractiveness of company's other aircrafts on the market, but also may prolong executing maintenance business on that aircraft type, to other outside customers.

To support such a decision making process, some kind of EoL Decision criteria model is needed to be established. Such a model could be combined with aviation market data and the result could possibly be managed, adjusted, updated and sorted to make a solid, reliable and complete End-Of-Life analysis possible. However, as a first step, retireability and disassembleability could be used (based on historical facts) as two higher level statistical indicators, which combined, can form the so-called Aircraft End-of-Life Status (AELS) of the aircraft.

e. **Retireability:** A retired aircraft is an aircraft which is removed from operational service. AELS has at its disposal information on retirement of individual aircraft when they were retired. The aircraft status is determined by 3 characteristics: the age of the aircraft, the amount of flying hours (TSN = Time Since New) and the amount of cycles (CSN = Cycles Since New). A further division of the data is made between regional jets, narrow body jets and wide body jets. The information on a specific aircraft is compared to these historical facts. The percentage shows the amount of aircraft that had a "younger" aircraft status, when retired. A retireability of 0% means that no aircraft were retired with similar or less characteristics. A retireability of 100% shows that all aircraft in the past have been younger in age, had fewer cycles and less flying hours when retired.

f. **Disassembleability:** Every now and then an aircraft is actively taken of the market for spare parts. This active removal from the market is analyzed in the same way as the 3 characteristics retireability consists of. A disassembleablity of 0% means that no aircraft have been actively disassembled with the characteristics of the aircraft investigated. When this value is 100% each aircraft that was disassembled actively had a lower age, less flying hours and less cycles.

g. **End-of-Life Status:** The two numbers (retireability and disassembleability) combined indicate if the disassembly of a specific airframe should be investigated further. Several (normally five(5)) different End-of-Life Status (ELS) can be defined, each reflecting another approach towards the investigation of the disassembly value.

This dissertation focused on the side of the revenues that can be achieved by selling or re-using the parts on the aircraft and the detailed information that can be produced to support this decision.

2.6.2 CRITERIA TO GUIDE DISASSEMBLY OF AEROSPACE PRODUCTS

Safely sustaining the ever-increasing numbers of aging aircraft in the United States Air Force (USAF) has brought an ever-increasing requirement to determine the true condition of service-aged aircraft structural components. The only means available to precisely determine the damage state of a given structure is by what is commonly referred to as a “teardown inspection” of that structure. Many such programs have been conducted by operators of both military and civil aircraft fleets. Programs have ranged from complete teardown of a given structural component to teardown of all major structural elements in a single aircraft or even the same elements in several aircraft. Teardown analysis program (TAP) reports yield valuable data for aircraft fleet managers. However, cross-platform sharing of successful teardown procedures and other lessons learned is often lacking. Recently, The Technical Cooperation Program (TTCP) between the Governments of Australia, New Zealand, Canada, United Kingdom and United States published a handbook to document best practices for aircraft teardown programs. The TTCP handbook focused on policy decisions and other programmatic issues as they applied to the international military and civil community. However, the procedures and requirements to be considered during each task of a teardown program were not addressed in great detail in the TTCP handbook.

For this reason, the USAF Academy’s Center for Aircraft Structural Life Extension (CAStLE), documented task-by-task procedures for planning and executing a teardown program and wherever possible capture lessons learned from past programs. This effort was based on more than two dozen teardown programs’ reports which were received and analyzed from Ogden and Tinker USAF Air Logistics Centers (ALC) as well as the U.S. Navy, U.S. Coast Guard, Delta Airlines and Federal Aviation Administration (FAA).

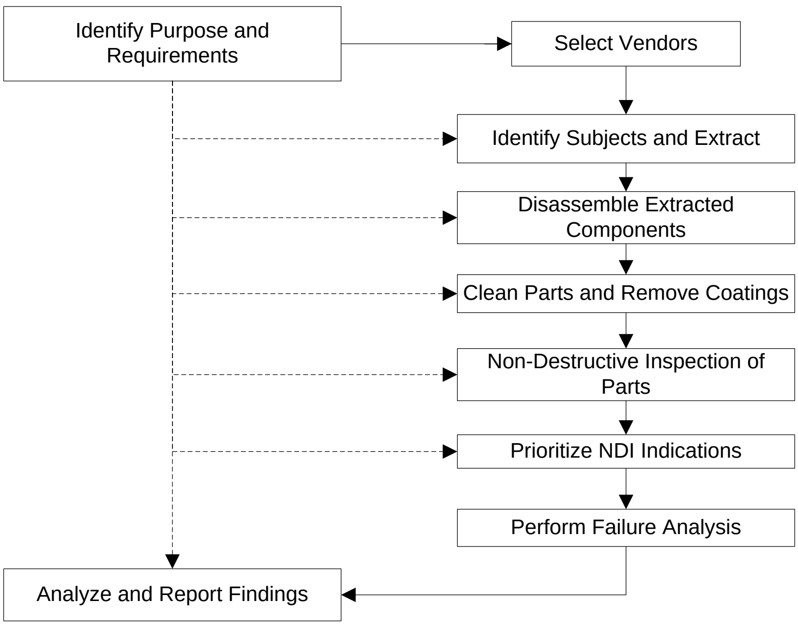


Figure 2-51: Typical Teardown Program Task Flow

The resulting teardown best practices handbook was published in early 2008 as “USAFA TR-2008-02, Procedures for Aircraft Structural Teardown Analysis” but has become informally known by its acronym PASTA. The chapters of PASTA are organized in order of task accomplishment during the execution of an aircraft structural TAP. The Figure 2-51 illustrates the flow of these tasks in a typical program. Typical teardown program task flow is shown by the solid line. The dashed line indicates the inter-dependence of the first task on all tasks which follow.

The basic chapters of PASTA are refered in the following paragraphs (for more details, the cited document (21) should be read):

1. **Identify Purpose and Requirements**: These issues set the tone for the entire teardown program and will therefore govern the level of detail for each program task.

    a. Identify the Purpose: After considering a number of economic and life cycle issues that could drive a program manager to consider some level of a teardown program and after the decision to proceed into teardown, the first two technical reasons for conducting a are mandated by the USAF Aircraft Structural Integrity Program (ASIP) Standard. These two reasons are (a) an assessment of damage state be conducted at the conclusion of full scale durability and damage tolerance testing and (b) a condition assessment after known usage if the aircraft is expected to operate beyond its service life or when it is suspected that service damage may jeopardize the aircraft’s structural integrity. A further reason to conduct a teardown is to validate non-destructive inspection (NDI) procedures.

    b. Required Fidelity of Findings: the most important decisions to be made in any teardown program are what type of findings will the program be focusing upon and what degree of fidelity will be required in these findings. It is vital that these decisions be made at the very onset of the TAP as it will drive all program tasks and impact the budget and the schedule. It is important to ensure that this decision is based upon what is “required” rather than what is “desired”. The required fidelity must be tied back to the purpose of the teardown program.

    c. Other Considerations: The program must establish what will be needed for analysis and for long term archival. Most current programs opt to electronically retain all data generated given the availability of database systems. Databases may be used for program management such as tracking teardown subjects or task progress as well as providing easy access to analysis results. Consequently, the database must be designed to permit easy access to any stored data required to satisfy program requirements. Databases may be used for program management such as tracking teardown subjects or task progress as well as providing easy access to analysis results. A further consideration of any teardown program management team is that any organization seeking to undertake a new teardown should have access to other organizations with teardown experience

2. **Select Vendors**: The vendor selection strategy depends upon the scope and timeline of the program.

a. Past Experience: Improper disassembly, cleaning, coating removal, polishing, and crack opening are just a few examples of tasks which, when performed improperly, can result in the loss of one of a kind data with no way to recover. For this reason, potential vendors considered for teardown program tasks must demonstrate previous success in conducting work of a similar nature.

b. Facilities and Equipment: vendors must have the appropriate facilities, tools, instrumentation and analytical equipment.

c. Qualifications and Certifications: recognized certifications are applicable to demonstrate the qualifications of vendors seeking to execute teardown program tasks.

d. Proficiency and Constancy: Given the criticality of each teardown task, vendors should be expected to demonstrate their proficiency. Furthermore, all program managers should include periodic performance audits of all their vendor program participants.

e. Cost: Cost will always be considered in the final vendor selection. However, it must not become the primary consideration. The quality of the resulting analysis is paramount and must not be compromised merely by selection of the lowest bidder. Therefore, it is imperative that selection criteria are written such that unqualified or even marginally qualified vendors are identified and eliminated during the selection process.

3. **Identify Teardown Subjects And Extract**: Teardown subjects are both the components removed from the aircraft for teardown analysis as well as the aircraft from which they are extracted.

a. Known Service History:

(1) Operational hours, Cycles and Missions: If the primary interest of the program is fatigue cracking then the relevant service history is stress spectra which would result in damage. Such service history is not to be confused with simple total flight hours. Fatigue relevant history requires more detail depending upon the structure being evaluated. Fatigue cracking in wing structure would require stress spectra at the point of evaluation.

(2) Calendar Time and Environment: In contrast to fatigue damage which depends on cyclic application of load, most corrosion damage mechanisms only require the presence of a corrosive environment over a period of time. The period of time is measured from the original manufacture of the teardown subject parts to the time of the teardown analysis.

(3) Repair History: A thorough review of repair history is required to fully understand any potential teardown subjects. Repair history represents an essential element of service history which must not be overlooked. If the program objective is to evaluate

high time components, then it follows that the service history of the individual components should meet that requirement.

(4) Extract Teardown Subjects: After the subject aircraft has been selected for a teardown program the next task is to remove the components which constitute the focus of the program. A key consideration in the extraction of teardown program subjects is to avoid inducing incidental damage by the extraction process itself. For smaller aircraft, sub-assemblies may be extracted directly from the airframe with minimal special provisions. Larger airframes, such as transports and military bombers, require additional considerations. In such structure, the weight involved with the individual extracted components, as well as the dependency of one section of structure to support the weight of another, requires significant preparation prior to any sub-sectioning and component extraction. In these cases, the aircraft original equipment manufacturer (OEM) is often a useful resource to provide component weight data, support requirements and plans to stabilize the remaining structure as component assemblies are removed. Support and stabilization requirements often dictate the order in which component assemblies are removed from a given teardown aircraft. For example, if the stabilization plan makes use of the main landing gear structure then it follows that structure near the landing gear will be the last region extracted from the subject aircraft. Figure 2-52 shows an example of extracting major assemblies from a KC-135R beginning with the empennage and working progressively closer to the main landing gear structure. Prior to making any of the section cuts, a detailed cut plan should be developed and approved by the program manager. This plan not only includes the aforementioned stabilization requirements but ensures the inclusion of all teardown subjects. Considerations when defining section cuts include:

(a) Provisions for handling of removed sections in terms of size and weight.

(b) Cuts made sufficiently far away from teardown subject locations so that the cutting process prevents incidental damage to the subjects themselves.

(c) Minimizing cutting required through complex, thick or otherwise difficult structure.

(d) Combining a number of teardown program subjects included into one assembly to maximize removal efficiency.

(e) Preserving remaining structure for potential follow-on programs.

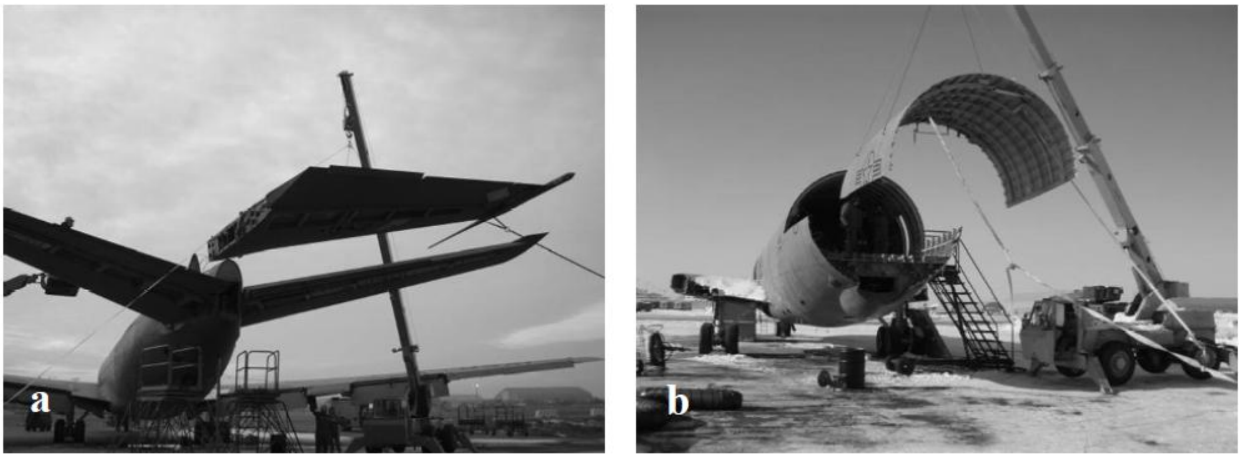


Figure 2-52: Extraction of Major Assemblies from a KC-135R

(Extraction of major assemblies from a KC-135R beginning with a) the removal of the vertical tail and b) progressing towards the main landing gear (Tinker AFB image)).

4. **Disassembly**: After component assembly (with their teardown program subjects) extraction, the process begins to execute the program evaluation requirements.

   a. Disassembly Requirements: Component disassembly for teardown programs differs from that of aircraft maintenance, in that joined parts must be separated from one another without inducing damage to the joined parts themselves. When fasteners are removed during structural maintenance operations, it is customary to oversize or in some way refinish the bore of the fastener hole, to prepare for fastener replacement. In contrast, for structural teardown analysis, the hole bores are often primary targets of the investigation; preserving the condition of the hole bore while removing the fastener is of paramount importance. Any damage induced during the disassembly process will create the extra task of distinguishing that damage from the operational damage data sought by the program. Since disassembly results in the creation of separate parts and the exposure of many faying surfaces, part identification, tracking and documentation take on additional importance during this task.

   b. Disassembly Tasks:

      (1) **Component Photo Documentation and Teardown Subject Part Identification**:

         (a) Before beginning the disassembly of an extracted component, the teardown subject parts must be identified. Since the precision fastener removal procedures described in the disassembly chapter of PASTA are designed to minimize damage to joined parts, it is important to identify the parts which require the most attention. If a program subject part is attached to a non program subject part, then this information will guide the disassembly technician's selection of tools and their application. Figure 2-53a contains a single teardown subject part. Figure

2-53b shows the wing carry-through fitting after disassembly. By knowing this information beforehand, the disassembly technicians could focus their efforts on efficiently preventing incidental disassembly damage to the critical component while not wasting effort on non critical scrap parts.

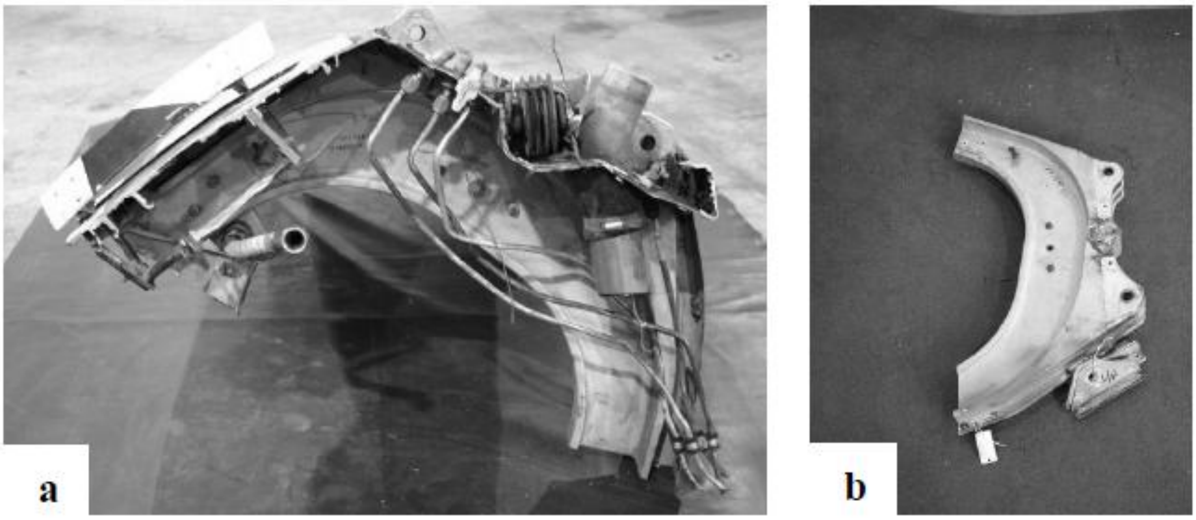


Figure 2-53: Images from T-37B Teardown Program

(Images from T-37B teardown program showing a) component assembly as removed from the aircraft and b) the teardown subject part after disassembly from surrounding structure (CAStLE image))

(b) Prior to disassembly, the inspection requirements for each teardown subject part should have been identified based upon the program requirements. This step ensures all parts are properly tracked throughout the subsequent program tasks. Accordingly, upon disassembly each program part should be tracked with a parts log of appropriate identifying data. Some examples of information which should be recorded in the part tracking log are as follows:

1/ Assembly identification

2/ Part identification

3/ Part nomenclature

4/ Inspection requirements

5/ Assembly photograph identification information

6/ Part photograph identification information

7/ Visual inspection observation and disassembly notes

(c) To aid accountability of disassembled parts, all program subject parts should be identified via part engraving or affixed tag. It is essential that the identification system be designed to survive all subsequent program tasks. Coating removal, described in the next section, puts the highest demands on identification system survivability. Past programs have had success with aluminum or stainless steel tags affixed by an aluminum or stainless steel wire.

(2) **Fastener Removal**. Several aircraft specific and general USAF maintenance documents provide guidance for performing fastener removal in aircraft structure. The development of this chapter of the teardown best practice began with this guidance but emphasizes practices which are essential for teardown programs. The resulting PASTA disassembly chapter is too detailed for inclusion in this work. However, the following points summarize the philosophies used in the disassembly chapter to ensure the highest precision during fastener removal and to minimize incidental damage.

(a) Ensure the work surface provides adequate stability while working on the part.

(b) Ensure adequate lighting exists to identify the important feature of each fastener.

(c) Teardown subject parts should be secured while removing fasteners such that the:

1/ Part will not move.

2/ Clamping system will not induce damage to critical areas of the part.

3/ Regions of the part around the fastener hole are backed up with thicker structure to prevent deformation. (This is particularly important for thin structure.)

(d) Removal techniques must emphasize preservation of the surface of the fastener hole bore:

1/ Removal tools must not contact the hole bore or countersink surface.

2/ Fasteners should not spin during the removal process.

(3) **Incidental Damage Reporting.** It is imperative that incidental damage be reported and tracked in any teardown program. These damage reports should be reviewed by program leadership in order to judge the impact on remaining program tasks. A history of incidental damage severity and frequency can also serve as a valuable tool to monitor vendor performance. It is also important that reports of damage reach the program technical management as soon as possible after the incident occurs. Overly frequent or severe instances may require retraining of that vendor's disassembly technicians or in extreme cases reassignment of the remaining work. Reports of in-

cidental damage should include, at minimum, the location, type, extent and cause of the damage as well as a detailed photographic record. The location should be given in terms of part number and aircraft coordinates to include any program specific location categories, such as a hole number scheme. If the location is near a fastener hole, it is important to note whether the damage is on the surface or in the fastener hole bore. The extent should be noted in terms of size and orientation if applicable. The photographic record must be sufficient to fully define the damage type, extent and location on the part or assembly.

5. **Clean Parts And Remove Coatings**: Upon disassembly of all extracted assemblies which contain teardown subject parts into those component parts, the parts must be prepared for NDI. The level of cleaning required, as well as which features must be cleaned is entirely dependent upon the TAP's NDI requirements.

   a. Initial Cleaning and Sealant Removal: To properly prepare a subject part for initial visual inspections and damage photographic documentation, the surfaces should be cleaned to remove all loose grease, sealant, dirt and particles. Specific guidance for cleaning can be found in USAF's Technical Order (TO) 1-1-691, Aircraft Weapons Systems Cleaning and Corrosion Control, Appendix E-2 and E-3. Remove sealants with sharp plastic scrapers or other removal tools that will not scratch or otherwise damage the substrate surfaces. Metallic tools should not be used. Chemicals that can assist in this task suggested by TO 1-1-691 are listed in this chapter along with their application.

      (1) Coating Removal: To complete surface preparation for NDI using methods such as close-visual, fluorescent penetrant and eddy-current inspections, it is important that all coatings be removed from parts after the initial visual inspections. There are two general categories of coating removal processes: chemical removal and media removal. It is critical to select and implement coating removal processes that:

         (a) Thoroughly remove all surface coatings.

         (b) Result in a chemically clean substrate surfaces without residues, providing optimum surface conditions for subsequent inspections.

         (c) Do not attack the substrate materials and therefore preserve fractographic evidence.

      (2) Chemical Removal. Chemical stripping is the method of choice for removal of sealant, topcoat and primer, as these processes result in chemically clean surfaces which are optimum for accepting penetrant inspection. Because of the environmental concerns related to hazardous materials handling and waste disposal, particularly when removing chromated coatings, the use of chemical stripping processes may be restricted. A thorough review of local environmental regulations must be conducted prior to application of these processes.

b. Media Blast. Media blast coating removal methods, (such as plastic media, grit blast and wheat starch) while attractive for their environmental reasons, are not recommended for use in detailed teardown programs.

c. Fastener Hole Preparation: Fastener holes are generally given greater scrutiny, as they are often locations of crack initiation and propagation due to load transfer and stress concentration. Fastener removal, even when conducted by skilled technicians, can cause hole damage (scratches, gauges, nick and burrs) that, if not addressed, will prevent an effective eddy current inspection.Two primary methods are recommended for bolt-hole preparation: emery cloth and flex-hones.

6. **Non Destructive Inspection (NDI):**

a. NDI, also sometimes referred to as Non Destructive Evaluation (NDE) or Non Destructive Testing (NDT), is a process employed to interrogate structures and materials for discontinuities, defects and damage without causing damage to the component being examined or resulting in loss of vital metallographic evidence. The selection of the appropriate NDI method to employ depends on many factors including:

(1) Component geometry, size and material type.

(2) Surface condition including coatings, plating, and finishes.

(3) Expected damage, location, orientation and type of interest.

(4) Part criticality.

(5) Detection fidelity (capability).

(6) Cost.

b. Establishing Teardown Program NDI Requirements: Establishing Teardown Program NDI Requirements Inspection processes should be implemented in an efficient fashion to maximize inspection fidelity for critical structures and minimize the cost for inspection of non-critical or secondary/tertiary structures, while ensuring the resulting teardown analysis is sufficiently robust to support reliable system management decisions. The scope and fidelity of the teardown effort will largely be driven by the program budget and schedule. Therefore, to optimize resources and manage cost and schedule risk, a tiered approach should be implemented, which focuses program resources in proportion to the structural criticality of the part or component being evaluated, per part category and/or criticality as follows:

(1) Fracture Critical, Durability Critical, Mission Critical, Safety-of-Flight Component.

(2) Non-Critical Load Bearing Components.

(3) Secondary, Non-Load Bearing Components.

c. Establishing a Teardown Program NDI Level III: Due to the complexity of the inspection technique selection process, a qualified NDI professional must be consulted when selecting the array of inspections methods to be applied on individual components. The NDI professional must have experience in applying an array of NDI methodologies, (i.e. an NDI Level III).

d. Typical Aircraft Teardown Analysis Program NDI Techniques: The following sub-sections provide TAP NDI recommendations based on part category and/or criticality.

(1) Fracture Critical, Durability Critical, Mission Critical, Safety-of-Flight Components:

(a) Close visual inspection (CVI).

(b) Bolt-hole eddy current (BHEC)–fastener holes and bore holes.

(c) Eddy current surface scan (ECSS)–edges, radii, critical details.

(d) Fluorescent penetrant inspection (FPI)–full field with attention to critical details.

(e) Enhance visual inspection (EVI)–only critical fastener holes and details as identified by the teardown program manager.

(f) Magnetic particle inspection (MPI)–critical ferromagnetic components such as fasteners, pins, rods and brackets.

(2) Non-Critical Load Bearing Components:

(a) CVI

(b) FPI

(c) Limited BHEC or ECSS

(d) MPI

(3) Secondary, Non-Load Bearing Components:

(a) CVI

7. **Prioritize NDI Indications:**

a. By the very nature of destructive TAPs, the number of subjects for each of the tasks just described tends to continuously increase. To satisfy the program analysis requirements a single teardown aircraft may generate many extracted assemblies. Each of these extracted assemblies will result in one or more teardown subject parts. Each part will need to be prepared for NDI by cleaning and coating removal. NDI of each part may result in multiple NDI indications. Each NDI indication must be considered for further failure analysis investigation. This growth in the number of subjects for each task as the teardown program progresses is illustrated simplistically in Figure 2-54. With the ever increasing number of subjects, prioritization is a powerful tool in any program to ensure finite program resources are best focused on achieving desired results.

