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Design for Manufacture and Assembly in an Aerospace Environment

A thesis submitted for the Degree of Engineering Doctorate at the
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To the memory of my dad, Joe Riley

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Nomenclature

ADLT	Acceptable Delivery Lead-time
AEM	Assemblability Evaluation Method
AI(R)	Aero International Regional
AMD	Aircraft Master Definition
AMRF	Automated Manufacturing Research Facility
ASF	Assembly Sequence Flowchart
ASO	Assembly Stage and Operation
ATP	Advanced Turboprop
BPIP	Business Plan Improvement Programme
BTO	Build to Order
CAA	Civil Aviation Authority
CAD	Computer Aided Design
CAM	Computer Aided Manufacturing
CAPP	Computer Aided Process Planning
CAT III	Category III
CCB	Configuration Control Board
CEO	Chief Executive Officer
CSG	Constructive Solid Geometry
DDI	Design Department Instruction
DFMA	Design for Manufacture and Assembly
DOF	Degrees of Freedom
DPA	Digital Pre-Assembly
DTC	Design to Cost
EMC	Electro-Magnetic Compatibility
ESOP	Electronic Schedule of Parts
FAA	Federal Aviation Authority
FAME	Final Assembly Manufacturing and Expediting
FEAST	FEature based ASsembly Techniques
FMEA	Failure Modes and Effects Analysis
GA	General Arrangement
GDP	Gross Domestic Product
GIDD	Galley Interface Definition Document
IAS	Independent Assembly Station
IGES	Initial Graphics Exchange Specification
ISO/STEP	International Standards Organisation/Standard for the Exchange of Product Model Data
IATA	International Air Transport Association
LCE	Life Cycle Engineering
MA	Manufacturing Analysis
MCC	Modification Control Committee
MEM	Machining-Producibility Evaluation Method
MOBAL	Model Based Learning
NC	Numerically Controlled
NIAM	Nijssen Analysis Method
NIST	National Institute of Standards & Technology

PC	Personal Computer
PCB	Printed Circuit Board
PEP	Production Easement Proposal
QFD	Quality Function Deployment
RJ	Regional Jet
RPK	Revenue Passenger Kilometres
RPM	Revenue Passenger Miles
WQN	Works Query Note

Abstract

This thesis describes the research into *Design for Manufacture and Assembly in an Aerospace Environment.* The motivation for this research came from a combination of two factors. Firstly, the dramatic changes in the civil aerospace market over the past decade have led to a situation where aerospace companies must be able to produce aircraft, in less time, at lower cost, and with fewer resources, if they are to survive and compete globally in the 1990s. This has put pressure on Avro to reassess and improve all its business processes. Secondly, the traditional approach of aerospace design has always been focused on product safety, functionality and performance, rather than manufacture and assembly. This has resulted in a poor, inefficient design philosophy which has now been exposed, after the self examination forced on the company by the external market pressures.

A review of the literature into the general topic of design, carried out to determine the scope of this Eng.D. study, revealed an extensive field of research which is concerned with the increasing focus on ensuring that the right information regarding all aspects of the product's life cycle, for example: functionality, performance, manufacture, assembly, maintenance, reliability etc., is available at the optimum time, to the correct people, on the premise that this will lead to reduced cycle time (design concept to market entry), reduced costs and higher quality products. This trend is called *Concurrent Engineering.*

The two areas of Concurrent Engineering research that are progressed further by this Eng.D. study are *Life Cycle Decision Support Tools* and *Product Modelling.* From these areas the specific topics of interest are, *Design for Manufacture and Assembly ("DFMA")* and *Feature-Based Design* respectively. Of these two topics, focus on DFMA predominates.

In summary this Eng.D. study:

- applied qualitative DFMA rules and principles in several projects aimed at improving the efficiency of the company's production activity. The main contribution was in

improving galley installation; the most troublesome aspect of the aircraft's customisation activity. This made a significant contribution to Avro's business position as it put in place improvements that will achieve savings in the order of £1 million per year;

- investigated quantitative DFMA tools through a series of pilot studies and assessed their value in the aerospace environment;
- put forward recommendations that will enhance the development of the next generation regional aircraft. These recommendations centre around two themes: firstly, changes to the overall design process and secondly, changes to the way aircraft customisation is approached from both a marketing and physical design point of view;
- progressed the research into Feature-Based Design by contributing to the Brite-Euram sponsored project on FEature based ASsembly Techniques ("FEAST"). This project investigated the identification and exploitation of assembly features in product modelling, for use in the development of future Computer Aided Design systems.