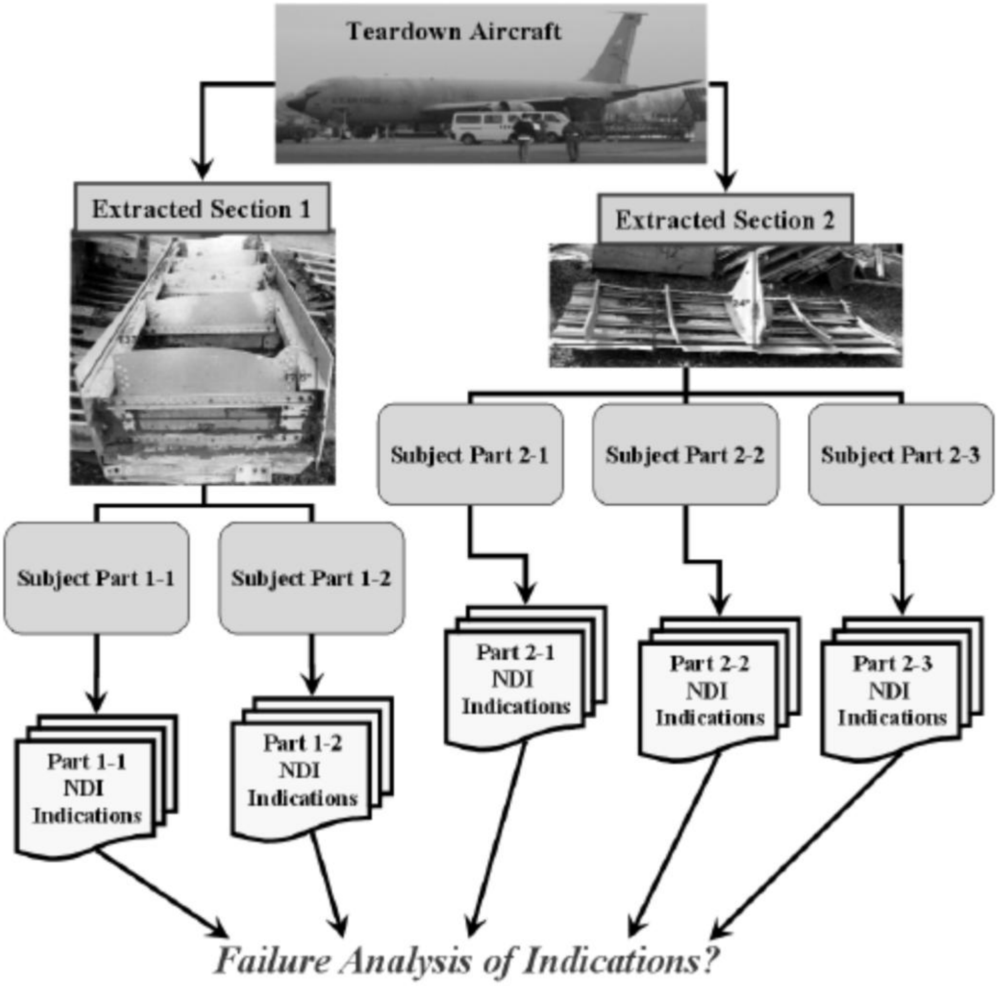


Figure 2-54: Simplistic Representation of the Growth in Number of Subjects for Each Task which Occurs During any TAP (CAStLE image)

b. Program requirements often serve to prioritize the extraction order of assemblies from a teardown airplane. Such priority would naturally carry through the subsequent tasks of disassembly, coating removal and NDI. However, especially with large aircraft, this input is often subordinate to jacking and shoring requirements as discussed in the previous subject extraction section. Recall that jacking and shoring requirements not only satisfy safety concerns but also are designed to minimize incidental damage to teardown subjects during the extraction process. Therefore, prioritizing the order of assembly extraction based on jacking and shoring also satisfies program requirements. As the number of subjects for each subsequent teardown program task increases the need to bring program data requirements into the prioritization scheme also increases. This fact becomes clear when extending Figure 2-54 to a realistic program scope. Each aircraft can produce hundreds of extracted assemblies. Depending on their size, each assembly likely results in dozens of disassembled parts. Each part could result in dozens to hundreds of indications. Investigating all indications by failure analysis techniques may be an unacceptable burden on both schedule and fiscal program constraints. Therefore, it is after the NDI task where prioritization based on analysis requirements of the teardown program becomes most important. Program managers are advised to have the prioritization system established before NDI indications present themselves. Even so, the prioritization scheme should also be a living system that can evolve throughout the program as data becomes available. Each TAP seeks to obtain a body of data for a given set of structures and frequently for a specific type of damage. As a result, NDI indication prioritization, like all tasks, is governed by the program requirements. This chapter is devoted to considerations and methodology for prioritizing NDI indications for further evaluation by failure analysis. The prioritization methods are tailored to the different types of program requirements.

8. **Perform Failure Analysis Of Indications:** Metallographic failure analysis is a destructive failure analysis technique, wherein the specimen is sectioned and broken in parts to identify and visualize the indications identified by the various NDI techniques discussed in the previous section. The aim is to identify the source of the indication documented by the NDI inspector. There are two major finding categories typical to most aircraft structure failure analyses; namely cracks and corrosion.

   a. Personnel Qualifications and Equipment Requirements: Metallographic failure analysis is both objective and subjective. Tell-tale signs of fracture features help to make the objective evaluations required during the failure analysis process. However, the presence of microscopic features often requires subjective interpretation. It is always helpful to have two pairs of eyes look at these subjective features to arrive at a consistent and reasonable conclusion. Successful interpretation of fracture surfaces and metallurgical observations also requires familiarity with the features under investigation. Therefore, there is no substitute for experience in correctly interpreting the fractograph or micrograph. Failure analysis must always be performed by a trained failure analysis engineer/technician who is fully conversant with failure mechanisms and features. Before a report can be finalized based on fractographic evaluation, it is necessary for a second failure analysis engineer to review and evaluate the data independently as a verification of the findings.

   b. Equipment Requirements: Not relevant to this dissertation.

   c. Failure Analysis Tasks: the specific tasks associated with conducting a proper failure analysis investigation on a given NDI indication. The tasks and sub-tasks included in this chapter are as follows:

(1) Visual examination

(2) Enhanced (high magnification) examination of the NDI indication site

(a) Stereoscopic Analysis

(b) Optical microscopy

(3) Specimen preparation

(a) Sectioning

(b) Mounting

(c) Polishing

(4) Crack opening

(a) Three-point bend method

(b) V-notch method

(5) Scanning electron microscopy

(a) Damage mechanism characteristics

(b) Identification techniques

(6) Corrosion product evaluation

(7) Fracture surface corrosion product removal

(8) The sequence and selection of each of these tasks is dependent upon the result of the preceding failure analysis task which is illustrated by various flow charts and other guidance.

d. Documentation of Findings: After the analysis of an NDI indication has been completed, the details of the finding must be fully documented. The report content must include a complete description of the indication leading to the failure analysis evaluation requirement, a description of analysis tools, and a finding summary to include the analysis methods, macroscopic description of the finding, and supporting evidence of the finding. The sections of such report are:

(1) Indication Description.

(2) Failure Analysis Investigation and Finding Summary.

(3) Macroscopic Indications and Finding Images.

(4) Supporting Finding Evidence. Programmatic Details.

9. **Analyze And Report Findings**: In this chapter, the possible uses of teardown and failure analysis data are discussed. The results of a teardown program have many uses in fleet management activities. For damage found during the teardown program, the fleet manager must understand the nature of the finding in order to properly use the information to manage the fleet.

3 DfD PROPOSAL FOR AEROSPACE INDUSTRY PRODUCTS

Extensive research in literature and open sources indicated that a lot of work was done in the areas of analytical DfD for commercial products. The approaches presented in the previous chapters however, show that due to the diversity and complexity of aerospace products, only few DfD methods can be applied per product and most probably, there is no way to define a "global" DfD method that covers all products. The purpose of this chapter is to present the process followed to collect suitable DfD methods in a matrix and to choose DfD criteria to be proposed for every case and type of aerospace products.

In order to build the proposed methods and criteria of DfD for aerospace products, the following basic considerations were made, after extensive research and study of a big volume of collected information:

a. The 12 principles of Green Engineering. Already discussed.

b. The Bretby Maintainability Index (BMI). Presented here; which can provide a potential solution to scoring disassembly detailed tasks using DfD criteria.

c. The predominant role of airworthiness, safety of flight, reliability, maintainability in Aerospace Industry. Already discussed.

d. The predominant involvement of human work in the manufacturing, assembly and disassembly of aerospace products in all the stages of the life cycle. Already discussed.

e. The need to build a proposed DfD criteria model, consistent to existing industrial manufacturing and supply standardiazation used for Aerospace Industry products.

f. The applicability of the proposed DfD criteria model of this dissertation.

The intention is to firstly demonstrate the complexity of DfD of aerospace products and the potential to tailor DfD in accordance wih the peculiarities and multicriteria optimization of those products' design, secondly to make a fist approach on the DfD issues for this family of products.

3.1 METHOD

It is literally impossible to develop one and single method for DfD of all Aerospace Industry products. What was done in this dissertation, was to develop an initial DfD criteria model (in the form of a spreadsheet with macros), which identifies candidate and most probably applicable DfD criteria per aerospace products category, but also excludes DfD criteria which have minimal or no applicability.

The approach was based on writer's personal experience, as well as on information collected from numerous relevant literature and other open sources, which identifies "no-go" situations to employ each DfD criterion. The applicability of the proposed DfD criteria model was evaluated and confirmed by a limited interview survey of specialized and experienced personel in the Maintainance Squadron of 115 Combat Wing (supporting F-16C/D Blk-52+ aircrafts) of Hellenic Air Force, Greece.

3.1.1 THE BRETBY MAINTAINABILITY INDEX

As maintenance can significantly reduce a mechanical product's (usually a machine) availability, engineers and designers ideally need quantitative information on the quality of the maintainability of complete machines. Existing maintainability indices (e.g. DoD MIL-HDBK-472, or Society of Automotive Engineers, SAE J817a) are either excessively time consuming to use or are incomplete. The Bretby Maintainability Index (BMI) was developed to specifically overcome the limitation of the current indices. The BMI was based on the SAE index, but was extensively modified to make it time based, and much more comprehensive. Its basic elements are divided into sections and parts, which categorize and separately address each factor that contributes into the total maintainability and maintainance costs (including disassembly costs), as shown below:

SECTION A: ACCESS	Part 1: Hatches & Covers Part 2: Apertures Part 3: Location
SECTION B: OPERATIONS	Part 1: Removal & Replacement Part 2: Slackening & Tightening Part 3: Carrying & Lifting Part 4: Preparation Part 5: Fluid Compartment Checks Part 6: Component Checking Part 7: Lubrication Part 8: Draining Part 9: Filling Part 10: Cleaning Part 11: Adjustment Part 12: Miscellaneous
SECTION C: ADDITIONAL ALLOWANCES	Percentage modifiers to take account of energy expenditure, posture, head room, visual demand, task requiring more than one man
SECTION D: FREQUENCY MULTIPLIER	Used to weight scores depending on whether job is done, for example, shiftly or weekly

The BMI has been described in detail by Mason et al., on 1989. It is an evaluation index that assigns time-based scores to various maintenance tasks and procedures. Developers of the

BMI noted that, if the maintenance tasks had any degree of added difficulty, the SAE system, which was relatively simple, was incapable of satisfactorily handling operational difficulties beyond the basic maintenance task. As far as the structure of the Bretby index is concerned, it is essentially classified into two distinct sections: gaining access to the job and the maintenance operations themselves. Two additional sections set allowances and multipliers to weight the scores and generate realistic and qualitative results.

3.1.1.1 ACCESS SECTION

The access section of the BMI is subdivided into two subsections. The first, concerns the removal and replacement of hatches and covers. This means it deals directly with gaining access to the mechanical component from outside. The second subsection deals with the space inside openings and apertures. However, a good maintenance methodology should also address other equally important and practically applicable factors, such as surface or component preparation and manual activities such as carrying and lifting. A consideration of manual activities further entails an inclusion of related factors, such as energy expenditure estimates and postural difficulty (important from the view point of musculoskeletal disorders). Table 3-1 summarizes some of the more important attributes covered by the access section of the Bretby index.

The Bretby index addresses in detail quite a few practically important points that the SAE index failed to even consider. A similar section for component location was added to the Bretby index to make it more comprehensive. The location section assigns scores to mechanical components based on how easy they are to reach. Ergonomically speaking, the components most within grasp and those that do not entail the adoption of awkward, unnatural postures receive the lowest score. It should be remembered that this is a linear scale of scoring. Each score is further converted into a time metric. The lower the score, the more time is needed to perform the operation, and vice versa. Table 3-2 depicts the location subsection of the access part of the method.

Table 3-1: Abridged Version of Miscellaneous Considerations from the SAE Index (Modified from SAE Information Report, SAE J817)

Description Points Score		
1.	Flip-up cover or flap, no fasteners	3 per cover
2.	Door or cover, hand-operated fasteners	4 per cover
3.	Door or cover, single fastener, tool operated	5 per cover
4.	Door or cover, multiple fasteners, tool operated	10 per cover
5.	Lift-off or lift-up panel, easy to handle, <12 kg	2 per cover
	12–24 kg	4 per cover
	25–35 kg	6 per cover
	>35 kg	10 per cover

Table 3-2: Location Subsection of the Access Section of the Bretby Maintainability Index (Modified from Mason, 1990)

Description Point Score		
1.	Ground level, working upright, within normal reach	1
2.	Ground level, bending or squatting, outside normal reach	2
3.	Ground level, squatting, kneeling, or lying (not under machine)	3
4.	Mount machine, normal reach	6
5.	Mount machine, bending, stretching, or squatting	8 (S)
6.	On machine, subsequent operations within normal reach	1 each
	Subsequent operations bending or stretching 2 each	
	Subsequent operations, squatting or kneeling 3 each	
7.	Any position (other than upright) under or within confi nes of machine	10 (S)
8.	Enter driver or operator cab	3

As is evident from Table 3-2, the Bretby index takes into account the need for assuming awkward postures to perform maintenance procedures. This inclusion of postural requirements addresses the concern of many professionals that such postures may lead to the onset of musculoskeletal disorders. This is very important during the disassembly operations of aerospace products. It is clear from the table that the simplest, most natural postures receive the lowest scores, which automatically means that they are less time consuming. A lower score also means that they are the most ideal postures on the list. Consequently, mechanical components, fasteners, and the like that need more complicated and unnatural postures are pinpointed accurately for design modifications to improve their degree of maintainability.

3.1.1.2 OPERATIONS SECTION

The operations section of the index is distinctly divided into 12 sections. The more important sections deal with component removal or replacement, component carrying and lifting, and component preparation. Component removal or replacement is further modified by way of a subsection on operations that do not involve complete removal of a component or fastener. Often times in industry, it is necessary to only slacken fasteners to effectively perform maintenance operations. Similarly, the converse is equally true: slackened fasteners need to be retightened post maintenance to ensure smooth operation of machinery. The clear subclassification of this process indeed is unique to the Bretby method and adds to the index much needed flexibility as well as practicality. An example of the removal or replacement index is presented in Table 3-3. The slackening or tightening index is presented in Table 3-4. It is noted however that Table 3-3 deals with only the removal (or replacement) of fasteners, also that mechanical components may not need fasteners to be held in place. Conversely, allowances have to be made for handling mechanical component weight (especially those that are heavy for the average worker to handle comfortably) once the fasteners are removed. The Bretby index makes allowances for handling unusually heavy components. For example, components that are easy to handle (weighing about 12 kg) are assigned a score of 2 points per component. This is necessary, since maintenance is largely a manual activity, especially in Aerospace Industry. As such, handling mechanical components during maintenance (lifting, moving, and refitting) is a time-consuming process. The lighter the components, the better the operation is from the maintenance perspective.

Table 3-3: Removal or Replacement Subsection of the Operations Section of the Bretby Maintainability Index (Modified from Mason, 1990)

	Description Point	Score
1.	Spin-on fastener	1
2.	Single fastener, not requiring tool	3
3.	Single fastener, requiring tool	4
4.	Additional fasteners, not requiring tool	2 each
5.	Additional fasteners, requiring tool	3 each

While the Bretby index takes into account the weight of individual components, it still has some margins for improvements. Examples are given in the following paragraphs.

The index does not assign weight scores to awkwardly shaped components (given that part variety in products and mechanical components is staggering). Components that are irregularly shaped, have sharp edges, are made of fragile materials, or have an eccentric center of gravity, for example, would need Bretby index and scores to be updated, as far as part handling is concerned. Additionally, Table 3-3 takes into consideration fasteners based on two criteria: those that need tools and those that do not. This is in addition to the typical spin-on type of fasteners however, no distinction is made between those spin-on fasteners that require tools and those that do not. Similarly, no distinction is made between fasteners and components that need extreme measures such as the use of a pry bar, for example. Here is an example of a situation that entails the use of a tool, with the exertion of force and requires substantial clearance within and around the mechanical component (depending on location of the fastener or component). A consideration of such situations, which are common on disassembly of aerospace products, would make the Bretby index, after some tailoring, even more valuable from a practical viewpoint. It is noted however that under this dissertation an effort to address such issues was made and proper considerations were included in the process of assigning scores (penalties) to the DfD criteria model, as shown in Appendix A

Table 3-4: Slackening or Tightening Section of the Bretby Maintainability Index (Modified from Mason, 1990)

	Description Point	Score
	Fastener type	
1.	Single fastener, not requiring tool	1
2.	Single fastener, requiring tool	2
3.	Additional fasteners	1 each
	Fastener force requirements	

4.	Slackening fastener, high forces needed	1 (H), (S)
	Requiring impact	1–8 (S)
5.	Tighten to unspecified torque.	2

3.1.1.3 OTHER FEATURES

The Bretby index has numerous features that underline its importance as a leading index on maintainability. These features include carrying and lifting tasks, preparation tasks, and inclusion of important practical factors. Consideration is given specifically to carrying and lifting activities, especially important in the case of large machines with heavy components and respectively, of heavy aerospace components. Within the carrying and lifting category, allowances were made for frequency of lifting as well as machines and mechanical component design, from the perspective of provision of headroom to enable satisfactory maintenance and lifting. Special consideration also was given to a one-person lifting task as against a two-person task (depending predominantly on the weight of components).

It is assumed that one person can satisfactorily perform all lifting and carrying tasks for all objects weighing up to 35 kg. This is too random an assumption, especially in the case of mechanical components that do not allow the requisite clearance in terms of either headroom or other clearances. Two people may be required for heavier objects (as is often the case in typical push-pull activities). A special allowance needed to be made for a second person in such cases. To ensure that this was incorporated effectively in the index, the carrying and lifting index needed to be split to incorporate allowance for the inclusion of an additional person. Each additional person performing the task in less maintenance-friendly conditions (such as insufficient clearances or headroom) needed to be assigned successively higher values to reflect obvious anomalies in mechanical component design from the maintenance perspective. An additional allowances section was included in the index, but it is noted that it needs careful interpretation and use, to couple the carrying index, as is, along with the allowances.

Most maintenance operations entail one or more preparatory tasks before the actual maintenance operations can be carried out. The Bretby index does a good job of including an entire section on preparation tasks to be performed prior to maintenance. To that end, specific points were allotted to discrete preparation tasks. For example, the task of cleaning around unions, fasteners, and the like was allotted 4 points. Jacking up and chocking the machine or mechanical component prior to maintenance was allotted 20 points. Similarly, donning protective equipment such as gloves or goggles (standard equipment) was allotted 2 points, since it is quick and habitual to don standard personal protective equipment (PPE) and can be performed quickly. The process of donning nonstandard PPE, on the other hand, was allotted a more generous 5 points due to more time spent in the process.

While the Bretby index includes most preparation tasks satisfactorily, special mention needs to be made about abrasive cleaning solutions, such as acids and alkalis, necessary to effectively complete preparation for maintenance. The use of such solutions entails the donning of nonstandard PPE (especially to protect the worker from noxious fumes). It also entails the use of concentrated chemicals that may take some time to complete the cleaning action before the mechanical component may be accessed for maintenance (as is often the case in cleaning tough grease and grime). This means that the worker essentially has to wait for some time before it is safe to commence further operations. The index could be modified to include this very important and widely utilized method of preparation, which is a very frequent practice in aerospace products, e.g. removing coating from external surfaces on an aircraft's landing gear strut.

Similarly, the index makes a mention of cleaning small and extensive areas of the mechanical component. This is quite subjective, since mechanical components come in all shapes and sizes. A modification could include affected surface area as a function (percentage) of total principal surface area. To this end, the parameter "surface area" could be classified as primary (essential functionally) and secondary. The point system could be modified to take this into account.

Additionally, as far as cleaning is concerned, the formulators left out an important variable: cleaning in hard-to-reach, inaccessible, and barely accessible areas. This action is most certainly time consuming and may require unnatural postures and abrasive cleaning products. The Bretby index scores positive points as far as inclusion of important practical factors, such as component checking, lubrication, and draining. It gives due consideration to tool access parameters to effect maintenance. For example, a 2–3 flats access for wrenches and Allen wrenches was considered sufficient clearance and awarded 1 point per fastener that affords this kind of clearance. The point score increases in inverse in proportion to clearance. The index also includes several miscellaneous items, such as energy output, frequency of operations, and visual fatigue.

A chief drawback with the energy output multiplier is that it takes into consideration only underground conditions and is a vague as far as quantification is concerned. Similarly, as far as visual fatigue is concerned, the index has no provisions to take into account lighting conditions while checking as well as performing the maintenance operation.

Once again, it is noted here that under this dissertation an effort to address such issues was made and proper considerations were included in the process of assigning scores (penalties) to the DfD criteria model, as shown in Appendix A.

3.1.1.4 USING THE INDEX

To use the index on a machine or mechanical (aerospace) component or assembly, it is necessary to obtain a list of all maintenance tasks to be performed as well as their frequency. Similarly, each task has to be described in sufficient detail (task analysis) for the necessary features of the index to be accessed. This description may be obtained from observations on the machine or discussion with experienced engineers and fitters. As discussed before, this approach was followed also for the DfD criteria model of this dissertation, by involving experienced and specialized personel of HAF.

The Bretby Maintainability Index assesses a complete maintenance procedure by allocating points to various aspects of each step in the procedure. The points cover different degrees of access, with force limitations on the use of hand tools and lifting capabilities, postures and even lighting conditions.

A very brief description of the normal BMI use could be as follows:

a. We use this method to analyse maintenance procedures, by quantifying each step with a value.

b. We then sort from highest point to lowest points and address a number of the highest point areas by brainstorming alternative ways of achieving the same outcome of the step. This could mean changing the design of a component, replacing it with a more reliable component to reduce frequency, improving access etc.

c. We calculate the costs of the modification and repeat the analysis.

d. We calculate the number of points changed and multiply it with 5 seconds per point. After dividing this by 3600, we know the number of hours saved.

e. With the hourly rate for maintainers and the modification costs we can calculate the payback time, to see whether the modification is justifiable.

f. Since the system 'normalizes' over six months, not a year, so to calculate savings per year you must multiply the points saved by two (simple enough).

g. A more accurate time value per point is 12,5 seconds, not 5 seconds. This has been confirmed by real life application of BMI and comparisons of the calculated time for a procedure (Bretby points * 5 seconds) to the real time. Nearly all confirm that 12,5 seconds is a better match with reality.

Another method to use the BMI could be:

a. In order to use the BMI, each task on the maintenance schedule must first be identified in terms of the actions needing to be performed and the recommended maintenance intervals.

b. Each task is then assessed independently against each section of the BMI.

    (1) Points are allocated depending on the number of body motions, degree of difficulty etc.

    (2) The total of the scores for each part of Sections 1 and 2 are then increased by the percentage modifier of Section 3. This allows for energy expenditure estimates, pos-

tural difficulty, etc.

(3) Finally this score is then modified to take into account the different maintenance intervals. For example a task which is performed on a daily basis is weighted more heavily than a similar task which is only performed monthly.

c. The weighted scores for all tasks in the maintenance schedule and then totalled to give the final BMI result.

After this discussion, it is obvious that Bretby Maintainability Index can support detailed mechanics for developing a DfD criteria model for aerospace products, by using a scoring system per criterion (possibly based on a Bretby tailored index), on each stage of the design. Such an approach was followed in building the proposed DfD criteria model and combined with the DSM (Design Structure Matrix) methodology.