Declaration

No portion of the work referred to in this thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.

Susan Riley October 1996

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Finally, to Paul ....we made it.

The Author

The author left school in 1987 with 'A' Levels in Maths, Physics and Chemistry and commenced a three year, full time B.Eng.(Hons.) degree in Aeronautical Engineering at the University of Manchester. The author Graduated with first class honours in 1990.

In October 1990 the author began work as a graduate engineer at British Aerospace Woodford, Cheshire (now Avro International Aerospace). In October 1992 sponsorship from the company led to the admission to the Engineering Doctorate scheme at Manchester University, which provided an opportunity to undertake research leading to the award of Eng.D.

The Engineering Doctorate (Eng.D.) Programme

The following extract is taken from the Eng.D. brochure published by the Total Technology Department at the University of Manchester Institute of Science and Technology.

"During recent years the traditional approach to doctoral research in universities has been subject to criticism regarding its suitability for producing engineers who are well suited to the management needs of manufacturing companies. It has been implied that a Ph.D. conducted within the confines of a university laboratory and restricted to a narrow field of study, is too specialised to meet all the demands of modern manufacturing companies.

As a result of these criticisms, the Science and Engineering Research Council (SERC) set up a working party to study postgraduate research training in Britain, and to establish its effectiveness in satisfying the needs of industry compared to schemes operated in other major industrial nations.

The result of the report is the instigation of the new Eng.D. degree, which is intended to take highly qualified and well motivated young engineers and put them through four years training, involving industry based research and taught management courses. This is a significant change from all previous doctoral programmes in Britain, as both the research and taught elements must be passed in order to gain the Eng.D. degree.

It is considered that the Eng.D. approach to research combines the best aspects of a conventional Ph.D. with the practical implications of linking the research to the specific needs of a collaborating company."

The sponsoring company for this Eng.D. research was Avro International Aerospace, a division of British Aerospace Plc.

Statement of Aims

This thesis aims to make a contribution to expanding the boundaries of knowledge in the field of Concurrent Engineering by focusing primarily on Design for Manufacture and Assembly ("DFMA") in an Aerospace Environment and secondly on Feature-Based Design.

The specific aims are to:

- understand how the aerospace industry market place has changed over the past decade, and the impact this has had on aircraft manufacturers;
- understand how the aerospace design process operates by gaining an appreciation of peculiarities associated with the nature of the product (i.e. the aircraft);
- show how the combination of changes in the marketplace, and the priorities of traditional aerospace design, is affecting the current business position of Avro International Aerospace;
- contribute towards improving Avro's current business position by improving the company's customisation activity, by applying qualitative DFMA rules and principles to galley installation; one of the most troublesome areas within customisation;
- investigate quantitative DFMA tools and assess their relevance in an aerospace design environment;
- progress the research into Feature-Based Design by contributing to the Brite-Euram sponsored project on FEature based ASsembly Techniques ("FEAST"). This project will investigate the identification and exploitation of assembly features in product modelling, for use in the development of future Computer Aided Design systems;
- put forward recommendations that will enhance the development of the next generation of regional aircraft. These recommendations will centre around two themes: firstly, general changes to the overall design process and secondly, changes to the way aircraft customisation is approached from both a marketing and physical design point of view.

Organisation of Thesis

The nine chapters of this thesis describe the work performed and the conclusions reached regarding DFMA in an aerospace environment and Feature-Based Design.

Chapter 1 presents a review of the literature into the general topic of design which revealed the extensive research being conducted in the field of Concurrent Engineering. It then provides introductions to two of the principal aspects of Concurrent Engineering that have been progressed by this Eng.D. study; DFMA and Feature-Based Design.

Chapter 2 discusses how the civil aircraft market has changed over the past decade, and how this has led to the exposure of opportunities to improve the design of the product. These opportunities have resulted from a neglect of manufacture and assembly issues in traditional aerospace design. There was therefore a pressing need for research into DFMA at Avro, not only to improve the efficiency of the current aircraft production process, but also to ensure that the new product development activity learns from the mistakes of the past.

Chapter 3 describes the methodology adopted for this research. It includes an account of how the research path had to change in order to maintain its relevance, and stay in line with changes in Avro's company strategy. It explains why the research path initially focused on new product development, using the current product, the Avro Regional Jet ("RJ"), simply to look for ideas for improvement. It then goes on to explain why new product development was scaled down and how emphasis then moved onto improving the RJ's production activity.

Chapter 4 describes in detail the main element of the study into the practical application of qualitative DFMA rules and principles at Avro. It describes how DFMA rules were applied to the production easement exercise aimed at improving galley installation.

Chapter 5 describes in detail the mechanics of the most popular quantitative DFMA tools; a brief critique is provided and related research activities are described. This is followed by an account of how the tools were tested at Avro.

Chapter 6 describes how Feature-Based Design was progressed, through involvement in the Brite-Euram sponsored FEAST project which is investigating the identification and exploitation of assembly features in product modelling. This will contribute to the development of future CAD systems in making them more capable of supporting Concurrent Engineering.

Chapter 7 discusses the issues raised during the research program:

- from the project investigating the problems with galley installation, recommendations on how the design process can be improved and proposals on how customisation should be approached on the next generation of regional jet are presented;
- from the investigation into quantitative DFMA tools, the applicability of the tools is discussed for the aerospace environment in general, and then specifically for Avro.

Chapter 8 provides suggestions for further work.

Finally, in Chapter 9 some overall conclusions as a result of this research are made.

Chapter 1 Introduction

Summary

There is an extensive field of research associated with design which is concerned with the increasing focus on ensuring that the right information regarding all aspects of the product's life cycle, for example: functionality, performance, manufacture, assembly, maintenance, reliability etc., is available at the optimum time, to the correct people, on the premise that this will lead to reduced cycle time (design concept to market entry), reduced costs and higher quality products. This trend is called *Concurrent Engineering*.

Section 1.1 presents an overview of the research activities into Concurrent Engineering.

The two areas of Concurrent Engineering research that will be progressed further by this Eng.D. study will be *Life Cycle Decision Support Tools* and *Product Modelling*. From these areas the specific topics of interest will be, *DFMA* and *Feature-Based Design* respectively. Of these two topics, focus on DFMA will predominate.

An overview of the basic philosophy of DFMA is given in section 1.2, followed by a discussion into the benefits and savings that can be achieved as a result of focusing on manufacture and assembly issues early in the design process. The operational issues surrounding DFMA are then discussed.

An introduction into Feature-Based Design is given in section 1.3, and the contribution which the use of features can make to improving Concurrent Engineering is explained, by highlighting the advantages of modelling a product using features over the current solid modelling approach.

1.1 Review of Literature

1.1.1 Introduction

Design is an extremely broad subject that encompasses many diverse aspects. Initial surveys on the general topic of design revealed that there is a large field of research which is concerned with ensuring that the right information regarding all aspects of the product's life cycle, for example: functionality, performance, manufacture, assembly, maintenance, reliability etc., is available at the optimum time, to the correct people, on the premise that this will lead to reduced cycle time (design concept to market entry), reduced costs and higher quality products.

There are lots of terms seemingly being used to describe this trend, for example, Concurrent Engineering (coined in the US in 1989), Simultaneous Engineering, Life Cycle Engineering, Parallel Engineering.

Some Definitions:

Concurrent Engineering: "A way of working where the various engineering activities in the product and production development process are integrated and performed as much as possible in parallel rather than in sequence." (Sohlenius (92)).

Concurrent Engineering: "The consideration and inclusion of product design attributes such as aesthetics, durability, ergonomics, interchangeability, maintainability, marketability, manufacturability, procurability, reliability, safety, schedulability, serviceability, simplicity, testability, and transportability in the product design process." (Dowlatshahi (94)).

Life Cycle Engineering ("LCE"): "The underlying principles in LCE focus on the consideration of the entire life of the product in the early stages of the design process. This concept essentially considers three interrelated activities: 1. Design considerations and product/system requirements, 2. Manufacturing activities and processes, 3. Product/system support and logistical considerations such as serviceability, maintainability, reliability, testability, availability, remanufacturability, and disposability." (Dowlatshahi (94)).

Simultaneous Engineering: "This philosophy involves simultaneously satisfying the functionality, reliability , produceability, and marketability concerns of new products in order to reduce product development time and cost, and to achieve higher product quality and value." (Molina (94)).