3.1.2 EXAMPLES OF COLLECTED CRITERIA

Almost all maintenance work requires some disassembly, the efficiency of which typically depends upon the component parts, the mating of these parts and connector devices. When these parts are properly designed, maintenance can be performed faster and with more assurance that it is done properly. Some of the principles of component part design to improve maintenance are:

a. **Minimize the number of component parts and connectors that must be disassembled to do the maintenance task.** When fewer parts and connectors must be taken apart, maintenance and repair can be done more easily. This reduces both the time needed and the chance of making mistakes. To ensure this goal is satisfied, it is often helpful to first build a model of the product. Such models can be created via CAD virtual applications and in some cases via rapid prototyping, or from simple, rough materials such as Lincoln logs, Erector-set components or fischertechnik assembly pieces.

b. **Group components by function into modules that can be separately removed or installed**. Ideally, no more than one disassembly step is required for each maintenance task. Although this is often not achievable, minimizing the number of steps is especially important for modules that are frequently replaced. Grouping by function also helps locate faults and simplifies the process of fault diagnosis. Some additional considerations are described next. One is that the physical connections between two component parts may be symmetrical, semisymmetrical, or asymmetrical in character. There is a clear and obvious advantage of symmetrical parts, as they can be joined in many orientations. Symmetrical parts reassemble faster than semisymmetrical or asymmetrical parts, as -Time Measurement Methods (MTM) tables show. On the other hand, if operation of the machine (e.g. aircraft hydraulic pump) requires a particular orientation of the component parts, a connection that seems to be symmetrical could mislead the maintenance person to reassemble the part incorrectly, which would necessitate another disassembly and reassembly. This leads us to the next principle:

c. **Symmetrical part mating is preferred when the assembly operates properly when so assembled, but otherwise go to semisymmetrical or asymmetrical mating.** It also follows that it is easy during part disassembly to forget how the part was oriented. So a second principle that helps reduce maintenance costs is to include markings that communicate how the part should be oriented. Writing across a part can indicate the part's orientation. Another example is marking parts with arrows that are aligned when two mating parts are correctly oriented. So another principle is as follows:

d. **Design the part in such a way that it is obvious how it is to be oriented during disassembly / reassembly.** It is better if mating parts can be fit together without requiring vision, but providing visual means of orientation is far better than providing nothing. Parts should be designed for easy manipulation during manual handling. The MTM tables show that certain types of grasps are more difficult and time consuming than others. So the MTM grasp table provides useful information on part manipulation. Part size and weight are also important considerations. Both factors limit the members of the population who can perform the service as workers come in multiple sizes and strengths. Ideally, the parts will be small enough for most workers to handle. Problems exist at the other extreme, too. Small parts are often easily bent or warped during disassembly or reassembly. Bent or warped parts must be replaced, and this further increases the time and effort required to finish the task. Sometimes it becomes necessary to assign particular maintenance personnel to tasks that require great strength or small but dexterous limbs. Most would agree, however, that such requirements should be avoided if possible. Some parts have an obvious sequence of disassembly and reassembly. It also follows that the person who performed the disassembly does not always perform the reassembly. Hence, memory cannot be counted on as a reliable guide to reassembly. While the reassembly sequence typically is the opposite of the disassembly sequence, in many situations that may not be the case. In such cases, some form of warning should be provided to help prevent mistakes. One way to communicate a sequence for the component parts is to have parts that increase gradually in size with disassembly. Another design consideration is to:

e. **Provide tactile feedback when the part is properly and fully joined, such as an audible snap and a noticeable vibration that occurs when parts are joined and unjoined.** Such feedback tells the assembler or disassembler that the part is properly and effectively mated or free from the connective part.

f. **Provide cues that make it easier to locate and identify fasteners.** Locating all of the fasteners is difficult for many products. Simple signs can be useful that direct the maintenance person's attention to the locations of fasteners. It is also useful to show the maintenance person the type of fastener. It is helpful to indicate which tool is needed to disconnect the fastener. Many maintenance situations require a variety of tools. If maintenance workers must walk some distance to the mechanical component requiring maintenance, they will normally want to carry only the tools they will need. This problem can be addressed by making the tools more multipurpose, even at a loss of efficiency. Otherwise, travel time between the task and the tool-storage location may become excessive. The best design follows the principle:

g. **Minimize the size and numbers of and the types of connective fasteners in the mechanical component design, subject to adequate strength**.

h. **Maintain open space in the design to accommodate at least the work envelope and vision requirements within this envelope.** Work envelopes are merely a defined spatial region that the parts of a person's body and/or hand tools occupy at some time while performing a particular task. Vision plays an enormously important role in disassembly executed by humans. It has been known for many years that providing an adequate work envelope with good visibility conditions reduces maintenance effort.

3.1.3 SELECT DfD CRITERIA - DEVELOP THE DfD CRITERIA MODEL

Extensive research was performed in open sources to identify and study information with regards to the design, disassembly, ease of disassembly, maintainability and EoL methodologies and strategies for aerospace platforms and products. As a result several sets of candidate DfD criteria were collected, out of which some were included in the proposed model of DfD criteria and other were rejected as inapplicable. Narrowing of the criteria list was executed in stages as presented in the following paragraphs.

3.1.3.1 STAGE I – AREAS OF SCOPE

In order to develop the combined DfD criteria modex (matrix), intensive research was performed in open sources and literature. Several books, electronic and paper publications of FAA/ USAF/ NASA/ ESA, international conference proceedings, reports, papers, articles and internet web sites were located, collected and studied. A considerable volume of information was processed and analyzed, to identify candidate criteria with respect to the following areas of this dissertation's scope:

1. Design for Disassembly.

2. Guidelines for DfD.

3. Disassembleability.

4. Disassemble Effort Index.

5. Maintainability.

6. Work Measurement and Bretby Maintainability Index.

7. Decision at EoL.

8. Design for Environment.

9. Design for Recycling (given that all Aerospace Industry products have several precious and recyclable materials, as well as other hazardous and toxic materials).

3.1.3.2 STAGE II – ENVISION DISASSEMBLY ENVIRONMENT BOUNDARIES

The principle way to process the collected criteria accounted considerations from the following principal standpoints, which were seen from a rather “mechanical” systems’ engineering for airworthy aerospace products point-of-view and not from an electronics / Information Technology point of view, which as previously discussed, is typically oriented and focused on intensive computing techniques and algorithms for robotic disassembly operations:

1. Purpose of disassembly:

    a. **Flight-Line Level maintainance** of the airborne platform (mainly for parting-out or repair reasons), which is normally performed:

        (1) In the open environment or in a little hangar or hardened shelter, under unfavorable environmental or light conditions,

        (2) Under high time constraints and urgency (therefore higher risk of human errors) to avail the aircraft and its systems for the next flights,

        (3) Under high risk of accident, due to the aircraft and its systems loaded with fuel, lubricants, nitrogen, oxygen, other gases, external filled fuel tanks, weapons (if applicable).

    b. **Intermediate Level or Depot Level maintainance** of the airborne platform, as well as Back Shop maintainance of the aircraft systems and replacable units (e.g. phase inspections and follow-on troubleshooting/ repairs of the aircraft systems, aircraft engine overhaul maintainance, aircraft structural repairs, egress systems maintainance, modifications of the aircraft and its systems) etc, which are normally performed:

        (1) In a big hangar, with dedicated ground support equipment and back shops,

        (2) Under normal time constraints to avail the aircraft and its systems to flight line personnel and works,

        (3) Under medium to high risk of accident, due to the aircraft and its systems loaded with nitrogen, oxygen, other gases and other hazardous materials in the internal as-

semblies,

(4) By involving high degree and depth of disassembling in order to effectively work in difficult locations (spots) of the aircraft.

c. **EoL dismantling** of the airborne platform and its assemblies, which is usually performed:

(1) Without time pressure,

(2) In convenient environmental and spatial conditions,

(3) By disassembling the reusable parts and components, only to the necessary depth of disassembling (defined normally by the retail value of the disassembled part),

(4) By destructive disassembly of the main parts of the aircraft and the components which are no longer usable, but are recyclable.

2. Time allowances for disassembly, depending on the purpose of disassembly as mentioned above in the purpose of disassembly paragraph.

3. Human Factors – Ergonomics, to ensure that respective considerations are met, for example:

   a. The execution of tasks by the involved personnel is facilitated and human errors are minimized,

   b. Personnel safety and flight safety are not compromised,

   c. Reusability of parts and materials is optimized,

   d. Airworthiness of the aircraft and its systems is continued and under no circumstance compromised.

4. Cost and operational value of the assembly, component, materials.

At this point, it is noted that the approach of this dissertation for disassembly operations performed in outer space is quite similar to the approach of disassembly for a fighter aircraft. For example:

1. When the aerospace products are located on earth, the same DfD model criteria can be applicable. In the case of aerospace products which returned from a space mission / spaceflight and need to be disassembled (e.g. for post-mision special inspections), special attention should be given to DfD model's criteria related to preparation operations prior to access and disassembly, also related to control / minimize use of toxic - hazardous materials. This attention is necessary for several reasons like, (a) the fact that these products use high per-

formance polymers, advanced composites - heat resistant matrix resins, (b) reentering spacecrafts generate nitrates, (c) most vehicles use propellants that are not carbon neutral, (d) many solid rockets have chlorine in the form of perchlorate or other chemicals.

2. While a space shuttle is in orbit:

   a. Purpose of disassembly: repairs of orbiter vehicle (spacecraft) internal pieces of equipment, or low depth disassembly tasks (during spacewalking outside the compressed cabin) on the payloads in the midfuselage payload bay, under:

      (1) hard outer space environment (vaccum, temperature etc) and poor lighting,

      (2) relative urgency to keep the allowable time margins,

      (3) risk of accident, due to the orbiter vehicle physical geometry and systems loaded with fuel, oxygen, other gases, filled fuel tanks.

      (4) product complexity and limitations of available tools, lack of enough room to work and surfaces to put parts, tools and publications.

   b. Human Factors – Ergonomics, to ensure that respective considerations are met, for example:

      (1) The execution of tasks by the involved personnel is facilitated and human errors are minimized, while additional considerations are made for factors like absence of gravity environment, inconvenience due to spacesuit clothing, special safety means (e.g. helmet, gloves and breathing devices, man maneuvering unit), decompression sickness.

      (2) Personnel safety and flight safety are not compromised,

   c. Cost and operational value of the assembly, component, materials.

It could also be argued that all the above considerations do not give first priority to the DfD of aerospace products at their EoL, but instead, they give higher priority to DfD during the useful (operational) life of those products. In response, it should be noted that, not only the acquisition cost of the aerospace products is usually high so that their early disposal or early dismantling should be avoided to the maximum extend, but also, it should be noted that during their useful (operational) life, these products need a big number of iterative inspections and iterative cycles of non-destructive disassembling/ reassembling for repair and maintainance, followed by extensive tests to ensure their safe-to-fly condition and airworthiness continuity, which as an overall result, makes DfD a concept of first priority in the useful (operational) life of these products and then a concept of secondary priority for their EoL dismantling.

At the end of the sources’ research stage, more than 160 criteria were collected and then, were analysed, consolidated, adapted (reworded as appropriate) and reduced to a total number of 133 criteria, based on their combined applicability in complex aerospace airborne products and under the prerequisite that each criterion is applicable to:

1. At least four complex aerospace airborne products (e.g. fuselage and wings components and structures, aero/hydraulics, landing gears, engines, replaceable units and parts etc).

2. At least two of the three design phases of complex aerospace airborne products (Conceptual design, Preliminary design, Detailed design).

As discussed before, this process was primarily based on real-life experience of the writer and of Hellenic Air Force (HAF) maintainance personnel, who provide daily Flight-Line/ Back-Shop / Depot-Level maintaintance support to the F-16 aircrafts of HAF, in specialties and technical skills of Crew-Chief, Aero/hydraulics (hydraulic and pneumatic systems), Structure, Fuel Systems/ Hydrazine, Corrosion Control, Survival Equipment, Egress, Propulsion, Electricity, Weapon Systems, Attack Systems, Comm-Nav Systems.

A basic Ground Rule and Assumption established is that, if a criterion is applicable to a fighter aircraft (e.g. F-16 aircraft) which is undouptedly a product which incorporates top-notch technologies in very limited space and operates in extremes of severe aerodynamic and environmental conditions, then in general, the criterion can further be relaxed or tailored to be applicable to another Aerospace Industry product like a commercial airliners aircraft.

3.1.3.3 STAGE III – RESEARCH AND COLLECT CRITERIA

3.1.3.3.1 CRITERIA COLLECTION SEQUENCE

1. Collect all respective and applicable literature from open sources.

2. Identify and collect all criteria found which are candidate for DfD of aerospace products.

3. Merge – consolidate criteria without compromising their key meaning and semantics.

4. For each Design Stage, evaluate if criterion is applicable (yes / no) and then:

   a. Define risk for the next design stages if criterion is not accounted / met in Conceptual design.

   b. Define risk for the next design stages if criterion is not accounted / met in Preliminary design.

   c. Define risk for the next design stages if criterion is not accounted / met in Detailed design.

5. Define risk for Useful Life problems if criterion is not accounted / met during design stages.

6. Define risk for EoL problems if criterion is not accounted / met during design stages.

7. Sort and name the criteria (format: “D.###”, e.g: D.1, D.2, D.3,…, D.133) i.a.w. the following priorities:

   a. Area of interest: Safety, Simplification, Frequency, Standardization, Physical , Coatings, Accessibility, Connectors, Disassembly Depth, Testability, Fasteners, Design - Cost, Tools, Force, Preparation.

   b. Applicability in all design stages, viz Conceptual, Preliminary and Detailed stage.

   c. Weighted score (or penalty) for disassembleability through the product’s Useful Life.

3.1.3.3.2 CRITERIA SCORING SEQUENCE

Every single criterion was evaluated and was given a “score” which pertains to the level of its applicability per Design phase, but at the same time, which pertains to a “penalty” metric of probable impact, if this criterion is not addressed and considered in the respective Design phase. As previously discussed, a very helpful tool to perform this evaluation was the Bretby Maintainability Index and its additional considerations for extension or updates. For example, the criterion: D.10 - “Has the system been searched for simplified alternatives?” was given:

a. At Conceptual Design: a score of 9, because a core function of Conceptual Design (as mentioned before) is to develop as many as possible alternate candidate designs which will be compared and evaluated via trade-studies, for the better possible result.

b. At Preliminary Design: a score of 7, because in this phase the predominant design is evaluated to find areas for design modifications, requiring further iterations and refinements of the design concept, before the top-level parameters are locked.

c. At Detailed Design: a score of 6, because failure to identify simplified alternatives has more risks to result in redesign decisions of the same component or other cooperative components.

Whenever a criterion was not applicable to the specific Design phase (Conceptual, Preliminary, Detailed) of any aerospace product of interest, no score was given to it and the respective cell in the matrix was left empty (grey).

The scores for Useful Life and EoL were defined also considering the repeatability of disassembly. Scores were categorized as:

a. **Advirosy**: Scores of 1, 2, 3: It is **nice and helpful** to be addressed and considered, otherwise there is a risk to experience impacts in the next stages of design (from DfD perspectives), or impacts the DfD considerations (disassembleability, maintainability etc) in the useful operational life of the product.

b. **Compulsory**: Scores of 4, 5, 6: It is **necessary** to be addressed and considered, otherwise there is a high risk to experience considerable impacts in the next stages of design (from DfD perspectives), or impacts the DfD considerations (disassembleability, maintainability etc) in the useful operational life of the product.

c. **Mandatory**: Scores of 7, 8, 9: It is **absolutely necessary** to be addressed and considered, otherwise there is a very high risk to experience severe impacts in the next stages of design (from DfD perspectives), or impacts the DfD considerations (disassembleability, maintainability etc) in the useful operational life of the product.

The “side” scores of each scoring category (e.g. scores 4 and 6 for category “compulsory”) were intented to give a more detailed meaning to the applicability of the respective criterion.

The weight factors which impact the total score for the Useful Life and the EoL of the product were defined per Desing Phase or Time of disassembly (Life Cycle or EoL):

d. Conceptual : Two(2)
e. Preliminary : Five(5)
f. Detailed : Six(6)
g. Life Cylce : Six(6)
h. EoL : Four(4)

3.1.3.4 STAGE IV – REWORD CRITERIA

Some of the criteria had to be reworded in order to better address the purpose of disassembly. In other cases, similar criteria could and were merged into fewer criteria. To make this process more understandable, some examples are presented below.

As a first example, two similar initial criteria:

1. Disassemblability Criterion: “weight, size, material and shape of components”

2. Design guidelines for DfD Criterion: “design factors such as weight, shape and size of components being disassembled”

were consolidated into a single final criterion: “Control and limit (as much as possible) design factors of weight/ size / shape of components”. In this way, the former criteria are limited to only weight, shape and size of components (not material), to be controlled and limited.

As a second example, three initial criteria:

1. DfD Criterion: “number of fastener types should be restricted”
2. DF Recycling Criterion: “select fastener systems that facilitate disassembly”
3. DF Recycling Criterion: “reduce the number and types of fasteners used”

were reduced into two final criteria (by deleting the third initial one):

1. DfD Criterion: “number of fastener types should be restricted”
2. DF Recycling Criterion: “select fastener systems that facilitate disassembly”

This was done because the third criterion was extending the first one by adding number of fasteners as a factor, however, in aerospace products, what matters are the types of fasteners, which drive the requirements for additional or specialized tools and increase variance of tasks and skills necessary for disassembly. Added to that, for flight safety reasons, reducing the number of fasteners on an aerospace component/ assembly in order to reduce the time and effort of disassembly, may lead to unsafe operation of the components and the assemblies during flight and may compromise the flight safety of the platform. As an example, Figure 3-1 below shows an F-16 fighter aircraft tacking access door , located on the skin of the aircraft. If the number of fasteners was reduced, then the door could probably be detached during flight at high speeds and this could lead to a serious mishap of the aircraft.

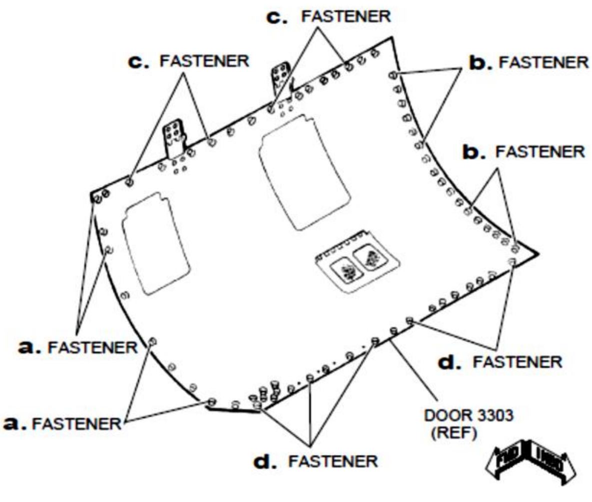


Figure 3-1: Example of Fasteners (F-16 Tacking Door)

As a third example, for accessibility, five(5) initial criteria:

1. Disassemblability: “accessibility issues to enhance quick and easy disassembly”
2. Design guidelines for DfD: “degree of accessibility of components and fasteners”

3. Maintainability: “can the item be reached easily (accessibility) for repair or adjustment?”

4. Maintainability: “general accessibility, work space, and work clearance.”

5. Maintainability: “accessibility considerations of parts, test points, adjustments, and connections”.

Were reduced into two(2) final criteria:

1. Disassemblability -guidelines for DfD: “degree of accessibility of components and fasteners to enhance quick and easy disassembly”

2. Maintainability: “general accessibility, work space, and work clearance of parts, test points, adjustments, and connections.”

In this case, the third initial criterion was deleted because it is covered by the others. Also, the first and the second initial criteria were consolidated into a single final criterion and the fourth - fifth initial criteria were consolidated into another single final one.

As another example, the initial criteria of tools for disassembly were eleven(11):

1. DfD: “operations, as much as possible, should be carried out with one tool only”

2. Work measurement: “tool positioning”

3. Work measurement: “number of necessary tools”

4. Disassembly effort index: “use of specialized tools”

5. Disassemblability: “use of hand tools”

6. Disassemblability: “the need for specialized manual tools in order to facilitate disassembly”

7. Guidelines for DfD: “minimize use of tools”

8. Guidelines for DfD: “minimize number of tools”

9. Guidelines for DfD: “requirements of common tools”

10. Guidelines for DfD: “requirements of special tools”

11. Maintainability: “limitation of numbers and varieties of necessary tools, accessories and support equipments”

Were reduced and reworded into four(4) final criteria which better address DfD for aerospace products:

1. Work measurement: "tool positioning"
2. Guidelines for DfD: "requirements of common tools"
3. Guidelines for DfD- Disassembly effort index: "requirements of specialized manual tools in order to facilitate disassembly"
4. Maintainability: "(limitation of) numbers and varieties of necessary tools, accessories and support equipments"

The initial criteria 2, 9 and 11 remained unchanged, criterion 6 was reworded to address the mandatory nature of requirements (and not the weaker nature of a need) and criteria 1, 3, 4, 5, 7, 8 and 10 were deleted, as they were either covered under the final ones (e.g. intial criteria 4 and 5 covered under initial criterion 6, as well as criteria 3, 7, 8 and 10 covered under criterion 11), or they were not driver factors of the total disassembly cost for products such as the aerospace products (e.g. criterion 1).

Many of the initially collected 160 DfD criteria were tailored in similar ways to produce the DfD Criteria full Model of Appendix A.

3.1.3.5 STAGE V - BUILDING THE DSM

Design structure matrix (DSM) is a straightforward and flexible modeling technique that can be used for designing, developing, and managing complex systems. A DSM is able to model and analyze dependencies of one single type within one single domain. For a product disassembly, e.g. the domain "criteria" can be regarded. Using the relationship type "change of criterion X causes change of criterion Y", an assembly can be analyzed with regard to the overall change impacts in order to model possible change propagations. DSMs can have different qualities: Binary DSMs represent only the existence of a relation whereas numerical DSMs represent a numerical value (also called "weight") to represent the strength of a relation. DSMs can either be directed (as shown in the figure below), or non-directed. For the purposes of this dissertation, the DfD Criteria Model was structured as a binary DSM.

The 133 Criteria of Appendix A were fed into a DSM, which resulted in a 133X133 matrix with 17.689 cells. Each one of the criteria was assessed with respect to its relationship to each of the rest 132 criteria. The fundamental "question asked" to assess the existence of relationship was:

"Does Vertical criterion A actively influence / define Horizontal criterion B?"

The answer to this question was defined on "all inclusive" basis, viz. the binary "X" (to declare relationship) was used when the answer to the above question was a confident "no".

3.1.4 RESULTS – COMMENTS - REMARKS

The result of the previously described process was the DSM shown in Figure 3-2. This matrix visualizes both the existence of a total of 2.854 relationships (marked with "X") as well as the distribution of these relationships among the criteria of the model.

As a second step, an effort was started to express the inter-relationships with positive and negative strength numbers e.g. {-2, -1, 1, 2}, however it was deemed as impossible to objectively assign to each pair of criteria numbers which would apply to **all** Aerospace Industry products. A workaround for this restriction would be to assign strength numbers in relationships of criteria, only after the DfD Criteria Model has been previously tailored for specific aerospace product of interest.

It should also be noted that due to the purpose of this dissertation to develop a first-cut DfD Criteria Model which generically applies to **all** aerospace products, no effort was made to distinguish between different domains of the DSM, e.g. materials, processes, humans. This distinction can be a probable area for future work to convert the DSM of the DfD Criteria Model into a respective MDM (Multi Domain Matrix).

The DSM of Figure 3-2 is available in its native file format.