For the purposes of this thesis the term Concurrent Engineering will be used to refer to this field of research.

From these definitions it could be said that Concurrent Engineering is simply a 'common sense' approach to design, which overcomes the limitations of sequential engineering steps typical of functional specialisation from the era of mass production. It is not a new phenomenon, it flourished during the 1940s and 1950s but got lost as companies grew and the complexity of products increased leading to specialists functions. Ziemke and Spann (93) presented an interesting paper which traces the practice of Concurrent Engineering in the US, back to World War II. In the 1980s, Concurrent Engineering re-entered engineering management philosophy and practice.

1.1.2 Structure of Concurrent Engineering Research Activities

All the recent key papers published on the general topic of Concurrent Engineering, for example, Peters et al. (90), van Houten (92), Sohlenius (92), Dowlatshahi (94), Molina (94), touch on the following topics:

- *Product Modelling;*
- *Integrated Systems Architecture;*
- *DFMA;*
- *Computer Aided Process Planning;*
- *Scientific Design Theories;*
- *Feature-Based Design,*

- *CAD/CAM Integration.*

This section will introduce three approaches to Concurrent Engineering and use the conceptual model developed by Jo et al. (90) to explain how the topics listed above link together.

1.1.2.1 Three Approaches to Concurrent Engineering

Jo et al. (93) speak about two basic approaches to implementing Concurrent Engineering: the team-based approach and the computer-based approach. In fact, it could be said that there is an intermediate; a team-based/computer-supported approach.

1.1.2.1.1 The Team-Based Approach

The team-based approach is human-oriented and involves representatives from all the necessary functions within the company, for example, Design, Manufacturing, Assembly, Customer Support, Procurement, Sales and Marketing etc., coming together to work as a team in order to satisfy the Concurrent Engineering philosophy. This approach relies on expertise of the team members and their effective communication.

The team-based approach has a major impact on the organisation and culture of the company and much research has been done in this area (Evans (90) & (93), Maddux & Souder (93), Fotta & Daley (93), Gilen & Fitzgerald (91), Karandikar et al. (92), Evans et al. (94), Stickley et al. (94)).

1.1.2.1.2 The Team-Based/Computer-Supported Approach

This approach involves the use of computer based support tools to assist the team in their consideration of all the life cycle aspects. When a new product is under development there are various elements of its life cycle that have to be analysed, so that optimal design decisions can be made. Some of these elements are: reliability, manufacturing planning, manufacturability, assembly planning, assemblability, and maintainability.

Many computer based tools have been, and are being, advanced to support this kind of analysis. This approach means that the effectiveness of the team does not rely so much on the expertise of individuals. Molina (94) refers to these tools as Life Cycle Decision Support Tools. These tools have been developed as stand-alone applications that improve product design by concurrently considering the different aspects of the life cycle.

1.1.2.1.3 The Computer-Based Approach

The computer-based approach relies on the total integration of all the computer systems to satisfy the concurrent engineering philosophy. At present, the approaches adopted by most companies are the team-based approach and the team-based/computer-supported approach. The computer-based approach is the 'utopia' and much research still needs to be done before a fully integrated, computer-supported, design environment can be achieved.

The research into the computer-based approach is concerned with the development of the linkages between the product model and the life cycle decision support tools. The ideal situation will be to have a computer system that allows a design to be created using human intelligence, and then artificial intelligence is used to analyse the design with respect to all the elements of the product's life cycle, to come up with the optimum design solution. The only way this can be achieved is if the product model holds all the relevant information and is stored in such a way that it can be automatically extracted and transferred for use by the decision support tools. There must also be a systems architecture in place that can effectively control all this data manipulation. The 'Concurrent Engineering Wheel' model developed by Jo et al. (90) illustrates this concept (see Figure 1.1).

The outer layer of the wheel represents the product model which provides the designer with the capability to invoke any of the life cycle decision support tools in the inner layer (or functional layer) to evaluate or optimise their design.

The core of the wheel is the control logic which involves steering of various CAD tools to provide a variety of services, helping to find a globally satisfied design.

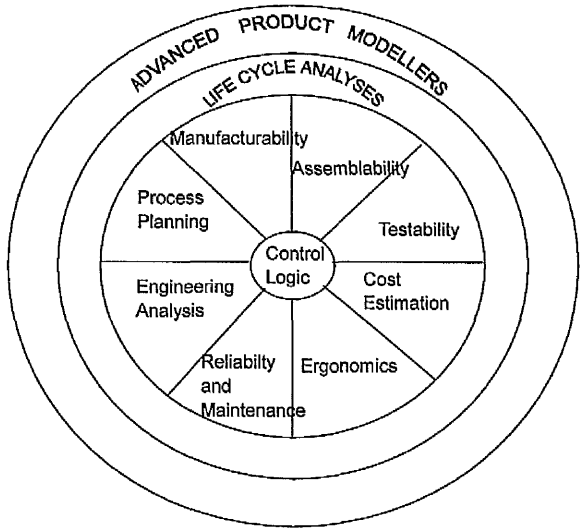


Figure 1.1 'Concurrent Engineering Wheel' Jo et al. (90)

Effectively there are two aspects to achieving total systems integration for Concurrent Engineering:

1. Storing the necessary data (modelling the product)

The latest product modelling research is focused on Feature-Based Design. This is a technology which will support Concurrent Engineering by enabling more than geometric information to be held in the product model. This will consequently lead to the automation of the downstream life cycle analysis activities using the life cycle decision support tools, mentioned above. Krause et al. (93) present an overview on the state-of-the-art and practice of product modelling.

2. Controlling the data manipulation

The key to the control logic is to understand the human thought process during design. The research activities associated with the development of scientific theories of the design process contribute to this. This research focuses on the purely theoretical aspects of understanding how the design process works from a scientific point of view, and much work has been done on trying to establish design theories.

Design is a difficult subject to understand and research. One of the most difficult tasks in design is the decision making as to whether or not a given idea is fundamentally sound in terms of basic principles. In the absence of generalisable basic principles, there is no basis for making rational decisions in judging the merit of a proposed idea. (Suh (88)). The main source of confusion about design is that it lacks sufficient scientific foundations. Design is at a pre-science phase and it must go through several phases before it constitutes a mature science. (Kuhn (70)). Dixon (87) argued that without an adequate base of scientific principles, engineering design education and practice are guided too much by the specialised empiricism, intuition, and experience.

Suh (88) developed a series of principles aimed at liberating the designers from their empirical procedure. Suh's 'axiomatic' approach is based on the idea that there are basic generalised principles which hold true in all design solutions. Axioms are by definition fundamental truths which are valid in all cases unless there are counter examples or exceptions. Suh has advanced two design Axioms (Axiom 1 – the Independence Axiom (how to make feasible designs), Axiom 2 – the Information Axiom (how to choose between designs that fulfil the functional requirements)) from which corollaries and theorems have been derived as well as methodologies for making design decisions.

Yoshikawa (85) tries to analyse the human thought process and develop a 'general' theory of design that explains how design is conceptually performed in terms of knowledge manipulation.

1.1.3 Elements Selected for Eng.D. Study

The two areas of Concurrent Engineering that will be progressed further by this Eng.D. research will be Life Cycle Decision Support Tools and Product Modelling. From these areas the specific topics of interest will be, DFMA and Feature-Based Design respectively. Of these two topics, focus on DFMA will predominate.

1.2 Design for Manufacture and Assembly

The concept of DFMA is not difficult to understand. In simple terms it is ensuring that all the *factors* that influence the efficiency of detail part manufacture and product assembly are understood and considered during the early stages of design whether the design be for new product development or for modification to an existing product at some stage in its life cycle.

DFMA does not mean "production easement". A production easement is a design change specifically done to benefit either the manufacturing or assembly aspect of the production activity, and has no other purpose. DFMA is a philosophy or check that must be applied to all design changes regardless of the purpose of the change.

1.2.1 Two Approaches to DFMA

A review of the literature has revealed that there are in fact two approaches to DFMA: *qualitative* and *quantitative*:

1. The qualitative approach

The qualitative approach is applying simple rules and principles of good design practice that have been empirically derived from years of design and production experience. This will enhance the design process with respect to manufacture and assembly. (Stoll 86). Examples of such principles are: design for minimum number of parts, develop a modular design, design parts for ease of fabrication, standardise parts, design parts to be multi-functional, design parts for multi-use, avoid separate fasteners, minimise assembly directions, minimise handling, eliminate or simplify adjustments etc..