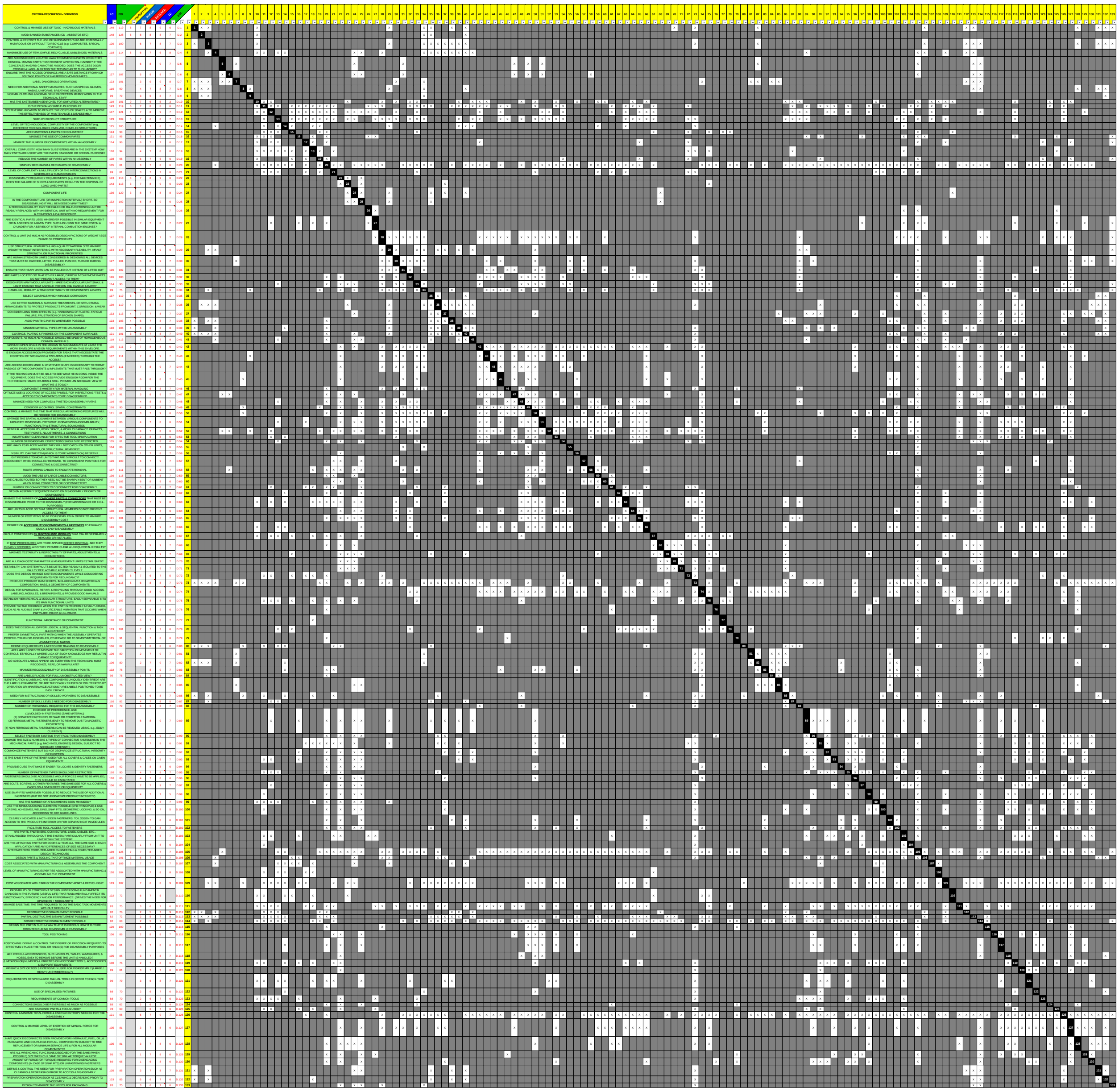


Figure 3-2: Initial DSM of the DfD Criteria Full Model

White areas filled with “X” declare relation between the respective pair of horizontal and vertical criteria, based on the fundamental question: “Does Vertical criterion A actively influence / define Horizontal criterion B?”

Another effort was made to partition the DSM matrix of the DfD Criteria full Model, in order to investigate its probable clustering. The result of this effort is presented in Figure 3-3. It is easily understood that the distribution of the interrelations among the DfD criteria does not allow for excessive clustring.

The initial order of criteria based on the scores given per criterion was D1, D2, …, D.132, D.133.

The partitioned order of criteria based on the binary expressed (as “X” or as “1”) interrelations among the criteria is: D.1, D.2, D.3, D.10, D.11, D.12, D.13, D.15, D.16, D.17, D.18, D.14, D.4, D.19, D.20, D.21, D.22, D.23, D.24, D.25, D.26, D.27, D.28, D.29, D.30, D.7, D.5, D.6, D.31, D.32, D.33, D.34, D.9, D.35, D.36, D.37, D.38, D.39, D.40, D.41, D.42, D.43, D.44, D.45, D.8, D.46, D.47, D.48, D.49, D.50, D.51, D.52, D.53, D.54, D.55, D.56, D.57, D.58, D.59, D.60, D.61, D.62, D.63, D.64, D.65, D.66, D.67, D.68, D.69, D.70, D.71, D.72, D.73, D.74, D.75, D.76, D.77, D.78, D.79, D.81, D.82, D.83, D.84, D.85, D.86, D.80, D.87, D.88, D.89, D.90, D.91, D.92, D.93, D.94, D.95, D.96, D.97, D.98, D.99, D.100, D.101, D.102, D.103, D.104, D.105, D.106, D.107, D.108, D.109, D.110, D.111, D.112, D.113, D.114, D.115, D.116, D.117, D.118, D.119, D.120, D.121, D.122, D.123, D.124, D.125, D.126, D.127, D.128, D.129, D.130, D.131, D.132, D.133.

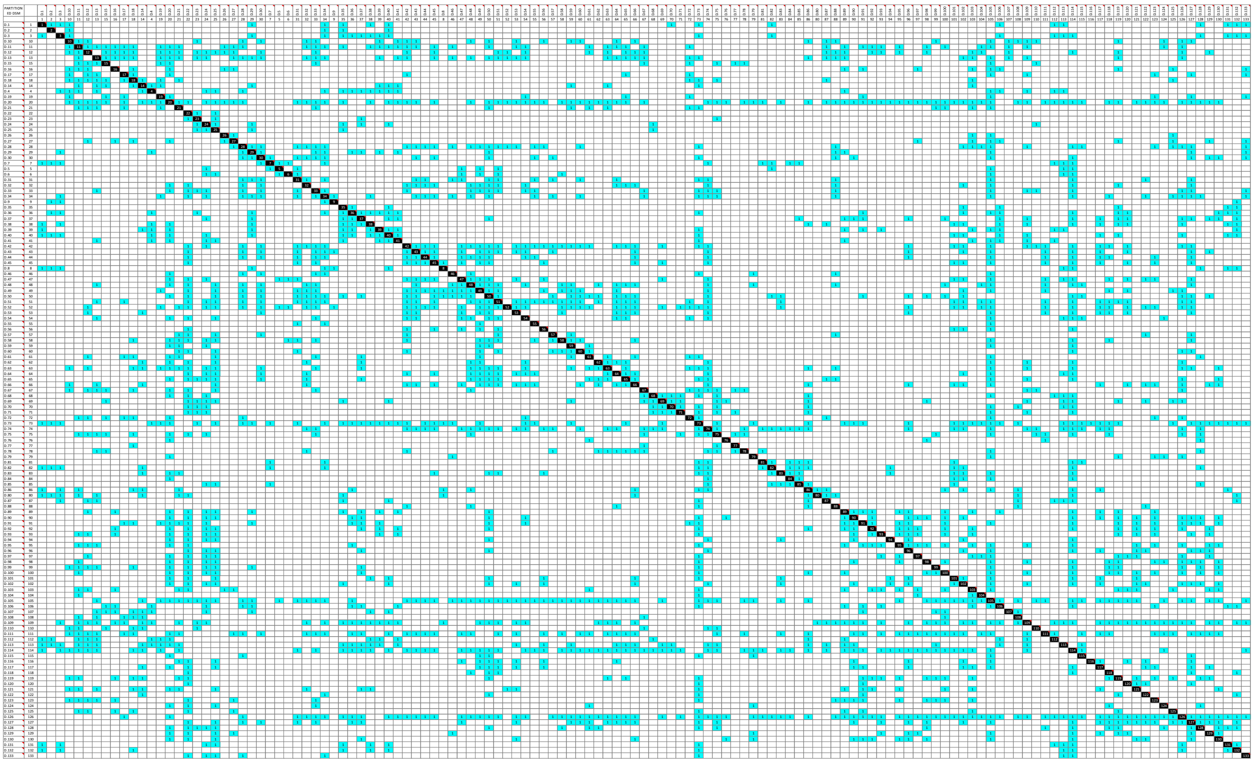


Figure 3-3: Partitioned DSM of the DfD Criteria Full Model

3.2 APPLYING THE MODEL - CASE STUDY

This section presents a case study in order to demonstrate the applicability and methodology to tailor and use the proposed DfD Criteria Model into the design of aerospace products. The case study was selected from the fighter aircraft industry for two main reasons:

a. The product studied gives some worst case for disassembly under considerably strict and unfavorable conditions. Disassembly of products on commercial aircrafts would be easier case studies and might not be enough to demonstrate the applicability and value of some DfD criteria of the model to cover all possible cases.

b. The actual disassembly sequence documentation (Technical Manuals of the fighter aircraft) was found and was available to be studied.

In order to validate and prove the DfD model applicability and methodology, it would be impossible to find manufacturers’ design data (non disclosable to outsiders) for the product and for this reason, excerpts from the official Technical Manuals (TM’s) of the fighter aircraft were used. In the case study, in the official TM’s text, citations to the applicable DfD model criteria were inserted. To avoid multiplication of citations, each applicable DfD model criterion was cited few times, regardless of its applicability in more than one assemblies / components.

3.2.1 DfD MODEL FOR A FIGHTER AIRCAFT ENGINE JET FUEL STARTER (JFS)

In this case we assume the disassembly of a JFS on a military fighter aircraft. For the purposes of this dissertation, the JFS is presented in a down to top approach, which will show the applicability of the DfD criteria listed in the developed model.

The Jet Fuel Starter (JFS) is a gas turbine which operates on aircraft fuel and drives the aircraft’s engine through the Accessory Drive Gearbox (ADG). The JFS is connected to the ADG and only provides torque when required to maintain aircraft’s engine rpm (rounds per minute). If the ADG is not able to rotate (i.e. seized engine), the JFS runs, but prevents it from rotating the ADG.

Figure 3-4: Engine Starting and Accessory Drive Gearbox System

The JFS receives fuel . The JFS is started by power from two brake/JFS accumulators used . The brake/JFS accumulators are charged . The JFS, the ADG and the respective connected equipment are located in the area of doors and of the aircraft.

The JFS is used to start the engine on the ground and to assist in engine airstart. During a ground engine start, the Brake/JFS accumulators begin to recharge after the engine accelerates through . As the engine accelerates through approximately a sensor causes the JFS to shut down automatically.

Figure 3-5: Modules of JFS and ADG

Both JFS and ADG are complex subassemblies (Figure 3-6) of the Engine Starting System (ESS) and are connected to many other complex assemblies as shown in Figure 3-7.

Figure 3-6: Accessory Drive Gearbox

Figure 3-7: Engine and Accessory Drive Gear boxes

3.2.1.1 ENGINE STARTING SYSTEM

Both JFS and ADG are assemblies of the aircraft's Engine Starting System (ESS), which is comprised from the subassemblies and components (criteria: D.33, D.67, D.74, D.75, D.114) listed in the following Table 3-5.

Table 3-5: Assemblies and Components - Fighter Aircraft Engine Starting System

a.	JET Fuel Start Switch (Jet Fuel Switch)	Three-position toggle switch . When the switch is moved it is latched. (criteria: D.20, D.48, D.52, D.56, D.66)
b.	JFS Hydraulic Solenoid Valves	Mounted in the . The valves are normally closed by a signal. Selection of both valves will cause the accumulator(s) to discharge its to the JFS hydraulic start motor (HSM). (criteria: D.1, D.3)
c.	JFS Lubrication (Lube) Pump Depriming Valve	Mounted . The valve is normally closed and opened . The valve taps into the ADG . (criteria: D.36)
d.	Hydraulic Accumulator Relay (Hyd Accumulator Relay)	. The relay is an electromagnetic device . It is used in conjunction with the controller to transfer an electrical signal . (criteria: D.59, D.60, D.61)
e.	ESS Controller/ Digital Engine Start System Controller (DESSC)	coupled to the engine starting system and It controls JFS operation (criteria: D.61, D.111)
f.	Door Open Relay	It is an electromagnetic, transfers a signal . (criteria: D.42, D.43, D.45)
g.	JFS Doors Control Valve	When energized, it shuttles the valve to port hydraulic pressure . (criteria: D.13, D.28)
h.	JFS Inlet and Exhaust Door Actuator	translates hydraulic pressure to mechanical motion (criteria: D.5, D.6, D.7, D.82)

i.	JFS Doors Switch	providing an electrical signal . (criteria: D.71)
j.	JFS Fuel Shutoff Valve	provides fuel shutoff and fuel supply for JFS operation. (criteria: D.63, D.93)
k.	JFS Fuel Filter	protects the engine starter system . (criteria: D.23, D.24, D.25, D.32, D.64, D.128)
l.	Hydraulic Start Motor Delay Valve	to react against sudden discharge pressure surges . (criteria: D.17)
m.	Hydraulic Start Motor	provides rotational power required (criteria: D.46, D.51, D.54, D.115, D.132)
n.	Jet Fuel Starter	The JFS is a gas turbine engine which consists of a flow compressor, a turbine, and a combustor. (criteria: D.34, D.91, D.99, D.131)
o.	JFS Fuel Control	The fuel control provides metered fuel to maintain JFS operation. (criteria: D.92, D.97, D.103, D.124, D.129)
p.	JFS Ignition Exciter	converting current into proper output . (criteria: D.19, D.44, D.47)
q.	JFS Fuel Valves	The valves provide metered fuel to the JFS during operation. (criteria: D.16, D.125)

r.	JFS Speed Sensor	The sensor produces an electrical impulse to sequence JFS operation. (criteria: D.11)
s.	PTO Speed Sensor	produces an electrical impulse . (criteria: D.12)
t.	JFS Lube Shutoff Valve	The valve is actuated to port lubrication to JFS . (criteria: D.18)
u.	JFS Servo Valve	Is a valve. The valve modulates pressure during JFS operation. (criteria: D.18, D.62)
v.	PTO Percent RPM Relay	the relay transfers an electrical signal to the main engine ignition system. (criteria: D.68, D.69, D.100)

Figure 3-8: Engine Starting System Access and Locator Data. (Sheet 1)

Figure 3-9: Engine Starting System Access and Locator Data. (Sheet 2)

Figure 3-10: Engine Starting System Access and Locator Data. (Sheet 3)

Figure 3-11: Engine Starting System Access and Locator Data. (Sheet 4)

Figure 3-12: Engine Starting System Access and Locator Data. (Sheet 5)

Figure 3-13: Engine Starting System Access and Locator Data. (Sheet 6)

Figure 3-14: Engine Starting System Access and Locator Data. (Sheet 7)

Figure 3-15: Engine Starting System Access and Locator Data. (Sheet 8)

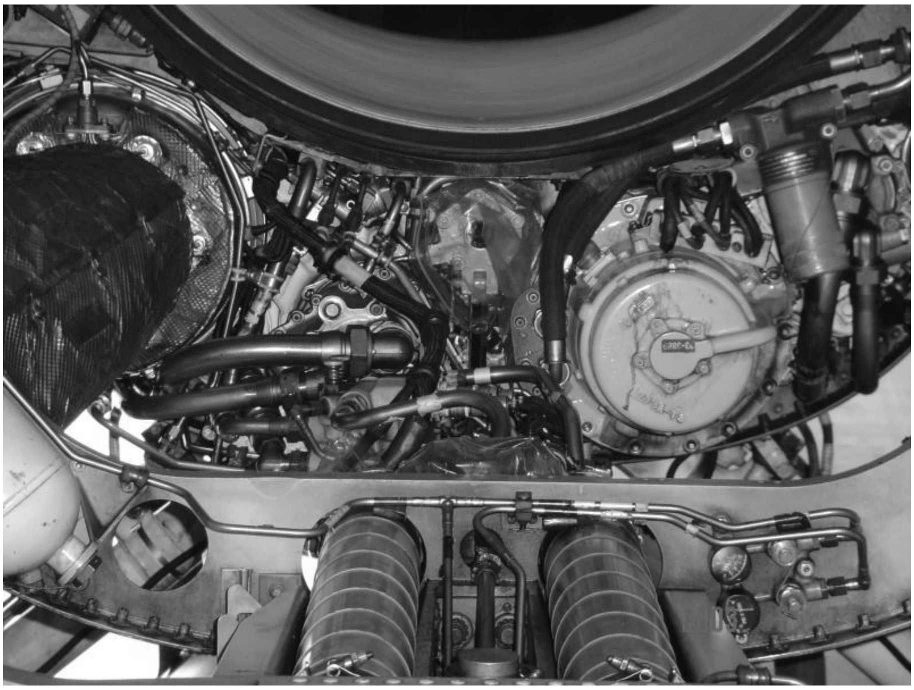


Figure 3-16: Fighter Aircraft F16 Engine Bay Area View

This is an F16 block 40 fighter aircraft engine bay with the panels completely removed. The tight design of assemblies and components is obvious

A pass-through reading of Table 3-5 reveals that during the design stages of the Engine Starting System, many of the criteria that comprise the DfD model of this dissertation were applied in this complex aerospace product. For the purposes of this dissertation however, the study will continue to the flight line removal - disassembly sequence of JFS (for parting-out purposes) and the applicable DfD criteria will be referenced for each task or group of tasks. In order to facilitate the understanding of how the DfD model criteria were allocated to each disassembly task some respective figures were added to the description of the sequence.

3.2.1.2 JET FUEL STARTER, REMOVAL - DISASSEMBLY

3.2.1.2.1 INPUT CONDITIONS

Disassembly Tasks:

1. Aircraft safe for maintenance. This is a proactive process which installs all safety devices (e.g. safety pins and locks) on the aircraft, to make sure that any work to be executed will not by any means jeopardize the safety of personnel and actuate or release any dangerous mechanisms, moving parts, fluids, gases, explosives of the aircraft (e.g. activate the actua-

tors which eject the aircraft's canopy and may even cause severe injury or death of personnel). For the purposes of this dissertation this "safe for maintenance" process it is not considered as part of the whole disassembly process, because it is independent from the exact area or the target item which is to be disassembled on the aircraft.

2. Remove access panel .

2.1. Personnel Recommended: One. Support Equipment: Torque Wrench (torque range 0-60 inch-pounds). Consumables: None. Safety Conditions: None. NOTE: Serviceable parts shall be retained for installation. Fasteners shall be pulled out to hold-open position to avoid binding.

2.2. Remove bolts. (criteria: D.35, D.37, D.41, D.61, D.88, D.89, D.90, D.93, D.95, D.97, D.103, D.104, D.123, D.124, D.126, D.127, D.129, D.130)

2.3. Remove panel. (criteria: D.47)

Figure 3-17: Access Panel of F-16 Aircraft

3. Open access door .

3.1. Personnel Recommended: Two. Technician A opens and closes the door. Technician B assists in opening and closing. Support Equipment: Torque Wrench (torque range 0-90 inch-pounds). Consumables: None. Safety Conditions: None. Additional Data: None (criteria: D.7, D.74)

3.2. Technicians (A,B): Disengage fasteners/latches on the door. (criteria: D.35, D.37, D.41, D.61, D.88, D.89, D.90, D.93, D.95, D.97, D.98, D.103, D.104, D.123, D.124, D.126, D.127, D.129, D.130)

3.3. Technicians (A,B): Open door. (criteria: D.47)

3.4. Technicians (A): Position strut on support bracket and engage retainer pin. (criteria: D.66, D.102, D.119)

Figure 3-18: Support Bracket of F-16 Aircraft Tacking Door

3.5. CAUTION: Technician A holds door (same tasks apply for door shown in the picture) while technician B carefully deploys forward and aft struts and engages strut retainer pins to prevent damage to door hinges or equipment. (criteria: D.5, D.7, D.74)

Personnel Recommended: Two. Technician A removes and installs JFS (at JFS). Technician B assists in removal and installation of JFS (at JFS).

Support Equipment:

a. Two (2) Torque Wrench (torque range 0-370 inch-pounds) (criteria: D.129, D.130)

b. One (1) Waste Fluid Container (criteria D.1, D.3)

3.2.1.2.2 REMOVAL OF JET FUEL STARTER

CAUTION: Use extreme care when in access door not to move cable out of normal routing; any bending or moving of the cable smaller than a bend radius will permanently damage cable control. This will be cause for cable control replacement. (criteria: D.7, D.49, D.74, D.86)

NOTE

a. Serviceable parts shall be retained for installation.

b. Protective devices shall be installed on open tubes, ports, and electrical connectors.

c. Two(2) wrenches shall be used when removing tubing and fittings. (criteria: D.123)

Disassembly Tasks:

1. Disconnect tube nuts and remove tube and purge tube. (criteria: D.3, D.61, D.65, D.78, D.114, D.117, D.118, D.124, D.133)

2. Disconnect connector. (criteria: D.58, D.76)

3. Remove safety wire and disconnect cable from ignitor. (criteria: D.58, D.59, D.60)

4. Remove safety wire and disconnect tube at JFS fuel control. Remove and discard seal(s) (if installed).NOTE: When disconnecting tubes, some residual fuel drainage may occur. Waste fluid container shall be used to catch fuel. (criteria: D.1, D.3, D.8, D.9, D.14, D.21, D.33, D.53, D.116, D.118, D.126)

5. Technician (A): Disconnect tubes. (criteria: D.50, D.61, D.83, D.96)

Figure 3-19: Removal of Jet Fuel Starter Fuel Tubes

CAUTION: JFS shall be supported until it is completely removed from alignment pins to prevent bending of alignment and damage to JFS . Care shall be used when removing JFS to prevent tube from being bent, twisted, or distorted. (criteria: D.30, D.54, D.74, D.77, D.80, D.86, D.87, D.88, D.109)

6. Technicians (A,B): Remove nut and expand coupling. (criteria: 63, 100)

   6.1. NOTE: When removing JFS from ADG, some residual lubricating oil drainage may occur. Waste fluid container shall be used to catch oil. (criteria: D.1, D.3)

7. Technicians (A,B): Carefully remove JFS from ADG and lower JFS out of aircraft. (criteria: D.26, D.28, D.30, D.31, D.42, D.43, D.44, D.45, D.49, D.51, D.52, D.63, D.73, D.78, D.81, D.85, D.86, D.87, D.88, D.105, D.109, D.114, D.115, D.126, D.127, D.128, D.131, D.132)

8. Technician (A): Remove from ADG. (criteria: D.61, D.63, D.90, D.91, D.92, D.100, D.114)

9. Technician (A): Remove and discard packings. (criteria: D.90, D.128)

Figure 3-20: Removal of JFS from ADG

10. Technician (A): Check all accessible wiring and connectors (and) for , , adequate support, and security. Repair if necessary. (criteria: D.68, D.69)

11. Technician (A): Check tubing for or damage. Repair or replace tubing if necessary.

12. Inspect ADG attach points for good condition.

    12.1. NOTE: If same JFS is to be installed (e.g. in case it was removed for access to other components on ADG), Step 13 through Step 16 shall be omitted.