2. The quantitative approach

Systemisation of a number of the qualitative fundamental rules into methodologies and tools has occurred. These tools are known as quantitative DFMA Tools and can be used as a decision support tool in the design process. They are commercially available and are actively being used in some industries (Eversheim & Baumann (91), Constance (92), Dvorak (92), Hulme (93), Green & Reder (93), Gerhardt et al. (90), Booty (91), Boothroyd & Dewhurst (83), Boothroyd & Alting (92), Boothroyd & Fairfield (91), Miles (89), Welter (90), Miyakawa & Ohashi (86)).

The quantitative approach is the one referred to the most in published literature. In an attempt to give an understanding of the general concept of DFMA, the following sections will describe the qualitative background.

1.2.2 Some Definitions

The term DFMA is open to many interpretations. The first things which need to be established are the definitions of: assembly, manufacture, production and product realisation. Sometimes the term manufacture is used to describe the entire process from raw material to finished product. In this thesis, production will be used to describe this process, manufacture will be used to describe the production of detail parts (i.e. the most basic items that form the larger sub-assemblies) from raw material. Assembly will refer to the process of joining all the details to form the larger sub-assemblies and, finally, the finished product. Product realisation will be used in two senses (a) to refer to the "design to first delivery" of a new product, and (b) to refer to the "design to first impact of a design modification" on an existing product.

It should be noted here that there are many products that undergo substantial modification throughout their production life, (i.e. the original design is never really "frozen". The design changes referred to here are not corrections of original design mistakes; certain industries have legitimate reasons for modifying products throughout the life cycle. The sources of design change with reference to the aerospace industry are described in Appendix 1).

1.2.2.1 Design for Manufacture

The literature on Design for Manufacture emphasises two aspects. One aspect is concerned with trying to improve the 'cost estimation' activity by providing designers with databases that will allow them to perform rough cost estimates on the use of different manufacturing processes. The second aspect of DFM refers to the economic manufacture of parts by ensuring that they are designed to suit either:

1. A specific manufacturing technology

An example of a form that cannot be manufactured by a specific manufacturing technology is shown in Figure 1.2. The cavity cannot be milled, on the assumption that the tolerances specified are much smaller than the radius of the smallest available mill, since two of the corners are not rounded (Delbressine(90)).

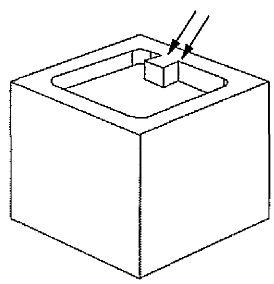


Figure 1.2 A Cavity that Cannot be Milled

2. A specific machine

In companies that perform in-house detail manufacturing, ideally, importance should be placed on designing the components to suit the equipment and machinery that is available.

The debate around designing for a specific technology and designing to suit available equipment, will be explored in Chapter 7 (section 7.1.1 number 9).

1.2.2.2 Design for Assembly

Design for Assembly refers to the economic assembly of the product by ensuring that the design considers factors such as: using standard parts and materials, minimising/rationalising the number of parts, avoiding the use of separate fasteners, ease of handling, ease of inserting and fixing, adequate access and unrestricted vision etc..

1.2.2.3 Design for X

In describing the design process, many authors have referred to the Design for X (Gatenby & Foo (90)) concept i.e. Design for Manufacture, for Assembly, for Service, for Reliability, for Functionality etc.. Consider the design process in two parts. One part could be called *Design for Producibility*, consisting of Design for Manufacture and Design for Assembly. The other part could be called *Design for Operation*, consisting of Design for Functionality, Design for Performance, Design for Reliability and Design for Maintenance. Traditionally designers have concentrated their efforts on functionality and performance. In striving to meet the goals of shorter lead-times, lower product cost and higher quality standards, designers can no longer neglect the other elements of the Design for X model during the design trade-off evaluations. During the design process there is effectively a Producibility/Functionality conflict that must be resolved.

DFMA should not be treated as something that is separate to the normal design process; it should be considered as an integral part of this process. Any design process which neglects DFMA is incomplete and inefficient. The basic principles of DFMA are common sense, the key is ensuring the right questions are asked at the right time. DFMA principles, once understood, should open up new avenues of conceptual thinking. This will result in better design habits and will enable an optimum balance to be achieved between the elements in the Design for X model.