13. Remove JFS duct (per substeps 13.xx below)

Figure 3-21: Jet Fuel Starter Exhaust Duct

13.1. Open access door

13.1.1. Personnel Recommended: Two(2). Technician A opens and closes doors (appropriate door). Technician B assists in opening and closing door. Support Equipment: two(2) Torque Wrench (torque range 0-90 inch-pounds). Consumables: None. Safety Conditions: None Additional Data: None (criteria: D.74)

13.1.1.1. Technicians (A,B): Disengage fasteners/latches. (criteria: D.35, D.37, D.41, D.61, D.66, D.88, D.89, D.90, D.95, D.98, D.103, D.104, D.123, D.126, D.127, D.129, D.130)

13.1.1.2. Technicians (A,B): Open door.

13.2. Personnel Recommended: Two(2). Technician A performs removal and installation of JFS duct and (access door). (4) Technician B assists in installation of JFS duct (in cockpit). Support Equipment: (3,4) Torque Wrench (torque range 0-50 inch-pounds) (criteria: D.7, D.74, D.129, D.130)

13.3. Remove wire and disconnect cable from JFS ignitor. (criteria: D.33, D.58, D.59, D.60, D.66)

13.4. Remove wire and insulation blankets. (criteria: D.90, D.100)

13.5. Remove wire and disconnect nut. (criteria: D.90)

13.6. Remove from duct mounting boss.(criteria:D.75, D.90)

13.6.1. CAUTION: Do not use lead pencil when marking JFS outer case; lead may cause damage to case. Only chalk or grease pencil is permissible. (criteria: D.38, D.40, D.41)

13.6.2. NOTE: The JFS duct is manufactured from 347 or 321 stainless steel. If welding is required to repair damage, repair shall be accomplished in accordance with MIL-W- 6858 using AMS 5680 filler. (criteria: D.29, D.38, D.39, D.40, D.41, D.106)

13.7. Loosen nut on coupling. Remove duct and check duct for damage. CAUTION: duct is made of thin sheet metal and is easily damaged. Use care when handling duct. (criteria: D.29, D.38, D.39, D.40, D.41, D.63, D.74, D.100, D.106, D.114)

Figure 3-22: Removal of Jet Fuel Starter Thermocouple Harness

14. Remove JFS harness (per substeps 14.xx below).

14.1. Personnel Recommended: One. Support Equipment: two (2) Torque Wrench (torque range 0-50 inch-pounds). Safety Conditions: None. Additional Data: None. (criteria: D.129, D.130)

14.2. Remove nut, bolt, and clamp. (criteria: D.58, D.61, D.101)

14.3. Remove wire and position insulation blankets out of way. (criteria: D.90, D.100)

14.4. Remove wire and disconnect nut. (criteria: D.90)

14.5. Remove from duct mounting . CAUTION: Use care when removing . Do not bend, twist, distort, or allow wrench to contact or damage may result. (criteria: D.4, D.7, D.18, D.29, D.33, D.34, D.40, D.73, D.74, D.80, D.86, D.90)

14.6. Remove bolts, , gasket, and from duct mounting . Discard gasket. (criteria: D.61, D.90, D.128)

14.7. Disconnect connector. (criteria: D.58, D.76)

14.8. Remove wire, nut, and harness from bracket.

15. Remove JFS duct (per substeps 15.xx below)

15.1. Personnel Recommended: One. Support Equipment: (2) Torque Wrench (torque range 0-40 inch-pounds). (1) Two 2 x 4 x 12 Inch Long Wooden Wedge-Shaped Blocks. (criteria: D.129, D.130)

15.2. CAUTION: Use care when removing . Do not bend, twist, distort, or allow wrench to contact or damage may result. (criteria: D.7, D.74)

15.3. Remove bolts, , gasket, and . Discard gasket. (criteria: D.61, D.75, D.90, D.128)

Figure 3-23: Removal of Jet Fuel Starter Inlet Duct

15.4. Remove wire, nut, and connector from . (criteria: D.61)

15.5. NOTE: duct is held securely in place with two packings. Wooden blocks may be used to aid in removal if required. JFS duct is manufactured from 6061 aluminum. If welding is required to repair damage, repair shall be made in accordance with using welding rod. (criteria: D.17, D.74, D.122)

15.6. Slide duct off end of JFS, discard , and visually check duct for damage. (criteria: D.48, D.90, D.128)

16. Technician (A): Remove wire; disconnect and remove from JFS. Remove and discard seal(s) (if installed) (criteria: D.90, D.128).

3.2.1.2.3 REVIEW OF RESULTS – BUILD THE DSM FOR JFS DISASSEMBLY

The disassembly sequence presented above, is listed in the official documentation of the aircraft F-16 Blk-30/50/52+ and constitutes the most effective sequence that is followed for years, in real life maintenance and technical support of the aircraft. This sequence provides proof of applicability for a total 92 of the 133 criteria of the proposed DfD Model of this dissertation. In particular, the criteria which were not deemed as applicable for the JFS disassembly are: D.2, D.6, D.10, D.11, D.12, D.13, D.15, D.16, D.19, D.20, D.22, D.23, D.24, D.25, D.27, D.32, D.36, D.46, D.55, D.56, D.57, D.62, D.64, D.67, D.70, D.71, D.72, D.79, D.82, D.84, D.94, D.99, D.107, D.108, D.110, D.111, D.112, D.113, D.120, D.121, D.125. This however does not mean that these criteria have no applicability on other aerospace products or the JFS itself, since JFS was not further disassembled to its lower level parts shown below in Figure 3-24.

Figure 3-24: Parts Breakdown -Jet Fuel Starter, Fuel Control, Cable and Exciter, Ducts and Engine Starter.

For example, criteria D.6, D.11, D.12, D.13, D.16, D.19, D.20, D.23, D.24, D.25, D.32, D.36, D.62, D.71, D.82, D.111 and D.125 were not deemed as applicable for the JFS dissassembly but they were indeed deemed as applicable for the whole Engine Start System of the aircraft, as previously presented in Table 3-5. Respectively, for other aerospace products, other set of DfD criteria included in the DfD Model can be applicable.

After identifying the applicable criteria for the JFS disassembly, then:

a. the non-applicable criteria were deleted from the DfD Criteria full Model (shown in Figure 3-2) to create a “tailored” DSM (dimension: 92x92) as shown in Figure 3-25.

b. the tailored DSM was processed to produce the partitioned DSM of Figure 3-26 where the criteria were arranged in order, based on their initial generic interrelations which were defined on the DfD Criteria full Model .

In order to process the tailored DSM matrix and produce the partitioned DSM, automated software found after research in open sources (internet) was used.

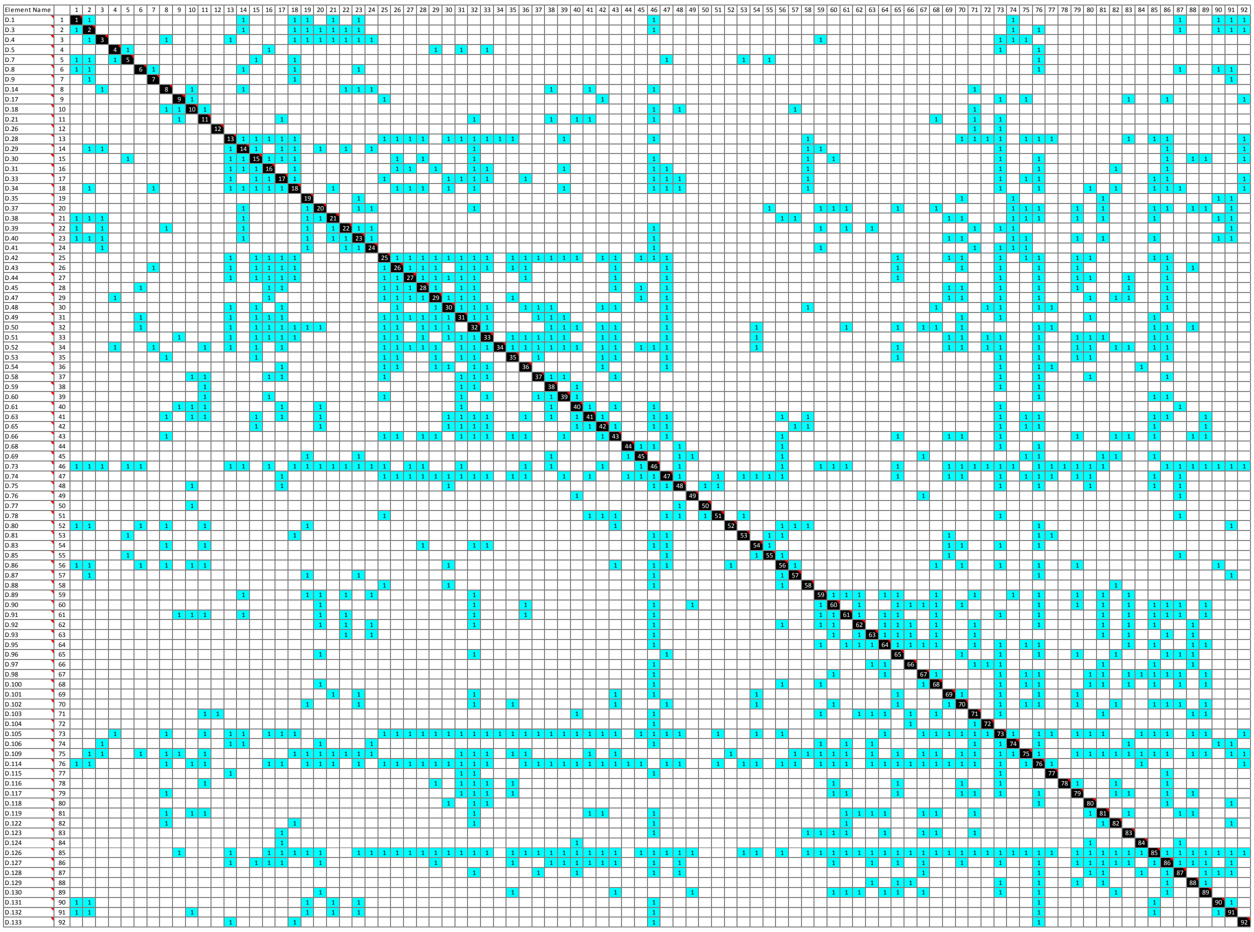


Figure 3-25: DfD Criteria for JFS of a Fighter Aircraft – Initial DSM

The initial order of criteria based on the scores given per criterion in the full Model was (Figure 3-25): D.1, D.3, D.4, D.5, D.7, D.8, D.9, D.14, D.17, D.18, D.21, D.26, D.28, D.29, D.30, D.31, D.33, D.34, D.35, D.37, D.38, D.39, D.40, D.41, D.42, D.43, D.44, D.45, D.47, D.48, D.49, D.50, D.51, D.52, D.53, D.54, D.58, D.59, D.60, D.61, D.63, D.65, D.66, D.68, D.69, D.73, D.74, D.75, D.76, D.77, D.78, D.80, D.81, D.83, D.85, D.86, D.87, D.88, D.89, D.90, D.91, D.92, D.93, D.95, D.96, D.97, D.98, D.100, D.101, D.102, D.103, D.104, D.105, D.106, D.109, D.114, D.115, D.116, D.117, D.118, D.119, D.122, D.123, D.124, D.126, D.127, D.128, D.129, D.130, D.131, D.132, D.133.

The final order of partitioned criteria is (Figure 3-26): D.1, D.3, D.29, D.4, D.14, D.18, D.17, D.21, D.28, D.30, D.7, D.5, D.31, D.33, D.34, D.9, D.35, D.37, D.38, D.39, D.40, D.41, D.42, D.43, D.44, D.45, D.8, D.47, D.48, D.49, D.50, D.51, D.52, D.53, D.54, D.58, D.59, D.60, D.61, D.63, D.65, D.66, D.69, D.68, D.73, D.74, D.75, D.76, D.77, D.78, D.81, D.83, D.85, D.86, D.80, D.87, D.88, D.89, D.90, D.91, D.92, D.93, D.95, D.96, D.97, D.98, D.100, D.101, D.102, D.103, D.26, D.104, D.105, D.106, D.109, D.114, D.115, D.116, D.117, D.118, D.119, D.122, D.123, D.124, D.126, D.127, D.128, D.129, D.130, D.131, D.132, D.133.

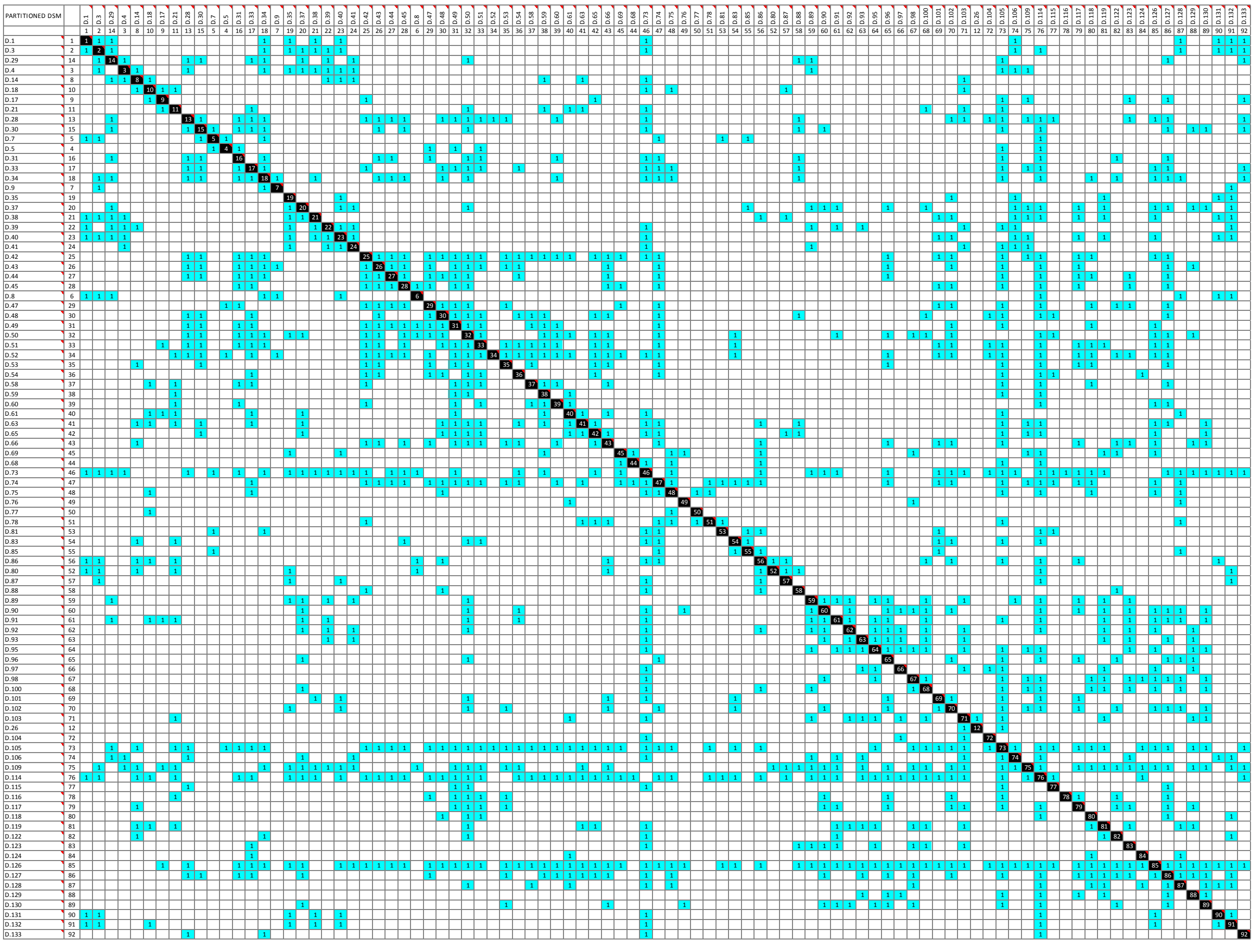


Figure 3-26: DfD Criteria for JFS of a Fighter Aircraft – Partitioned DSM

Both the initial and the partitioned DSM matrices are available in their native format. It is also reminded that the interrelations between each pair of criteria were not changed from what they were in the DfD Criteria full Model and their nature is binary (none or 1) declaring only the existence of a relationship, but neither its nature (positive or negative), nor its strength.

3.3 CONCLUSIONS

The executed research and developmental work revealed and proved that:

1. Human factors and ergonomy have a key role in disassembly and DfD of aerospace products.

2. Since disassembly is exercised on daily basis on aerospace products throughout their useful life, Design for Disassembly can and should be a widely applicable design consideration in Aerospace Industry. DfD applicability at products' EoL is already a proven approach.

3. The proposed DfD criteria full model is sufficient and tailorable, highly applicable for airworthy aerospace products. Its applicability at aerospace products' EoL is normally simpler.

4. For each aerospace product, a tailored DfD criteria model can be produced based on the proposed full model. This tailored model can accordingly influence products' design in several constructive and benefitial manners, but it should be used as advice / guidance and not as a mandatory driver for design decisions.

5. The DfD criteria full model has many binary inter-relationships among different or similar criteria. Its processing (e.g. partitioning) was an intensive complex task and in this dissertation could be applied only partially. Further elaboration of the model is possible, but in that case, its processing will probably require developlment or purchase of specialized software. This complexity should not be understood as a weakness of the DfD criteria full model; on the contrary, the model is recommended to be seen as a proof of realism in approaching the DfD of aerospace products, whose technological, physical and functional complexity is obvious and undouptable.

3.4 FUTURE WORK

Some options identified and recommended for future research on DfD for aerospace products:

1. Evolving – consolidating DfD criteria of the model with even more lean and efficient wording.

2. Collection of more information about aerospace products design and reevaluation of the DfD criteria weight factors (Appendix A, columns 2 until 8) in the DfD criteria full model.

3. Application of the model to more case studies, regarding specific aerospace products with frequent disassembly requirements or with high value of recovered or recycled components.

4. For specific aerospace products of interest, improvement of the model by assigning numeric values to its inter-relationships e.g. {-2, -1, 1, 2} and evolving the current Binary to a future Numeric DSM. This effort may require development or purchase of appropriate software to process (partitioning, tearing, banding) the resulting numeric DSM.

5. Trial exercise and verification of the DfD criteria full model's applicability to the early design of commercial aviation products, e.g. an airliner's assemblies or components. Such an investigation could drive many important conclusions but would need very close cooperation and access to design sections and teams in big Aerospace Industry companies.

6. Further evolution of the DfD model, based on study of the trends in Environmental protection Legislation, or potential cooperation with associates of AFRA, WINGNet, Tarmac Aerosave, to even better address the aircrafts' EoL decisions and disassembly.

Such work however, should aim to harmonically promote sustainable product design, rather than overriding primary criteria and disciplines in the design of Aerospace Industry products.

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APPENDIX A

[1]: Description of DfD criterion
[2]: Resulting weighted score for Life Cycle (= 2 * [4] + 5 * [5] + 6 * [6] + 4 * [7])
[3]: Resulting weighted score for EoL (= 2 * [4] + 5 * [5] + 6 * [6] + 4 * [8])
[4]: Score/ penalty for conceptual phase only
[5]: Score/ penalty for preliminary phase only
[6]: Score/ penalty for detailed phase only
[7]: Score/ penalty for Life Cycle phase only
[8]: Score/ penalty for EoL phase only
[9]: Codename of DfD criterion

CRITERIA DESCRIPTION - DEFINITION	LC	EoL	CONCEPTUAL	PRELIM	DETAILED	LC	EoL	CODENAME
[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]
CONTROL & MINIMIZE USE OF TOXIC - HAZARDOUS MATERIALS	149	119	6	7	8	9	6	**D.1**
AVOID BANNED SUBSTANCES (CD , ASBESTOS ETC)	148	128	6	8	8	8	7	**D.2**
CONTROL & RESTRICT THE USE OF SUBSTANCES THAT ARE POTENTIALLY HAZARDOUS OR DIFFICULT TO RECYCLE (e.g. COMPOSITES, SPECIAL COATINGS)	130	110	5	6	7	8	7	**D.3**
MAXIMIMIZE USE OF FEW, SIMPLE, RECYCLABLE, UNBLENDED MATERIALS	118	114	5	6	7	6	8	**D.4**
ARE ACCESS DOORS LOCATED AWAY FROM MOVING PARTS OR DO THEY CONCEAL MOVING PARTS THAT PRESENT A POTENTIAL HAZARD? IF THE CONCEALED HAZARD CANNOT BE AVOIDED, DOES THE ACCESS DOOR CONTAIN A LABEL ALERTING THE TECHNICIAN TO THIS HAZARD?	132	106		6	8	9	7	**D.5**
ENSURE THAT THE ACCESS OPENINGS ARE A SAFE DISTANCE FROM HIGH VOLTAGE POINTS OR HAZARDOUS MOVING PARTS	127	107		5	9	8	7	**D.6**
LABEL DANGEROUS OPERATIONS	123	101		3	9	9	8	**D.7**
NEED FOR ADDITIONAL SAFETY MEASURES, SUCH AS SPECIAL GLOVES, MASKS, UNIFORMS, BREATHING DEVICES	110	90		4	7	8	7	**D.8**
NORMAL CLOTHING & NORMAL SELF PROTECTION MEANS WORN BY THE TECHNICAL STAFF	99	79		3	6	8	7	**D.9**
HAS THE SYSTEM BEEN SEARCHED FOR SIMPLIFIED ALTERNATIVES?	119	101	9	7	6	5	3	**D.10**
IS THE DESIGN AS SIMPLE AS POSSIBLE?	143	119	6	7	8	8	6	**D.11**
SYSTEM SIMPLIFICATION TO REDUCE THE COSTS OF SPARES & TO IMPROVE THE EFFECTIVENESS OF MAINTENANCE & DISASSEMBLY	147	121	5	7	8	9	7	**D.12**
SIMPLIFY PRODUCT STRUCTURE	129	109	5	7	6	8	7	**D.13**
LEVEL OF TECHNOLOGICAL COMPLEXITY OF THE COMPONENT (e.g. DIFFERENT TECHNOLOGIES INVOLVED, COMPLEX STRUCTURE)	125	105		7	7	8	7	**D.14**
ARE FUNCTIONS & PARTS CONSOLIDATED?	124	98		8	7	7	4	**D.15**
MAXIMIZE THE USE OF COMMON PARTS	121	95		5	7	9	7	**D.16**

[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]
MINIMIZE THE NUMBER OF COMPONENTS WITHIN AN ASSEMBLY	114	96		6	7	7	6	**D.17**
OVERALL COMPLEXITY: HOW MANY SUBSYSTEMS ARE IN THE SYSTEM? HOW MANY PARTS ARE USED? ARE THE PARTS STANDARD OR SPECIAL PURPOSE?	110	94		4	7	8	8	**D.18**
REDUCE THE NUMBER OF PARTS WITHIN AN ASSEMBLY	108	96		6	7	6	6	**D.19**
SIMPLIFY MECHANISM & MECHANICS OF DISASSEMBLY	105	81		3	7	8	6	**D.20**
LEVEL OF COMPLEXITY & MULTIPLICITY OF THE INTERCONNECTIONS IN ASSEMBLIES & SUBASSEMBLIES	99	81		3	7	7	6	**D.21**
DISASSEMBLY FREQUENCY REQUIREMENTS (e.g. FOR MAINTENANCE)	143	113	3	7	8	9	6	**D.22**
DOES THE FAILURE OF SHORT-LIVED PARTS RESULT IN THE DISPOSAL OF LONG-LIVED PARTS?	143	113	3	7	8	9	6	**D.23**
COMPONENT LIFE	136	120	3	8	7	8	8	**D.24**
IS THE COMPONENT LIFE (OR INSPECTION INTERVAL) SHORT, SO DISASSEMBLING IT WILL BE NEEDED MANY TIMES?	132	102		6	8	9	6	**D.25**
INTERCHANGEABILITY: CAN THE FAILED OR MALFUNCTIONING UNIT BE READILY REPLACED WITH AN IDENTICAL UNIT WITH NO REQUIREMENT FOR ALTERATIONS & CALIBRATIONS?	143	117		7	9	9	7	**D.26**
ARE IDENTICAL PARTS USED WHEREVER POSSIBLE IN SIMILAR EQUIPMENT OR IN A SERIES OF A GIVEN TYPE, SUCH AS USING THE SAME PISTON & CYLINDER FOR A SERIES OF INTERNAL COMBUSTION ENGINES?	125	105		7	7	8	7	**D.27**
CONTROL & LIMIT (AS MUCH AS POSSIBLE) DESIGN FACTORS OF WEIGHT / SIZE / SHAPE OF COMPONENTS	142	128	9	8	7	7	7	**D.28**
USE STRUCTURAL FEATURES & HIGH-QUALITY MATERIALS TO MINIMIZE WEIGHT WITHOUT INTERFERING WITH NECESSARY FLEXIBILITY, IMPACT STRENGTH, OR FUNCTIONAL PROPERTIES	134	116	4	6	7	9	9	**D.29**
ARE HUMAN STRENGTH LIMITS CONSIDERED IN DESIGNING ALL DEVICES THAT MUST BE CARRIED, LIFTED, PULLED, PUSHED, TURNED DURING DISASSEMBLY?	127	101		5	8	9	7	**D.30**
ENSURE THAT HEAVY UNITS CAN BE PULLED OUT INSTEAD OF LIFTED OUT	126	102		6	8	8	6	**D.31**
ARE PARTS LOCATED SO THAT OTHER LARGE, DIFFICULT-TO-REMOVE PARTS DO NOT PREVENT ACCESS TO THEM?	126	100		6	7	9	7	**D.32**
DESIGN FOR MANY MODULAR UNITS - MAKE EACH MODULAR UNIT SMALL & LIGHT ENOUGH THAT A SINGLE PERSON CAN HANDLE & CARRY	114	90		6	6	8	6	**D.33**
HANDLING, MOBILITY, & TRANSPORTABILITY OF COMPONENTS & PARTS	99	75		3	6	8	6	**D.34**
SELECT COATINGS WHICH MINIMIZE CORROSION	137	119	6	7	8	7	6	**D.35**
USE BETTER MATERIALS, SURFACE TREATMENTS, OR STRUCTURAL ARRANGEMENTS TO PROTECT PRODUCTS FROM DIRT, CORROSION, & WEAR	139	119	4	7	8	8	7	**D.36**
CONSIDER LONG TERM EFFECTS (e.g. HARDENING OF PLASTIC, FATIGUE FAILURE, FRUSTRATION OF BROKEN SNAPS).	133	113	4	7	7	8	7	**D.37**

[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]
AVOID PAINTING PARTS WHEREVER POSSIBLE	123	103	4	5	7	8	7	**D.38**
MINIMIZE MATERIAL TYPES WITHIN AN ASSEMBLY	110	106	4	6	6	6	8	**D.39**
COATINGS, PLATING & FINISHES ON THE COMPONENT SURFACES	121	101	3	5	7	8	7	**D.40**
COMPONENTS, AS MUCH AS POSSIBLE, SHOULD BE MADE OF HOMOGENEOUS - COMMON MATERIALS	119	113		7	7	7	9	**D.41**
MAINTAIN OPEN SPACE IN THE DESIGN TO ACCOMMODATE AT LEAST THE WORK ENVELOPE & VISION REQUIREMENTS WITHIN THIS ENVELOPE.	135	111	2	7	8	8	6	**D.42**
IS ENOUGH ACCESS ROOM PROVIDED FOR TASKS THAT NECESSITATE THE INSERTION OF TWO HANDS & TWO ARMS (IF NEEDED) THROUGH THE ACCESS?	137	111		7	8	9	7	**D.43**
ARE ACCESS DOORS MADE IN WHATEVER SHAPE IS NECESSARY TO PERMIT PASSAGE OF THE COMPONENTS & IMPLEMENTS THAT MUST PASS THROUGH?	137	111		7	8	9	7	**D.44**
IF THE TECHNICIAN MUST BE ABLE TO SEE WHAT HE IS DOING INSIDE THE EQUIPMENT, DOES THE ACCESS PROVIDE ENOUGH ROOM FOR THE TECHNICIAN'S HANDS OR ARMS & STILL PROVIDE AN ADEQUATE VIEW OF WHAT HE IS TO DO?	126	106		6	8	8	7	**D.45**
COMPONENT SYMMETRY FOR MATERIAL HANDLING	119	99		7	6	8	7	**D.46**
OPTIMIZE USE (& LOCATION) OF ACCESS PANELS, FOR INSPECTIONS / TESTS & ACCESS TO COMPONENTS TO BE DISASSEMBLED	117	91		3	8	9	7	**D.47**
MINIMIZE NEED FOR COMPLEX & TWISTED DISASSEMBLY PATHS	116	96		4	8	8	7	**D.48**
CONSIDER & CONTROL SPATIAL CONSTRAINTS	116	90		4	7	9	7	**D.49**
CONTROL & MINIMIZE THE TIME THAT IRREGULAR WORKING POSTURES WILL BE NEEDED FOR DISASSEMBLY	111	81		3	7	9	6	**D.50**
OPTIMIZE THE SPATIAL ALIGNMENT BETWEEN VARIOUS COMPONENTS TO FACILITATE DISASSEMBLY WITHOUT JEOPARDIZING ASSEMBLABILITY, FUNCTIONALITY & STRUCTURAL SOUNDNESS	110	86		4	7	8	6	**D.51**
GENERAL ACCESSIBILITY, WORK SPACE, & WORK CLEARANCE OF PARTS, TEST POINTS, ADJUSTMENTS, & CONNECTIONS	110	86		4	7	8	6	**D.52**
INSUFFICIENT CLEARANCE FOR EFFECTIVE TOOL MANIPULATION	106	82		2	8	8	6	**D.53**
NUMBER OF DISASSEMBLY DIRECTIONS SHOULD BE RESTRICTED	105	81		3	7	8	6	**D.54**
ARE HANDLES PLACED WHERE THEY WILL NOT CATCH ON OTHER UNITS, WIRING, OR STRUCTURAL MEMBERS?	104	86		4	7	7	6	**D.55**
VISIBILITY. CAN THE ITEM (WHICH IS TO BE WORKED ON) BE SEEN?	95	75		1	7	8	7	**D.56**
IS IT POSSIBLE TO MOVE UNITS THAT ARE DIFFICULT TO CONNECT/ DISCONNECT, WHEN INSTALLED/ REMOVED, TO CONVENIENT POSITIONS FOR CONNECTING & DISCONNECTING?	126	100		6	7	9	7	**D.57**
ROUTE WIRING CABLES TO FACILITATE REMOVAL	137	111		7	8	9	7	**D.58**
AVOID THE USE OF LARGE CABLE CONNECTORS	136	116		8	8	8	7	**D.59**
ARE CABLES ROUTED SO THEY NEED NOT BE SHARPLY BENT OR UNBENT WHEN BEING CONNECTED OR DISCONNECTED?	132	102		6	8	9	6	**D.60**
NUMBER OF CONNECTORS TO DISCONNECT FOR DISASSEMBLY	109	89		5	6	8	7	**D.61**

[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]
DESIGN ASSEMBLY SEQUENCE BASED ON DISASSEMBLY PRIORITY OF COMPONENTS	136	106		8	7	9	6	**D.62**
MINIMIZE THE NUMBER OF **COMPONENT PARTS & CONNECTORS** THAT MUST BE DISASSEMBLED PRIOR TO THE DISASSEMBLY (FOR MAINTENANCE OR E.O.L. PURPOSES)	131	109		7	7	9	8	**D.63**
ARE UNITS PLACED SO THAT STRUCTURAL MEMBERS DO NOT PREVENT ACCESS TO THEM?	130	106		8	7	8	6	**D.64**
NUMBER OF ROOT ITEMS TO BE DISASSEMBLED IN ORDER TO MINIMIZE DISASSEMBLY COST	121	101		5	8	8	7	**D.65**
DEGREE OF **ACCESSIBILITY OF COMPONENTS & FASTENERS** TO ENHANCE QUICK & EASY DISASSEMBLY	116	90		4	7	9	7	**D.66**
GROUP COMPONENTS **BY FUNCTION INTO MODULES** THAT CAN BE SEPARATELY REMOVED OR INSTALLED.	125	101		7	7	8	6	**D.67**
IF TEST PROCEDURES ARE TO BE APPLIED BEFORE DISPOSAL, ARE THEY CLEARLY SPECIFIED, & DO THEY PROVIDE CLEAR & UNEQUIVOCAL RESULTS?	133	107		5	9	9	7	**D.68**
MAXIMIZE TESTABILITY & INSPECTABILITY OF PARTS, ADJUSTMENTS, & CONNECTIONS.	122	96		4	8	9	7	**D.69**
ARE ALL DIAGNOSTIC PARAMETER & MEASUREMENT LIMITS ESTABLISHED?	118	92		2	9	9	7	**D.70**
TESTABILITY. CAN SYSTEM FAULTS BE DETECTED READILY & ISOLATED TO THE FAULTY REPLACEABLE ASSEMBLY LEVEL?	106	80		2	7	9	7	**D.71**
DOES THE DESIGN MINIMIZE SYSTEM COMPONENTS WHILE CONSIDERING REQUIREMENTS FOR REDUNDANCY?	125	103	6	7	6	7	5	**D.72**
PRODUCE PRODUCT DATA SHEETS, INCLUDING DATA ON MATERIALS COMPOSITION, MASS, & GEOMETRY OF COMPONENTS	136	116	5	6	8	8	7	**D.73**
DESIGN FOR UPGRADING, REPAIR, & RECYCLING THROUGH GOOD ACCESS, LABELING, MODULES, & BREAKPOINTS, & PROVIDE GOOD MANUALS	132	114		6	8	9	9	**D.74**
ESTABLISH HIERARCHICAL & MODULAR STRUCTURE, EASILY SEPARABLE INTO ITS MAIN FUNCTIONAL UNITS	125	107		7	8	7	6	**D.75**
PROVIDE TACTILE FEEDBACK WHEN THE PART IS PROPERLY & FULLY JOINED, SUCH AS AN AUDIBLE SNAP & A NOTICEABLE VIBRATION THAT OCCURS WHEN PARTS ARE JOINED & UN-JOINED.	122	92		4	8	9	6	**D.76**
FUNCTIONAL IMPORTANCE OF COMPONENT	120	100		6	7	8	7	**D.77**
DOES THE DESIGN ALLOW FOR LOGICAL & SEQUENTIAL FUNCTION & TASK ALLOCATIONS?	119	101		7	7	7	6	**D.78**
PREFER SYMMETRICAL PART MATING WHEN THE ASSEMBLY OPERATES PROPERLY WHEN SO ASSEMBLED, OTHERWISE GO TO SEMISYMMETRICAL OR ASYMMETRICAL MATING.	115	91		5	7	8	6	**D.79**
DEFINE REQUIREMENTS & NEEDS FOR TRAINING TO DISASSEMBLE	106	82		2	8	8	6	**D.80**
ARE LABELS USED TO INDICATE THE DIRECTION OF MOVEMENT OF CONTROLS, ESPECIALLY WHERE LACK OF SUCH KNOWLEDGE MAY RESULT IN DAMAGE TO EQUIPMENT?	106	80		2	7	9	7	**D.81**
DO ADEQUATE LABELS APPEAR ON EVERY ITEM THE TECHNICIAN MUST RECOG-	106	80		2	7	9	7	**D.82**

[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]
NIZE, READ, OR MANIPULATE?								
MAXIMIZE RECOGNIZABILITY OF DISASSEMBLY POINTS	102	76			8	9	7	**D.83**
ARE LABELS PLACED FOR FULL, UNOBSTRUCTED VIEW?	95	75		1	7	8	7	**D.84**
IDENTIFICATION & LABELING. ARE COMPONENTS UNIQUELY IDENTIFIED? ARE THE LABELS PERMANENT, OR ARE THEY EASILY ERASED OR OBLITERATED BY OPERATION OR MAINTENANCE ACTIONS? ARE LABELS POSITIONED TO BE EASILY READ?	95	75		1	7	8	7	**D.85**
NEED FOR INSTRUCTIONS OR SKILLED WORKERS TO DISASSEMBLE	89	69		1	6	8	7	**D.86**
NUMBER OF SKILL LEVELS NEEDED FOR DISASSEMBLY	110	82		4	7	8	5	**D.87**
NUMBER OF PERSONNEL REQUIRED FOF THE DISASSEMBLY	99	79		3	6	8	7	**D.88**
IN ORDER OF PREFERENCE, USE (1) MOLDED-IN FASTENERS (SAME MATERIAL) (2) SEPARATE FASTENERS OF SAME OR COMPATIBLE MATERIAL (3) FERROUS METAL FASTENERS (EASY TO REMOVE DUE TO MAGNETIC PROPERTIES) (4) NON-FERROUS METAL FASTENERS (CAN BE REMOVED USING, e.g., EDDY-CURRENT)	132	106		6	8	9	7	**D.89**
SELECT FASTENER SYSTEMS THAT FACILITATE DISASSEMBLY	127	101		5	8	9	7	**D.90**
MINIMIZE THE SIZE & NUMBERS & TYPES OF CONNECTIVE FASTENERS IN THE MECHANICAL PARTS (e.g. MACHINES, ENGINES) DESIGN, SUBJECT TO ADEQUATE STRENGTH.	125	101		7	7	8	6	**D.91**
COMMONIZE FASTENERS BUT DO NOT JEOPARDIZE STRUCTURAL INTEGRITY OR FUNCTION	120	100		6	7	8	7	**D.92**
IS THE SAME TYPE OF FASTENER USED FOR ALL COVERS & CASES ON GIVEN EQUIPMENT?	116	96		4	8	8	7	**D.93**
PROVIDE CUES THAT MAKE IT EASIER TO LOCATE & IDENTIFY FASTENERS	116	92		4	8	8	6	**D.94**
NUMBER OF FASTENER TYPES SHOULD BE RESTRICTED	110	90		4	7	8	7	**D.95**
FASTENERS SHOULD BE ACCESSIBLE AND, IF FORCES HAVE TO BE APPLIED, THIS SHOULD BE FACILITATED	110	86		4	7	8	6	**D.96**
ARE BOLTS, SCREWS, & OTHER FEATURES THE SAME SIZE FOR ALL COVERS & CASES ON A GIVEN PIECE OF EQUIPMENT?	106	80		2	7	9	7	**D.97**
USE SNAP FITS WHEREVER POSSIBLE TO REDUCE THE USE OF ADDITIONAL FASTENERS (BUT DO NOT JEOPARDIZE PRODUCT INTEGRITY)	104	82		4	7	7	5	**D.98**
HAS THE NUMBER OF ATTACHMENTS BEEN MINIMIZED?	100	80		2	7	8	7	**D.99**
USE THE MINIMUM JOINING ELEMENTS POSSIBLE (DFD PRINCIPLE) & USE SCREWS, ADHESIVES, WELDING, SNAP FITS, GEOMETRIC LOCKING, & SO ON, ACCORDING TO DFD GUIDELINES.	99	77		3	7	7	5	**D.100**
CLEARLY INDICATED & NOT HIDDEN FASTENERS, TO LOOSEN TO GAIN ACCESS TO THE PRODUCT'S INTERIOR OR FOR SEPARATING IT IN MODULES	90	66			7	8	6	**D.101**
FACILITATE TOOL ACCESS TO FASTENERS	115	95		5	7	8	7	**D.102**

[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]
ARE PARTS, FASTENERS, CONNECTORS, LINES, CABLES, ETC., STANDARDIZED THROUGHOUT THE SYSTEM, PARTICULARLY FROM UNIT TO UNIT WITHIN THE SYSTEM?	110	90		4	7	8	7	**D.103**
ARE THE ATTACHING PARTS FOR DOORS & ITEMS ALL THE SAME SIZE IN EACH APPLICATION? ARE ANY DIFFERENCES OF SIZE NECESSARY?	95	71		1	7	8	6	**D.104**
INTERFACE WITH COMPUTER-AIDED ENGINEERING & COMPUTER-AIDED DESIGN TECHNIQUES	139	125	7	7	8	7	7	**D.105**
DESIGN PARTS & TOOLING THAT OPTIMIZE MATERIAL USAGE	115	101	3	5	7	7	7	**D.106**
COST ASSOCIATED WITH MANUFACTURING & ASSEMBLING THE COMPONENT	129	109	2	7	7	8	7	**D.107**
LEVEL OF MANUFACTURING EXPERTISE ASSOCIATED WITH MANUFACTURING & ASSEMBLING THE COMPONENT	120	104		6	7	8	8	**D.108**
COST ASSOCIATED WITH TAKING THE COMPONENT APART & RECYCLING IT	119	107		7	6	8	9	**D.109**
PROBABILITY OF COMPONENT DESIGN UNDERGOING FUNDAMENTAL CHANGES IN THE FUTURE (USEFUL LIFE) THAT FUNDAMENTALLY AFFECT ITS FUNCTIONALITY, EFFICIENCY AND/OR PERFORMANCE (DRIVES THE NEED FOR UPGRADES + MOD-ULARITY)	102	72		6	7	5		**D.110**
MINIMIZE BASE TIME: THE TIME REQUIRED TO DO THE BASIC TASK MOVEMENTS WITHOUT DIFFICULTY	93	75		3	6	7	6	**D.111**
DESTRUCTIVE DISMANTLEMENT POSSIBLE	82	76		2	5	7	9	**D.112**
PARTIAL DESTRUCTIVE DISMANTLEMENT POSSIBLE	82	72		2	5	7	8	**D.113**
NONDESTRUCTIVE DISMANTLEMENT POSSIBLE	82	68		2	5	7	7	**D.114**
DESIGN THE PART IN SUCH A WAY THAT IT IS OBVIOUS HOW IT IS TO BE ORIENT-ED DURING DISASSEMBLY/ REASSEMBLY.	120	100		6	7	8	7	**D.115**
TOOL POSITIONING	106	86		2	8	8	7	**D.116**
POSITIONING: DEFINE & CONTROL THE DEGREE OF PRECISION REQUIRED TO EF-FECTIVELY PLACE THE TOOL OR HAND(S) FOR DISASSEMBLY PURPOSES	105	81		3	7	8	6	**D.117**
ARE IRREGULAR EXTENSIONS, SUCH AS BOLTS, TABLES, WAVEGUIDES, & HOSES, EASY TO REMOVE BEFORE THE UNIT IS HANDLED?	105	85		3	7	8	7	**D.118**
(LIMITATION OF) NUMBERS & VARIETIES OF NECESSARY TOOLS, ACCESSORIES & SUPPORT EQUIPMENTS	100	76		2	7	8	6	**D.119**
WEIGHT & SIZE OF TOOLS EXTENSIVELY USED FOR DISASSEMBLY (LARGE / HEAVY / UNSYMMETRICAL?)	99	81		3	7	7	6	**D.120**
REQUIREMENTS OF SPECIALIZED MANUAL TOOLS IN ORDER TO FACILITATE DIS-ASSEMBLY	99	79		3	6	8	7	**D.121**
USE OF SPECIALIZED FIXTURES	88	70		2	6	7	6	**D.122**
REQUIREMENTS OF COMMON TOOLS	88	70		2	6	7	6	**D.123**
CONNECTIONS SHOULD BE REVERSIBLE AS MUCH AS POSSIBLE	88	62		2	6	7	4	**D.124**

[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]
ARE STANDARD PARTS & TOOLS USED?	78	60			6	7	6	**D.125**
CONTROL & MINIMIZE TOTAL FORCE & ENERGY/ ENTROPY NEEDED FOR THE DIS-ASSEMBLY	121	95		5	7	9	7	**D.126**
CONTROL & MINIMIZE LEVEL OF EXERTION OF MANUAL FORCE FOR DISASSEMBLY	105	81		3	7	8	6	**D.127**
HAVE QUICK DISCONNECTS BEEN PROVIDED FOR HYDRAULIC, FUEL, OIL, & PNEUMATIC LINE COUPLINGS FOR ALL COMPONENTS SUBJECT TO TIME RE-PLACEMENT OR MINIMUM SERVICE LIFE & FOR ALL MODULAR COMPONENTS?	105	81		3	7	8	6	**D.128**
ARE ALL WRENCHING FUNCTIONS DESIGNED FOR THE SAME (WHEN POSSIBLE) SIZE WRENCH? SAME OR SIMILAR TORQUE VALUES?	95	71		1	7	8	6	**D.129**
AMOUNT OF FORCE (OR TORQUE) REQUIRED FOR DISENGAGING COMPONENTS (IN CASE OF SNAP FITS) OR UNFASTENING FASTENERS	89	65		1	6	8	6	**D.130**
DEFINE & CONTROL THE NEED FOR PREPARATION OPERATION SUCH AS CLEAN-ING & DEGREASING PRIOR TO ACCESS & DISASSEMBLY	105	85		3	7	8	7	**D.131**
PREPARATION OPERATION SUCH AS CLEANING & DEGREASING PRIOR TO DISAS-SEMBLY	103	85		5	6	7	6	**D.132**
DESIGN TO MINIMIZE THE NEEDS FOR PACKAGING	93	75		3	6	7	6	**D.133**

APPENDIX B

DEPENDENCY REPORT - COMPLETE DFD CRITERIA MODEL

CRITERION	DEPENDS ON
D.1	D.2, D.3, D.10, D.29, D.34, D.35, D.38, D.40, D.70, D.73, D.82, D.106, D.112, D.113, D.128, D.131, D.132, D.133.
D.2	D.10, D.34, D.35, D.40.
D.3	D.1, D.10, D.29, D.34, D.35, D.36, D.37, D.38, D.39, D.40, D.73, D.82, D.106, D.112, D.113, D.114, D.128, D.131, D.132, D.133.
D.4	D.3, D.10, D.11, D.13, D.14, D.24, D.25, D.28, D.34, D.35, D.36, D.37, D.38, D.39, D.40, D.41, D.89, D.105, D.106, D.109, D.112, D.113.
D.5	D.7, D.24, D.31, D.47, D.49, D.51, D.82, D.105, D.113, D.114.
D.6	D.5, D.24, D.25, D.31, D.47, D.49, D.51, D.58, D.105, D.113, D.114.
D.7	D.1, D.2, D.3, D.5, D.6, D.30, D.34, D.74, D.81, D.82, D.84, D.85, D.112, D.113, D.114.
D.8	D.1, D.2, D.3, D.9, D.29, D.34, D.40, D.113, D.114, D.128, D.131, D.132.
D.9	D.2, D.3, D.34, D.132.
D.10	D.11, D.12, D.23, D.28, D.30, D.32, D.33, D.39, D.41, D.42, D.43, D.48, D.50, D.53, D.56, D.59, D.60, D.64, D.66, D.86, D.87, D.88, D.99, D.105, D.107, D.108, D.109, D.110, D.119, D.124, D.126, D.127.
D.11	D.10, D.12, D.13, D.15, D.16, D.17, D.18, D.19, D.20, D.21, D.26, D.27, D.28, D.32, D.33, D.34, D.35, D.38, D.39, D.40, D.41, D.42, D.43, D.45, D.46, D.50, D.53, D.54, D.61, D.63, D.64, D.65, D.67, D.72, D.87, D.89, D.91, D.92, D.93, D.95, D.98, D.100, D.104, D.105, D.107, D.109, D.124, D.126.
D.12	D.10, D.11, D.15, D.16, D.17, D.18, D.19, D.20, D.21, D.23, D.24, D.25, D.26, D.27, D.30, D.33, D.42, D.45, D.51, D.52, D.54, D.61, D.63, D.65, D.66, D.67, D.87, D.88, D.89, D.92, D.93, D.95, D.98, D.103, D.104, D.107, D.114, D.119, D.126, D.129.
D.13	D.11, D.15, D.16, D.17, D.18, D.19, D.20, D.21, D.23, D.24, D.27, D.28, D.29, D.30, D.32, D.33, D.34, D.39, D.41, D.42, D.45, D.46, D.48, D.50, D.51, D.52, D.53, D.54, D.63, D.64, D.65, D.66, D.67, D.72, D.73, D.86, D.87, D.88, D.89, D.102, D.103, D.105, D.107, D.109, D.119, D.126.
D.14	D.4, D.11, D.13, D.15, D.18, D.19, D.29, D.39, D.40, D.41, D.59, D.63, D.73, D.103.
D.15	D.11, D.12, D.13, D.19, D.20, D.33, D.67, D.72, D.75, D.77, D.78, D.105, D.110.
D.16	D.10, D.11, D.12, D.18, D.20, D.26, D.27, D.89, D.91, D.97, D.103, D.105, D.106, D.119, D.125, D.133.
D.17	D.10, D.12, D.13, D.18, D.20, D.42, D.65, D.72, D.105, D.109, D.123, D.127, D.133.
D.18	D.10, D.11, D.12, D.13, D.14, D.15, D.17, D.19, D.21, D.72, D.73, D.75, D.87, D.103, D.125.
D.19	D.10, D.15, D.17, D.20, D.54, D.65, D.72, D.91, D.105, D.123, D.127, D.133.
D.20	D.4, D.10, D.11, D.12, D.13, D.14, D.15, D.17, D.19, D.21, D.22, D.24, D.25, D.26, D.27, D.28, D.31, D.32, D.33, D.34, D.35, D.38, D.40, D.41, D.42, D.43, D.45, D.48, D.50, D.51, D.52, D.53, D.54, D.55, D.56, D.58, D.59, D.60, D.61, D.62, D.63, D.64, D.65, D.67, D.74, D.75, D.76, D.78, D.79, D.81, D.83, D.86, D.87, D.88, D.89, D.90, D.91, D.92, D.93, D.94, D.95, D.96, D.97, D.98, D.99, D.100, D.101, D.102, D.103, D.104, D.105, D.108, D.109, D.111, D.112, D.113, D.114, D.115, D.118, D.119, D.121, D.122, D.123, D.124, D.126, D.127, D.128, D.129, D.130.
D.21	D.11, D.12, D.13, D.17, D.19, D.33, D.50, D.59, D.61, D.63, D.72, D.73, D.99, D.100, D.103, D.105.
D.22	D.23, D.25.
D.23	D.22, D.25, D.37, D.75.
D.24	D.23, D.25, D.29, D.35, D.37, D.40, D.68, D.110.
D.25	D.23, D.24, D.29, D.35, D.68.
D.26	D.27, D.103, D.105, D.125.

CRITERION	DEPENDS ON
D.27	D.12, D.16, D.18, D.20, D.26, D.97, D.103, D.105, D.106, D.119, D.125, D.129, D.133.
D.28	D.27, D.29, D.30, D.31, D.32, D.33, D.34, D.42, D.43, D.44, D.45, D.46, D.48, D.49, D.50, D.51, D.52, D.53, D.55, D.56, D.60, D.73, D.88, D.102, D.103, D.104, D.105, D.109, D.114, D.115, D.123, D.125, D.126, D.127, D.133.
D.29	D.3, D.4, D.28, D.30, D.33, D.34, D.36, D.37, D.39, D.41, D.50, D.88, D.89, D.105, D.127, D.133.
D.30	D.7, D.28, D.29, D.31, D.32, D.33, D.34, D.43, D.45, D.50, D.55, D.57, D.73, D.88, D.90, D.105, D.114, D.127, D.129, D.130, D.133.
D.31	D.28, D.29, D.30, D.32, D.34, D.43, D.44, D.46, D.47, D.50, D.51, D.55, D.57, D.60, D.64, D.73, D.74, D.88, D.105, D.114, D.122, D.127.
D.32	D.20, D.22, D.28, D.30, D.42, D.43, D.44, D.45, D.48, D.49, D.50, D.51, D.54, D.64, D.65, D.66, D.74, D.88, D.102, D.105, D.114, D.119, D.127.
D.33	D.13, D.20, D.22, D.23, D.24, D.28, D.30, D.31, D.34, D.42, D.48, D.49, D.50, D.51, D.54, D.55, D.67, D.73, D.74, D.75, D.88, D.105, D.109, D.110, D.114, D.126, D.127, D.133.
D.34	D.3, D.9, D.19, D.22, D.24, D.28, D.29, D.30, D.31, D.33, D.38, D.43, D.44, D.45, D.46, D.48, D.50, D.55, D.57, D.60, D.67, D.73, D.74, D.75, D.88, D.105, D.114, D.118, D.122, D.125, D.126, D.127, D.128, D.133.
D.35	D.36, D.40, D.102, D.106, D.119, D.131, D.132.
D.36	D.2, D.3, D.4, D.23, D.29, D.34, D.35, D.37, D.38, D.39, D.40, D.41, D.73, D.91, D.102, D.105, D.106, D.114, D.119, D.120, D.130, D.131, D.132.
D.37	D.24, D.29, D.35, D.36, D.40, D.41, D.50, D.85, D.89, D.90, D.91, D.96, D.100, D.106, D.109, D.114, D.117, D.119, D.120, D.126, D.127, D.129, D.130, D.132.
D.38	D.1, D.3, D.4, D.20, D.29, D.35, D.36, D.37, D.86, D.87, D.101, D.102, D.106, D.109, D.114, D.117, D.119, D.120, D.126, D.131, D.132.
D.39	D.1, D.4, D.14, D.20, D.29, D.35, D.36, D.38, D.40, D.41, D.73, D.89, D.91, D.93, D.103, D.105, D.106, D.112, D.113, D.132.
D.40	D.1, D.2, D.3, D.4, D.20, D.24, D.29, D.35, D.36, D.38, D.39, D.41, D.73, D.101, D.102, D.106, D.109, D.117, D.119, D.126, D.131, D.132.
D.41	D.4, D.13, D.20, D.24, D.25, D.35, D.39, D.40, D.73, D.89, D.103, D.105, D.106, D.109, D.112.
D.42	D.22, D.24, D.28, D.30, D.31, D.32, D.33, D.34, D.43, D.44, D.45, D.47, D.48, D.49, D.50, D.51, D.53, D.54, D.55, D.56, D.57, D.58, D.59, D.60, D.61, D.64, D.65, D.66, D.69, D.73, D.74, D.96, D.101, D.102, D.105, D.109, D.110, D.111, D.114, D.117, D.118, D.120, D.126, D.127.
D.43	D.9, D.22, D.28, D.30, D.31, D.33, D.34, D.42, D.44, D.45, D.47, D.49, D.50, D.51, D.53, D.54, D.57, D.66, D.74, D.96, D.102, D.105, D.111, D.114, D.117, D.120, D.127, D.129.
D.44	D.22, D.28, D.30, D.31, D.33, D.34, D.42, D.43, D.45, D.47, D.48, D.49, D.50, D.54, D.55, D.66, D.74, D.96, D.105, D.111, D.114, D.117, D.118, D.123, D.127.
D.45	D.8, D.22, D.31, D.33, D.42, D.43, D.44, D.47, D.49, D.50, D.56, D.66, D.69, D.74, D.101, D.102, D.105, D.111, D.114, D.117, D.120, D.123, D.127.
D.46	D.20, D.28, D.30, D.33, D.34, D.48, D.73, D.79, D.88, D.105.
D.47	D.5, D.6, D.20, D.22, D.24, D.31, D.42, D.43, D.44, D.45, D.48, D.49, D.50, D.53, D.56, D.69, D.74, D.101, D.102, D.105, D.111, D.113, D.114, D.118, D.120, D.122, D.123, D.127.
D.48	D.13, D.20, D.22, D.25, D.28, D.30, D.32, D.33, D.43, D.46, D.47, D.49, D.50, D.51, D.54, D.58, D.59, D.62, D.64, D.65, D.66, D.74, D.79, D.88, D.100, D.104, D.105, D.111, D.114, D.115, D.127.
D.49	D.8, D.19, D.22, D.25, D.28, D.30, D.31, D.32, D.33, D.42, D.43, D.44, D.45, D.46, D.47, D.48, D.50, D.51, D.56, D.58, D.59, D.60, D.64, D.74, D.102, D.105, D.111, D.118, D.120, D.125, D.126.
D.50	D.8, D.20, D.22, D.25, D.28, D.30, D.31, D.32, D.33, D.34, D.35, D.37, D.42, D.43, D.45, D.46, D.47, D.48, D.51, D.57, D.59, D.60, D.61, D.62, D.64, D.65, D.66, D.74, D.82, D.83, D.91, D.96, D.98, D.100, D.102, D.114, D.115, D.126, D.127, D.129.
D.51	D.13, D.17, D.22, D.24, D.25, D.28, D.30, D.31, D.32, D.33, D.34, D.42, D.43, D.45, D.48, D.49, D.50, D.53, D.54, D.55, D.56, D.57, D.58, D.59, D.60, D.62, D.64, D.65, D.66, D.72, D.74, D.83, D.101, D.102, D.104, D.105, D.111, D.114, D.117, D.118, D.119, D.120, D.126, D.127.

CRITERION	DEPENDS ON
D.52	D.5, D.6, D.9, D.12, D.19, D.21, D.22, D.24, D.25, D.28, D.30, D.32, D.33, D.42, D.43, D.44, D.45, D.47, D.49, D.50, D.51, D.53, D.54, D.58, D.59, D.60, D.61, D.64, D.65, D.66, D.69, D.71, D.72, D.73, D.74, D.83, D.96, D.101, D.102, D.104, D.105, D.111, D.114, D.117, D.118, D.120, D.122, D.123, D.126, D.127.
D.53	D.12, D.14, D.30, D.42, D.43, D.47, D.49, D.50, D.58, D.64, D.65, D.66, D.74, D.96, D.105, D.111, D.114, D.117, D.118, D.120, D.127.
D.54	D.13, D.20, D.22, D.25, D.33, D.42, D.43, D.47, D.48, D.50, D.51, D.64, D.65, D.72, D.74, D.105, D.113, D.114, D.115, D.124.
D.55	D.31, D.34, D.49, D.105.
D.56	D.22, D.42, D.45, D.47, D.49, D.51, D.101, D.102, D.105, D.114.
D.57	D.21, D.22, D.25, D.30, D.42, D.51, D.59, D.88, D.122, D.127.
D.58	D.6, D.18, D.20, D.21, D.22, D.24, D.25, D.31, D.33, D.42, D.49, D.50, D.51, D.55, D.57, D.59, D.60, D.66, D.105, D.114, D.118, D.127.
D.59	D.20, D.21, D.24, D.49, D.50, D.61, D.105, D.114.
D.60	D.21, D.22, D.25, D.31, D.42, D.49, D.51, D.57, D.58, D.59, D.61, D.114, D.126, D.127.
D.61	D.12, D.17, D.18, D.20, D.21, D.25, D.33, D.37, D.49, D.59, D.63, D.66, D.72, D.73, D.105, D.128.
D.62	D.14, D.20, D.22, D.25, D.32, D.37, D.48, D.49, D.54, D.63, D.64, D.65, D.74, D.105, D.109, D.114, D.126.
D.63	D.10, D.12, D.14, D.18, D.19, D.20, D.21, D.22, D.24, D.25, D.30, D.33, D.37, D.48, D.49, D.50, D.51, D.54, D.59, D.61, D.62, D.65, D.72, D.73, D.74, D.86, D.88, D.105, D.109, D.114, D.126, D.127, D.130.
D.64	D.22, D.24, D.25, D.30, D.32, D.42, D.45, D.48, D.49, D.50, D.51, D.53, D.54, D.55, D.63, D.65, D.66, D.74, D.102, D.105, D.113, D.114.
D.65	D.20, D.22, D.23, D.24, D.25, D.30, D.32, D.37, D.48, D.49, D.50, D.51, D.61, D.62, D.63, D.66, D.73, D.74, D.87, D.88, D.105, D.109, D.114, D.126, D.130.
D.66	D.10, D.13, D.14, D.25, D.32, D.42, D.43, D.45, D.47, D.49, D.50, D.51, D.53, D.54, D.55, D.60, D.62, D.64, D.65, D.74, D.86, D.96, D.101, D.102, D.105, D.117, D.120, D.122, D.123, D.126, D.129, D.130.
D.67	D.10, D.12, D.13, D.15, D.18, D.20, D.22, D.25, D.33, D.48, D.72, D.73, D.74, D.75, D.77, D.78, D.109, D.110, D.126.
D.68	D.20, D.22, D.24, D.67, D.69, D.70, D.71, D.73, D.75, D.86, D.105, D.112, D.113, D.114.
D.69	D.15, D.22, D.23, D.24, D.25, D.35, D.40, D.59, D.67, D.68, D.70, D.71, D.75, D.76, D.86, D.98, D.109, D.113, D.114, D.119, D.122, D.125, D.126.
D.70	D.22, D.23, D.24, D.68, D.69, D.71, D.73, D.75, D.86, D.105, D.108, D.113, D.114.
D.71	D.22, D.23, D.24, D.68, D.69, D.70, D.73, D.75, D.77, D.86, D.105, D.109, D.114.
D.72	D.11, D.12, D.15, D.17, D.18, D.20, D.28, D.54, D.73, D.87, D.105, D.123, D.126.
D.73	D.1, D.2, D.3, D.4, D.7, D.8, D.19, D.20, D.23, D.25, D.28, D.29, D.31, D.34, D.35, D.36, D.37, D.38, D.39, D.40, D.41, D.42, D.44, D.45, D.46, D.49, D.54, D.55, D.59, D.65, D.69, D.75, D.79, D.86, D.89, D.90, D.91, D.96, D.101, D.102, D.103, D.104, D.105, D.106, D.108, D.113, D.114, D.115, D.116, D.117, D.118, D.119, D.125, D.127, D.128, D.129, D.130, D.131, D.132, D.133.
D.74	D.32, D.33, D.42, D.43, D.44, D.45, D.47, D.48, D.49, D.50, D.51, D.53, D.54, D.56, D.57, D.60, D.63, D.64, D.67, D.68, D.69, D.73, D.75, D.78, D.81, D.82, D.83, D.84, D.85, D.86, D.96, D.101, D.102, D.105, D.109, D.110, D.113, D.114, D.115, D.117, D.118, D.126, D.128.
D.75	D.11, D.12, D.13, D.15, D.18, D.20, D.22, D.24, D.33, D.48, D.67, D.71, D.73, D.74, D.77, D.78, D.99, D.105, D.110, D.111, D.114, D.118, D.126, D.128.
D.76	D.20, D.61, D.98, D.111, D.128.
D.77	D.18, D.67, D.75.
D.78	D.13, D.15, D.32, D.42, D.57, D.62, D.63, D.64, D.65, D.66, D.67, D.74, D.75, D.77, D.81, D.105, D.128.
D.79	D.20, D.46, D.105, D.119, D.123, D.124, D.126.
D.80	D.1, D.2, D.3, D.8, D.11, D.13, D.14, D.21, D.22, D.35, D.66, D.86, D.87, D.88, D.108, D.114, D.132.

CRITERION	DEPENDS ON
D.81	D.7, D.34, D.73, D.74, D.82, D.84, D.85, D.86, D.101, D.114, D.115.
D.82	D.1, D.2, D.3, D.7, D.14, D.34, D.73, D.74, D.81, D.84, D.85, D.86, D.94, D.101, D.102, D.114, D.128.
D.83	D.14, D.20, D.21, D.45, D.50, D.51, D.56, D.73, D.74, D.82, D.84, D.85, D.94, D.101, D.102, D.105, D.114.
D.84	D.20, D.74, D.85, D.101, D.102, D.105, D.114.
D.85	D.7, D.24, D.25, D.74, D.82, D.83, D.84, D.86, D.101, D.128.
D.86	D.1, D.3, D.8, D.11, D.14, D.18, D.21, D.36, D.48, D.66, D.73, D.74, D.80, D.87, D.100, D.102, D.105, D.108, D.114, D.117, D.131.
D.87	D.3, D.12, D.13, D.35, D.40, D.73, D.86, D.108, D.112, D.113, D.114, D.132.
D.88	D.42, D.48, D.64, D.73, D.86, D.108, D.122.
D.89	D.12, D.16, D.20, D.22, D.24, D.25, D.29, D.35, D.37, D.39, D.41, D.50, D.90, D.91, D.92, D.95, D.96, D.100, D.103, D.106, D.114, D.117, D.119, D.123.
D.90	D.20, D.22, D.24, D.25, D.36, D.37, D.50, D.54, D.73, D.76, D.89, D.92, D.96, D.97, D.98, D.100, D.102, D.114, D.117, D.119, D.121, D.123, D.126, D.127, D.128, D.130.
D.91	D.17, D.18, D.19, D.20, D.21, D.22, D.24, D.29, D.36, D.37, D.39, D.50, D.54, D.72, D.73, D.89, D.90, D.92, D.95, D.96, D.100, D.105, D.114, D.119, D.121, D.123, D.126, D.127, D.128, D.130.
D.92	D.16, D.20, D.22, D.24, D.25, D.37, D.39, D.41, D.50, D.73, D.86, D.89, D.90, D.95, D.96, D.97, D.100, D.103, D.114, D.119, D.121, D.123, D.126, D.129.
D.93	D.11, D.12, D.16, D.20, D.22, D.24, D.25, D.39, D.41, D.73, D.90, D.92, D.95, D.96, D.97, D.100, D.103, D.119, D.121, D.123, D.127, D.129.
D.94	D.20, D.22, D.24, D.25, D.50, D.74, D.83, D.90, D.96, D.102, D.114.
D.95	D.11, D.12, D.13, D.20, D.22, D.36, D.73, D.89, D.91, D.92, D.93, D.96, D.97, D.98, D.100, D.103, D.105, D.109, D.114, D.121, D.123, D.126, D.129, D.130.
D.96	D.22, D.24, D.25, D.37, D.50, D.74, D.102, D.105, D.114, D.117, D.121, D.122, D.127, D.128, D.129.
D.97	D.12, D.20, D.22, D.24, D.25, D.73, D.93, D.95, D.103, D.104, D.105, D.119, D.120, D.121, D.126, D.129.
D.98	D.11, D.20, D.22, D.24, D.25, D.73, D.90, D.95, D.100, D.105, D.109, D.114, D.118, D.119, D.123, D.124, D.126, D.127, D.128, D.130.
D.99	D.10, D.11, D.12, D.13, D.18, D.20, D.22, D.24, D.25, D.29, D.37, D.73, D.105, D.114, D.118, D.119, D.126, D.128, D.130.
D.100	D.11, D.20, D.22, D.24, D.25, D.37, D.73, D.86, D.89, D.98, D.99, D.105, D.109, D.114, D.118, D.119, D.121, D.123, D.126, D.128, D.130.
D.101	D.20, D.22, D.25, D.38, D.40, D.50, D.56, D.66, D.73, D.83, D.94, D.96, D.102, D.105, D.114, D.117, D.121.
D.102	D.20, D.22, D.24, D.25, D.35, D.40, D.50, D.53, D.56, D.66, D.74, D.83, D.90, D.94, D.96, D.101, D.105, D.109, D.114, D.117, D.121, D.122, D.126, D.127, D.128, D.130.
D.103	D.11, D.12, D.16, D.21, D.22, D.26, D.27, D.61, D.73, D.89, D.92, D.93, D.95, D.97, D.100, D.105, D.119, D.120, D.121, D.125, D.129, D.130.
D.104	D.11, D.73, D.97, D.103.
D.105	D.5, D.13, D.14, D.19, D.20, D.21, D.22, D.23, D.24, D.25, D.28, D.29, D.31, D.32, D.33, D.34, D.36, D.42, D.43, D.44, D.45, D.46, D.47, D.48, D.49, D.50, D.51, D.52, D.53, D.54, D.55, D.56, D.57, D.58, D.59, D.60, D.61, D.62, D.63, D.64, D.65, D.66, D.69, D.73, D.74, D.75, D.78, D.79, D.83, D.86, D.95, D.98, D.99, D.100, D.101, D.102, D.103, D.104, D.106, D.108, D.110, D.111, D.114, D.115, D.117, D.118, D.119, D.120, D.121, D.124, D.126, D.127, D.129, D.130, D.133.
D.106	D.4, D.15, D.16, D.24, D.28, D.29, D.36, D.37, D.41, D.73, D.89, D.91, D.93, D.103, D.105, D.114, D.123, D.131, D.132.
D.107	D.4, D.13, D.14, D.15, D.16, D.18, D.24, D.29, D.38, D.40, D.91, D.99, D.100, D.108.
D.108	D.11, D.13, D.14, D.17, D.18, D.67, D.100.
D.109	D.3, D.4, D.8, D.11, D.12, D.13, D.14, D.16, D.17, D.21, D.23, D.24, D.32, D.34, D.35, D.36, D.37, D.38, D.39, D.40, D.41, D.49, D.50, D.51, D.53, D.54, D.62, D.63, D.64, D.66, D.80, D.87, D.88, D.89, D.90, D.91,

CRITERION	DEPENDS ON
	D.93, D.96, D.98, D.99, D.100, D.102, D.103, D.105, D.106, D.108, D.112, D.113, D.114, D.117, D.118, D.119, D.120, D.121, D.122, D.123, D.124, D.125, D.126, D.127, D.129, D.130, D.132, D.133.
D.110	D.10, D.11, D.14, D.15, D.18, D.23, D.67, D.74, D.75.
D.111	D.10, D.11, D.12, D.13, D.17, D.18, D.20, D.21, D.27, D.28, D.30, D.32, D.33, D.34, D.36, D.37, D.40, D.42, D.43, D.44, D.45, D.47, D.48, D.51, D.53, D.56, D.58, D.60, D.61, D.63, D.64, D.65, D.66, D.75, D.78, D.83, D.86, D.90, D.91, D.93, D.95, D.96, D.97, D.98, D.99, D.100, D.101, D.102, D.104, D.105, D.109, D.112, D.115, D.117, D.118, D.123, D.124, D.125, D.127, D.128, D.129, D.130.
D.112	D.1, D.2, D.4, D.11, D.12, D.13, D.19, D.20, D.38, D.39, D.41, D.68, D.86, D.89, D.106, D.109.
D.113	D.1, D.2, D.3, D.4, D.11, D.12, D.13, D.14, D.19, D.20, D.21, D.35, D.36, D.37, D.38, D.39, D.41, D.53, D.56, D.59, D.64, D.65, D.66, D.69, D.70, D.74, D.75, D.86, D.87, D.89, D.90, D.99, D.106, D.109, D.115.
D.114	D.1, D.3, D.10, D.11, D.12, D.13, D.14, D.18, D.19, D.21, D.31, D.33, D.35, D.36, D.37, D.38, D.40, D.42, D.43, D.44, D.45, D.47, D.48, D.49, D.50, D.51, D.54, D.55, D.56, D.58, D.59, D.60, D.61, D.62, D.63, D.64, D.65, D.66, D.67, D.68, D.69, D.70, D.71, D.74, D.75, D.78, D.79, D.81, D.83, D.84, D.86, D.87, D.89, D.90, D.91, D.93, D.94, D.95, D.96, D.97, D.98, D.99, D.100, D.101, D.102, D.103, D.105, D.109, D.115, D.124, D.133.
D.115	D.20, D.28, D.49, D.50, D.73, D.79, D.105, D.127.
D.116	D.21, D.22, D.25, D.47, D.49, D.50, D.51, D.53, D.56, D.64, D.90, D.96, D.102, D.105, D.117, D.120, D.122, D.127.
D.117	D.14, D.20, D.22, D.25, D.49, D.50, D.51, D.53, D.56, D.90, D.91, D.96, D.102, D.103, D.105, D.114, D.122, D.123, D.127, D.129.
D.118	D.22, D.48, D.50, D.51, D.114, D.127, D.132.
D.119	D.10, D.11, D.14, D.16, D.18, D.21, D.22, D.50, D.63, D.65, D.73, D.91, D.92, D.93, D.95, D.98, D.99, D.100, D.103, D.118, D.121, D.123, D.125, D.128, D.129.
D.120	D.22, D.73, D.91, D.121, D.122, D.127.
D.121	D.10, D.11, D.13, D.14, D.18, D.20, D.21, D.25, D.32, D.37, D.38, D.52, D.53, D.73, D.89, D.91, D.92, D.95, D.100, D.103, D.117, D.130.
D.122	D.14, D.34, D.50, D.73, D.91, D.119, D.132.
D.123	D.10, D.11, D.12, D.13, D.16, D.22, D.27, D.33, D.73, D.88, D.89, D.90, D.91, D.95, D.98, D.99, D.100, D.103.
D.124	D.20, D.22, D.25, D.33, D.61, D.79, D.118, D.128.
D.125	D.11, D.12, D.16, D.18, D.22, D.27, D.73, D.89, D.91, D.103, D.119.
D.126	D.17, D.20, D.28, D.31, D.32, D.33, D.34, D.35, D.36, D.37, D.40, D.41, D.42, D.43, D.44, D.45, D.47, D.48, D.49, D.50, D.51, D.53, D.54, D.57, D.58, D.59, D.60, D.61, D.62, D.63, D.64, D.65, D.66, D.69, D.71, D.73, D.74, D.75, D.76, D.79, D.81, D.82, D.83, D.84, D.86, D.88, D.89, D.90, D.91, D.92, D.93, D.95, D.96, D.97, D.98, D.99, D.100, D.101, D.102, D.103, D.104, D.105, D.106, D.108, D.109, D.111, D.112, D.113, D.114, D.115, D.117, D.118, D.119, D.120, D.121, D.122, D.123, D.124, D.125, D.127, D.128, D.129, D.130, D.131, D.132, D.133.
D.127	D.22, D.25, D.28, D.30, D.31, D.33, D.36, D.37, D.47, D.53, D.59, D.60, D.61, D.63, D.64, D.65, D.66, D.73, D.75, D.90, D.93, D.96, D.98, D.102, D.105, D.114, D.117, D.118, D.119, D.120, D.121, D.122, D.123, D.125, D.126, D.128, D.129, D.130, D.132.
D.128	D.20, D.22, D.23, D.24, D.25, D.50, D.58, D.61, D.62, D.73, D.75, D.98, D.111, D.114, D.118, D.119, D.124, D.127, D.130, D.131, D.132.
D.129	D.20, D.22, D.25, D.27, D.46, D.79, D.93, D.96, D.97, D.105, D.114, D.117, D.119, D.120, D.127, D.130.
D.130	D.20, D.22, D.25, D.37, D.53, D.66, D.76, D.79, D.90, D.91, D.92, D.95, D.96, D.98, D.105, D.114, D.121, D.122, D.127.
D.131	D.1, D.3, D.24, D.25, D.35, D.38, D.40, D.73, D.112, D.113, D.114, D.126, D.132.
D.132	D.1, D.3, D.18, D.35, D.38, D.40, D.73, D.113, D.114, D.126, D.131.
D.133	D.22, D.24, D.25, D.28, D.34, D.73, D.113, D.114.

CRITERION	DEPENDS ON

DEPENDENCY REPORT - JFS DFD CRITERIA MODEL

CRITERION	DEPENDS ON
D.1	D.3, D.29, D.34, D.35, D.38, D.40, D.73, D.106, D.128, D.131, D.132, D.133.
D.3	D.1, D.29, D.34, D.35, D.37, D.38, D.39, D.40, D.73, D.106, D.114, D.128, D.131, D.132, D.133.
D.4	D.3, D.14, D.28, D.34, D.35, D.37, D.38, D.39, D.40, D.41, D.89, D.105, D.106, D.109.
D.5	D.7, D.31, D.47, D.49, D.51, D.105, D.114.
D.7	D.1, D.3, D.5, D.30, D.34, D.74, D.81, D.85, D.114.
D.8	D.1, D.3, D.9, D.29, D.34, D.40, D.114, D.128, D.131, D.132.
D.9	D.3, D.34, D.132.
D.14	D.4, D.18, D.29, D.39, D.40, D.41, D.59, D.63, D.73, D.103.
D.17	D.18, D.42, D.65, D.105, D.109, D.123, D.127, D.133.
D.18	D.14, D.17, D.21, D.73, D.75, D.87, D.103.
D.21	D.17, D.33, D.50, D.59, D.61, D.63, D.73, D.100, D.103, D.105.
D.26	D.103, D.105.
D.28	D.29, D.30, D.31, D.33, D.34, D.42, D.43, D.44, D.45, D.48, D.49, D.50, D.51, D.52, D.53, D.60, D.73, D.88, D.102, D.103, D.104, D.105, D.109, D.114, D.115, D.123, D.126, D.127, D.133.
D.29	D.3, D.4, D.28, D.30, D.33, D.34, D.37, D.39, D.41, D.50, D.88, D.89, D.105, D.127, D.133.
D.30	D.7, D.28, D.29, D.31, D.33, D.34, D.43, D.45, D.50, D.73, D.88, D.90, D.105, D.114, D.127, D.129, D.130, D.133.
D.31	D.28, D.29, D.30, D.34, D.43, D.44, D.47, D.50, D.51, D.60, D.73, D.74, D.88, D.105, D.114, D.122, D.127.
D.33	D.28, D.30, D.31, D.34, D.42, D.48, D.49, D.50, D.51, D.54, D.73, D.74, D.75, D.88, D.105, D.109, D.114, D.126, D.127, D.133.
D.34	D.3, D.9, D.28, D.29, D.30, D.31, D.33, D.38, D.43, D.44, D.45, D.48, D.50, D.60, D.73, D.74, D.75, D.88, D.105, D.114, D.118, D.122, D.126, D.127, D.128, D.133.
D.35	D.40, D.102, D.106, D.119, D.131, D.132.
D.37	D.29, D.35, D.40, D.41, D.50, D.85, D.89, D.90, D.91, D.96, D.100, D.106, D.109, D.114, D.117, D.119, D.126, D.127, D.129, D.130, D.132.
D.38	D.1, D.3, D.4, D.29, D.35, D.37, D.86, D.87, D.101, D.102, D.106, D.109, D.114, D.117, D.119, D.126, D.131, D.132.
D.39	D.1, D.4, D.14, D.29, D.35, D.38, D.40, D.41, D.73, D.89, D.91, D.93, D.103, D.105, D.106, D.132.
D.40	D.1, D.3, D.4, D.29, D.35, D.38, D.39, D.41, D.73, D.101, D.102, D.106, D.109, D.117, D.119, D.126, D.131, D.132.
D.41	D.4, D.35, D.39, D.40, D.73, D.89, D.103, D.105, D.106, D.109.
D.42	D.28, D.30, D.31, D.33, D.34, D.43, D.44, D.45, D.47, D.48, D.49, D.50, D.51, D.53, D.54, D.58, D.59, D.60, D.61, D.65, D.66, D.69, D.73, D.74, D.96, D.101, D.102, D.105, D.109, D.114, D.117, D.118, D.126, D.127.
D.43	D.9, D.28, D.30, D.31, D.33, D.34, D.42, D.44, D.45, D.47, D.49, D.50, D.51, D.53, D.54, D.66, D.74, D.96, D.102, D.105, D.114, D.117, D.127, D.129.
D.44	D.28, D.30, D.31, D.33, D.34, D.42, D.43, D.45, D.47, D.48, D.49, D.50, D.54, D.66, D.74, D.96, D.105, D.114, D.117, D.118, D.123, D.127.
D.45	D.8, D.31, D.33, D.42, D.43, D.44, D.47, D.49, D.50, D.66, D.69, D.74, D.101, D.102, D.105, D.114, D.117, D.123, D.127.
D.47	D.5, D.31, D.42, D.43, D.44, D.45, D.48, D.49, D.50, D.53, D.69, D.74, D.101, D.102, D.105, D.114, D.118, D.122, D.123, D.127.
D.48	D.28, D.30, D.33, D.43, D.47, D.49, D.50, D.51, D.54, D.58, D.59, D.65, D.66, D.74, D.88, D.100, D.104, D.105, D.114, D.115, D.127.
D.49	D.8, D.28, D.30, D.31, D.33, D.42, D.43, D.44, D.45, D.47, D.48, D.50, D.51, D.58, D.59, D.60, D.74, D.102, D.105, D.118, D.126.
D.50	D.8, D.28, D.30, D.31, D.33, D.34, D.35, D.37, D.42, D.43, D.45, D.47, D.48, D.51, D.59, D.60, D.61, D.65, D.66, D.74, D.83, D.91, D.96, D.98, D.100, D.102, D.114, D.115, D.126, D.127, D.129.
D.51	D.17, D.28, D.30, D.31, D.33, D.34, D.42, D.43, D.45, D.48, D.49, D.50, D.53, D.54, D.58, D.59, D.60, D.65, D.66, D.74, D.83, D.101, D.102, D.104, D.105, D.114, D.117, D.118, D.119, D.126, D.127.
D.52	D.5, D.9, D.21, D.28, D.30, D.33, D.42, D.43, D.44, D.45, D.47, D.49, D.50, D.51, D.53, D.54, D.58, D.59, D.60, D.61, D.65, D.66, D.69, D.73, D.74, D.83, D.96, D.101, D.102, D.104, D.105, D.114, D.117, D.118, D.122, D.123, D.126, D.127.

CRITERION	DEPENDS ON
D.53	D.14, D.30, D.42, D.43, D.47, D.49, D.50, D.58, D.65, D.66, D.74, D.96, D.105, D.114, D.117, D.118, D.127.
D.54	D.33, D.42, D.43, D.47, D.48, D.50, D.51, D.65, D.74, D.105, D.114, D.115, D.124.
D.58	D.18, D.21, D.31, D.33, D.42, D.49, D.50, D.51, D.59, D.60, D.66, D.105, D.114, D.118, D.127.
D.59	D.21, D.49, D.50, D.61, D.105, D.114.
D.60	D.21, D.31, D.42, D.49, D.51, D.58, D.59, D.61, D.114, D.126, D.127.
D.61	D.17, D.18, D.21, D.33, D.37, D.49, D.59, D.63, D.66, D.73, D.105, D.128.
D.63	D.14, D.18, D.21, D.30, D.33, D.37, D.48, D.49, D.50, D.51, D.54, D.59, D.61, D.65, D.73, D.74, D.86, D.88, D.105, D.109, D.114, D.126, D.127, D.130.
D.65	D.30, D.37, D.48, D.49, D.50, D.51, D.61, D.63, D.66, D.73, D.74, D.87, D.88, D.105, D.109, D.114, D.126, D.130.
D.66	D.14, D.42, D.43, D.45, D.47, D.49, D.50, D.51, D.53, D.54, D.60, D.65, D.74, D.86, D.96, D.101, D.102, D.105, D.117, D.122, D.123, D.126, D.129, D.130.
D.68	D.69, D.73, D.75, D.86, D.105, D.114.
D.69	D.35, D.40, D.59, D.68, D.75, D.76, D.86, D.98, D.109, D.114, D.119, D.122, D.126.
D.73	D.1, D.3, D.4, D.7, D.8, D.28, D.29, D.31, D.34, D.35, D.37, D.38, D.39, D.40, D.41, D.42, D.44, D.45, D.49, D.54, D.59, D.65, D.69, D.75, D.86, D.89, D.90, D.91, D.96, D.101, D.102, D.103, D.104, D.105, D.106, D.114, D.115, D.116, D.117, D.118, D.119, D.127, D.128, D.129, D.130, D.131, D.132, D.133.
D.74	D.33, D.42, D.43, D.44, D.45, D.47, D.48, D.49, D.50, D.51, D.53, D.54, D.60, D.63, D.68, D.69, D.73, D.75, D.78, D.81, D.83, D.85, D.86, D.96, D.101, D.102, D.105, D.109, D.114, D.115, D.117, D.118, D.126, D.128.
D.75	D.18, D.33, D.48, D.73, D.74, D.77, D.78, D.105, D.114, D.118, D.126, D.128.
D.76	D.61, D.98, D.128.
D.77	D.18, D.75.
D.78	D.42, D.63, D.65, D.66, D.74, D.75, D.77, D.81, D.105, D.128.
D.80	D.1, D.3, D.8, D.14, D.21, D.35, D.66, D.86, D.87, D.88, D.114, D.132.
D.81	D.7, D.34, D.73, D.74, D.85, D.86, D.101, D.114, D.115.
D.83	D.14, D.21, D.45, D.50, D.51, D.73, D.74, D.85, D.101, D.102, D.105, D.114.
D.85	D.7, D.74, D.83, D.86, D.101, D.128.
D.86	D.1, D.3, D.8, D.14, D.18, D.21, D.48, D.66, D.73, D.74, D.80, D.87, D.100, D.102, D.105, D.114, D.117, D.131.
D.87	D.3, D.35, D.40, D.73, D.86, D.114, D.132.
D.88	D.42, D.48, D.73, D.86, D.122.
D.89	D.29, D.35, D.37, D.39, D.41, D.50, D.90, D.91, D.92, D.95, D.96, D.100, D.103, D.106, D.114, D.117, D.119, D.123.
D.90	D.37, D.50, D.54, D.73, D.76, D.89, D.92, D.96, D.97, D.98, D.100, D.102, D.114, D.117, D.119, D.123, D.126, D.127, D.128, D.130.
D.91	D.17, D.18, D.21, D.29, D.37, D.39, D.50, D.54, D.73, D.89, D.90, D.92, D.95, D.96, D.100, D.105, D.114, D.119, D.123, D.126, D.127, D.128, D.130.
D.92	D.37, D.39, D.41, D.50, D.73, D.86, D.89, D.90, D.95, D.96, D.97, D.100, D.103, D.114, D.119, D.123, D.126, D.129.
D.93	D.39, D.41, D.73, D.90, D.92, D.95, D.96, D.97, D.100, D.103, D.119, D.123, D.127, D.129.
D.95	D.73, D.89, D.91, D.92, D.93, D.96, D.97, D.98, D.100, D.103, D.105, D.109, D.114, D.123, D.126, D.129, D.130.
D.96	D.37, D.50, D.74, D.102, D.105, D.114, D.117, D.122, D.127, D.128, D.129.
D.97	D.73, D.93, D.95, D.103, D.104, D.105, D.119, D.126, D.129.
D.98	D.73, D.90, D.95, D.100, D.105, D.109, D.114, D.118, D.119, D.123, D.124, D.126, D.127, D.128, D.130.
D.100	D.37, D.73, D.86, D.89, D.98, D.105, D.109, D.114, D.118, D.119, D.123, D.126, D.128, D.130.
D.101	D.38, D.40, D.50, D.66, D.73, D.83, D.96, D.102, D.105, D.114, D.117.
D.102	D.35, D.40, D.50, D.53, D.66, D.74, D.83, D.90, D.96, D.101, D.105, D.109, D.114, D.117, D.122, D.126, D.127, D.128, D.130.
D.103	D.21, D.26, D.61, D.73, D.89, D.92, D.93, D.95, D.97, D.100, D.105, D.119, D.129, D.130.
D.104	D.73, D.97, D.103.
D.105	D.5, D.14, D.21, D.28, D.29, D.31, D.33, D.34, D.42, D.43, D.44, D.45, D.47, D.48, D.49, D.50, D.51, D.52, D.53, D.54, D.58, D.59, D.60, D.61, D.63, D.65, D.66, D.69, D.73, D.74, D.75, D.78, D.83, D.86, D.95, D.98, D.100, D.101, D.102, D.103, D.104, D.106, D.114, D.115, D.117, D.118, D.119, D.124, D.126, D.127, D.129, D.130, D.133.

CRITERION	DEPENDS ON
D.106	D.4, D.28, D.29, D.37, D.41, D.73, D.89, D.91, D.93, D.103, D.105, D.114, D.123, D.131, D.132.
D.109	D.3, D.4, D.8, D.14, D.17, D.21, D.34, D.35, D.37, D.38, D.39, D.40, D.41, D.49, D.50, D.51, D.53, D.54, D.63, D.66, D.80, D.87, D.88, D.89, D.90, D.91, D.93, D.96, D.98, D.100, D.102, D.103, D.105, D.106, D.114, D.117, D.118, D.119, D.122, D.123, D.124, D.126, D.127, D.129, D.130, D.132, D.133.
D.114	D.1, D.3, D.14, D.18, D.21, D.31, D.33, D.35, D.37, D.38, D.40, D.42, D.43, D.44, D.45, D.47, D.48, D.49, D.50, D.51, D.54, D.58, D.59, D.60, D.61, D.63, D.65, D.66, D.68, D.69, D.74, D.75, D.78, D.81, D.83, D.86, D.87, D.89, D.90, D.91, D.93, D.95, D.96, D.97, D.98, D.100, D.101, D.102, D.103, D.105, D.109, D.115, D.124, D.133.
D.115	D.28, D.49, D.50, D.73, D.105, D.127.
D.116	D.21, D.47, D.49, D.50, D.51, D.53, D.90, D.96, D.102, D.105, D.117, D.122, D.127.
D.117	D.14, D.49, D.50, D.51, D.53, D.90, D.91, D.96, D.102, D.103, D.105, D.114, D.122, D.123, D.127, D.129.
D.118	D.48, D.50, D.51, D.114, D.127, D.132.
D.119	D.14, D.18, D.21, D.50, D.63, D.65, D.73, D.91, D.92, D.93, D.95, D.98, D.100, D.103, D.118, D.123, D.128, D.129.
D.122	D.14, D.34, D.50, D.73, D.91, D.119, D.132.
D.123	D.33, D.73, D.88, D.89, D.90, D.91, D.95, D.98, D.100, D.103.
D.124	D.33, D.61, D.118, D.128.
D.126	D.17, D.28, D.31, D.33, D.34, D.35, D.37, D.40, D.41, D.42, D.43, D.44, D.45, D.47, D.48, D.49, D.50, D.51, D.53, D.54, D.58, D.59, D.60, D.61, D.63, D.65, D.66, D.69, D.73, D.74, D.75, D.76, D.81, D.83, D.86, D.88, D.89, D.90, D.91, D.92, D.93, D.95, D.96, D.97, D.98, D.100, D.101, D.102, D.103, D.104, D.105, D.106, D.109, D.114, D.115, D.117, D.118, D.119, D.122, D.123, D.124, D.127, D.128, D.129, D.130, D.131, D.132, D.133.
D.127	D.28, D.30, D.31, D.33, D.37, D.47, D.53, D.59, D.60, D.61, D.63, D.65, D.66, D.73, D.75, D.90, D.93, D.96, D.98, D.102, D.105, D.114, D.117, D.118, D.119, D.122, D.123, D.126, D.128, D.129, D.130, D.132.
D.128	D.50, D.58, D.61, D.73, D.75, D.98, D.114, D.118, D.119, D.124, D.127, D.130, D.131, D.132.
D.129	D.93, D.96, D.97, D.105, D.114, D.117, D.119, D.127, D.130.
D.130	D.37, D.53, D.66, D.76, D.90, D.91, D.92, D.95, D.96, D.98, D.105, D.114, D.122, D.127.
D.131	D.1, D.3, D.35, D.38, D.40, D.73, D.114, D.126, D.132.
D.132	D.1, D.3, D.18, D.35, D.38, D.40, D.73, D.114, D.126, D.131.

APPENDIX C

THE BRETBY MAINTAINABILITY INDEX

Factors	Points Score
Access	
PART 1. HATCHES AND COVERS	
(a) Flip-up cover or flap - no fasteners	3 per cover
(b) Door or cover (hand operated fasteners)	4 per cover
(c) Door or cover - single fastener (tool operated)	5 per cover
(d) Door or cover - multiple fasteners (tool operated)	10 per cover
(e) Lift off/lift up panel - easy to handle, < 12 kg	2 per cover
… … … … … 12 to 24 kg	4 per cover
… … … … … 25 to 35 kg	6 per cover
… … … … … >35kg	10 per cover
PART 2. APERTURES	
KEY	
H = height off floor (mm)	d = depth inside aperture (ram)
h = height of aperture (mm)	w = width of aperture (mm)
For all tasks	Score tor each fastener/component
(a) Obstructed access to/around component moderate	2
(b) Obstructed access to/around component - severe	4
(c) Restricted sightlines to component/fastener	1
(d) Obstructed sightlines to component/fastener	4
(e) If (H + 3100)/d > 9	
… … … Aperture width < 300 mm or < 270 + 0'46d mm	2
… … … Aperture width < 250 mm or < 0"7d mm	5
… … … Aperture height < 150 + 0"1 d mm (two-handed task)	2
… … … … … < 150 + 0"6d mm (two handed task)	1
… … … … … or < 115 mm (one hand task)	2
… … … Depth inside aperture > 500 mm	2
(f) If (H + 3100)/d < 9 (whole body access is needed)	2
… … … Aperture smaller than 460 x 460 mm	3 extra
… … … … … or 310 mm (h) x 560 mm (w)	3 extra
For tool access only	Score tor each fastener/component
For spanners/allen keys:	
(g) 2 to 3 fiats access	add 1 per fastener
(h) 1 to 1½ fiats access	add 2 per fastener
(i) Less than 1 fiat access (spanners only)	add 4 per fastener
PART 3. LOCATION	
(a) Ground level - working upright, within normal reach	1
(b) Ground level - bending or stretching outside normal reach	2
(c) Ground level - squatting, kneeling or lying (not under m/c)	3
(d) Mount machine normal reach	6
(e) Mount machine - bending, stretching or squatting	8 (S)
(f) On machine - subsequent operations within normal reach	1 each
… … … … … subsequent operations bending/stretching	2 each (S)
… … … … … subsequent operations squatting/kneeling	3 each (S)
(g) Any position (other than upright) under or within the confines of the machine	10 (S)
(h) Enter driver/operator cab	3

Operations

PART 1. REMOVAL / REPLACEMENT

Fastener Type	
(a) Spin on	1
(b) Single fastener not requiring tool	3
(c) Single fastener requiring tool	4
(d) Additional fasteners not requiring tool	2 each
(e) Additional fasteners requiring tool	3 each

Fastener force requirements for tools	per fastener
(f) Slackening fastener - high forces needed	1 (H), (S)
Slackening fastener - requiring impact	1 - 8 (S)
(g) Tighten to unspecified torque (other than nip tight)	2
(h) Tighten to torque levels up to: (see *)	
… … … … … [(Torque (N.m)/((9* nut size in mm) + 25)*1000] > 450	2
… … … … … > 600	4
… … … … … > 800	8 (H), (S)
(i) Component weight:	per component
… … … … … easy to handle < 12 kg	9
… … … … … 12 to 24 kg	4
… … … … … 25 to 35 kg	6 (poss H)
… … … … … >35 kg	10 (H)

(* if fasteners are above l m off the floor and no bracing is possible add 5, unless powered hand tools are used, then score 0)

PART 2. SLACKENING/TIGHTENING ONLY

Fastener type	
(a) Single fastener not requiring tool	1
(b) Single fastener requiring tool	2
(c) Additional fasteners	1 each

Fastener force requirements	per fastener
(d) Slackening fastener - high forces needed	1 (H), (S)
Slackening fastener - requiring impact	1 - 8 (S)
(e) Tighten to unspecified torque	2
(f) Tighten to torque levels up to: (see *)	
… … … … … [(Torque (N.m)/((9* nut size in mm) + 25)*1000] > 450	2
… … … … … > 600	4
… … … … … > 800	8 (H), (S)

(* if fasteners are above 1 m off the floor and no bracing is possible add 5, unless powered hand tools are used, then score 0)

PART 3. CARRYING AND LIFTING

(a) Component weight:	per component
… … … … … easy to handle < 12 kg	1
… … … … … 12 to 24 kg	2
… … … … … 25 to 35 kg	3 (poss H)
… … … … … >35 kg	5 (H)
(b) Inadequate manual lifting point design/location	5, (S), (H)
(c) Inadequate powered lifting point design/location	30, (S)
(d) Carrying/frequent lifting restricted head room < 12 .5 kg	-
… … … … … > 12.5 kg	(H)
(e) Carrying/frequent lifting unrestricted head room < 24.5 kg	-
… … … … … > 24.5 kg	(H)
(f) Single person lifting restricted head room < 15 kg	-
… … … … … > 15 kg	(H)
(g) Single person lifting unrestricted head room > 35 kg	-
… … … … … < 35 kg	(H)
(h) Two people lifting in restricted head room < 23 kg	-
… … … … … > 23 kg	(H)
(i) Two people lifting in unrestricted head room < 53 kg	-
… … … … … > 53 kg	(H)

PART 4. PREPARATION	
(a) Cleaning around unions, fasteners, etc	4 each
(b) Cleaning small area on machine	5 each
(c) Cleaning extensive areas on machine	30
(d) Jack up and chock machine	20
(e) Make roof safe	30
(f) Collect/transport special tools, etc	20
(g) Don gloves, goggles, etc	2
(h) Don non-standard protection	5

PART 5. FLUID COMPARTMENT CHECKING	
(a) Visual check - easy	1
(b) Visual check - difficult	2
(c) Dip stick - push fit	3
(d) Dip stick - screw-in type	11
(e) Screw cap - hand removable	4
(f) Multiple screw cap - hand removable	6
(g) Screw cap or plug requiring tool	8
(h) Multiple screw cap or plug requiring the same tool	10

PART 6. COMPONENT CHECKING	
(a) Visual check - easy	1 each
(b) Visual check - difficult	2 each
(c) Manual check	3 each
(d) Requires 'non-precision tool'	5 each
(e) Requires a 'precision tool'	10 each

PART 7. LUBRICATION	
(a) Fitting through an entry point	1
(b) Fitting requiring special adapter	3
(c) Lubricate with brush	3
(d) Lubricate with oil can/grease gun (see *)	3
(e) Fitting requiring secondary action	5
(f) Hand packing (each)	20
(g) (* if grease coming out of joint cannot be seen	2 each point)

PART 8. DRAINING	
(a) Through drain valve	1
(b) Through plug on vertical surface	6
(c) Through plug on horizontal surface	8
(d) Through a cover plate	10
(e) Through multiple plugs or covers using one tool	15
(f) Drainage indirectly collectable (i e, need pipe)	2

PART 9. FILLING	
Method of entry	
(a) Hand removed cap	1
(b) Tool removed cap or plug on horizontal surface	3
(c) Tool removed cap or plug on vertical surface	10
(d) Multiple caps or plugs	15
Method of filling	
(e) Hand connected filler hose	5
(f) Tool connected filler hose	10
(g) Use hand pump to top up	30
(h) Use hand pump to fill	2 per litre
(i) Filling from oil drum	1 per litre
(j) Top up water from hose	4 first point
(Additional top up points	1 each)
(k) Filler size inadequate	5

PART 10. CLEANING	
(a) Wipe with cloth or tap/scrape out dirt	3
(b) Blow with air/water line	3
(c) Single bath wash	5
(d) Multiple bath wash or wash and oil	10
(e) Drain and wash filter housing	8

PART 11. ADJUSTMENT	
(a) Single step	2
(b) Multiple step	4
(c) Multiple location multiple step	10

PART 12. MISCELLANEOUS	
(a) Need to operate a control	3
(b) Need to power up machine	5
(c) Need to operate or position the machine	10
(d) Operation requiring caution	30
(e) Position requiring caution	30 (S)
(0 Difficult to illuminate adequately with cap lamp	3
(g) Vulnerable to contamination	
… … … … … low probability/consequence	1
… … … … … moderate probability/consequences	3
… … … … … high probability/consequences	5
(tl) Bleeding, priming or flushing required	3
(i) Delay	I per 5 seconds

Additional allowances

Energy output	
(Taking into consideration the environmental conditions likely underground)	
Negligible	0 - 6%
Very little	6 - 7.5% -
Light	7.5 - 12% -
Medium	12 - 19% -
Heavy	19 - 30% -
Very heavy	30 - 50% (H)
Exceptional	(H), (S)

Posture	
Sitting	0 - 1%
Standing	1 - 2.5%
Lying down	2.5 - 4%
Crouching/stretching	4 - 10%

Motions	
Normal	0
Limited	0 - 5%
Awkward	0 - 5%
Confined (limbs)	5 - 10%
Confined (body)	10 - 15%

Working head room	
Head room < 1.8 m	10%
Head room < 1.4 m	15%
Head room < 1.0 m	20%

Visual fatigue	
Intermittent attention	1%
Almost continuous attention	2%
Continuous attention	5%
Continuous (fixed focus)	8%

Manpower	
Operation needs extra man	100%
Operation needs extra 2 men	200%

Frequency multiplier

2000 hours or annually	0.5
1000 hours or semi-annually	1 - 0
500 hours or quarterly	2.0
250 hours or monthly	4.0
100 hours or semi-monthly	10.0
50 hours or weekly	20 - 0
daily	100 - 0
10 hours or each shift	100 - 0 per shift *
5 hours or part shift	200.0 per shift *

(* Shift and part shift weightings are multiplied by the number of production shifts worked.For most applications this is considered as two)

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