1.2.3 Benefits of DFMA

Having a product that is easy to manufacture and assemble produces savings in many areas of the business:

- tailoring designs to suit the chosen manufacturing process minimises the risk of scrap;
- seeking part count reduction brings with it a whole host of associated cost savings, since parts that do not exist:

    *Are never wrong on the bill of materials;

    *Do not require a drawing or specification;

*Require no tooling or production equipment;

*Require no methods or routing;

*Are not sourced by any vendor;

*Have no lead time;

*Do not need to be scheduled or re-scheduled to production forecast;

*Add nothing to product cost;

*Require no purchase order;

*Have no shipping expense;

*Cannot be rejected, reworked or scrapped;

*Never travel from dock to stock from work in progress to ship;

*Do not require unpacking, counting, put-away, pick or staging;

*Do not create excess obsolete inventory;

*Never cause line down in production;

*Require no design changes;

*Always fit at assembly, never loose, missing or wrong;

*Are never ordered or stocked for spares or field service.

(DFM Team PPD Wichita)

An interesting statistic from NCR Plc. is that the cost associated with a simple fastener throughout its life cycle was $125,000. Therefore, any possible reduction in part count should be a priority within design. However, part count reduction should not exceed the point of diminishing return where further part elimination adds cost and complexity because the remaining parts are too heavy, or too complicated to make or assemble;

- seeking part type and material standardisation minimises the proliferation of parts. Standard parts can be ordered in any quantity at any time, require little or no lead-time, and are usually easier to repair and replace. A standard item is always less expensive than a custom-made item and is more reliable because characteristics and weaknesses are well known. Standard parts also allow designs to be re-used for other applications.
- avoiding the use of separate fasteners wherever possible can lead to substantial savings. In manual assembly the cost of driving a screw can be six to ten times the cost of the screw (Lewis, 1986). One of the easiest things to do is eliminate fasteners in assembly by using tabs or snap fits; however, if fasteners must be used, cost as well as quality

risks can be significantly reduced by minimising the number, size and variations used and by using standard fasteners whenever possible;

- ensuring designs are easy to handle, insert and fix contributes towards:

  (a) assembly cycle time (that is the time between the start of assembly and delivery of the product) reduction in the final assembly process and hence financial savings for the business. The shorter the cycle time for assembly of a product the lower the inventory interest payments are for the work in progress;

  (b) a less frustrated shop floor work force. This then has an impact on reducing the number of mistakes that are likely to occur and hence reduces the risk of scrap and rework during the final assembly activity;

- producing "modular" designs has the advantage of simplifying the final assembly process and it has the added benefit of allowing re-configuration to occur with minimum disruption to the overall production process.

This list is by no means exhaustive. Its purpose is to expand on just some of the qualitative DFMA rules and principles and explain the benefits that can be realised through encouraging their use within the design process.

1.2.4 Issues to Consider When Implementing DFMA

If DFMA is to be successfully introduced, there are many operational issues that need to be addressed.

1.2.4.1 Timing

Consideration of manufacture and assembly issues has to be done during the early stages of new product development for maximum effect. The following examples illustrate the importance of the design stage:

- a study at Rolls Royce revealed that design determined 80% of the final production cost of 2000 components (Corbett 86);
- according to General Motors executives, 70% of the cost of manufacturing truck transmissions is determined in the design stage (Whitney 1988);

- studies at British Aerospace in the 1970s reported in the National Research Council's Report on a National Design Strategy, show that 85% of the cost of components of a product can be attributed directly to decisions made before the product design is released to manufacturing (Tseng & Jiao 96);
- Ford Motor Company has estimated that among the four manufacturing elements of design, material, labour and overhead, 70% of all production savings stem from improvements in design (Cohodas 88);
- a study revealed that the product design is responsible for only 5% of a product's cost; it can, however, determine 75% of all manufacturing costs and 80% of a product's quality performance (Huthwaite 88);
- another study shows that 70% of the life cycle cost of a product is determined at the design stage. The life cycle cost here refers to cost of materials, manufacture, use, repair and disposal of a product (Nevins and Whitney 89).

Of course, as mentioned earlier, manufacture and assembly should be taken into consideration during all design changes, regardless of when in the product's life cycle the change is being made. This point is simply stating that for maximum benefit, DFMA should be considered sooner in the product life cycle rather than later. Figure 1.3 illustrates the relationship between incurred costs and committed costs over the product development cycle.

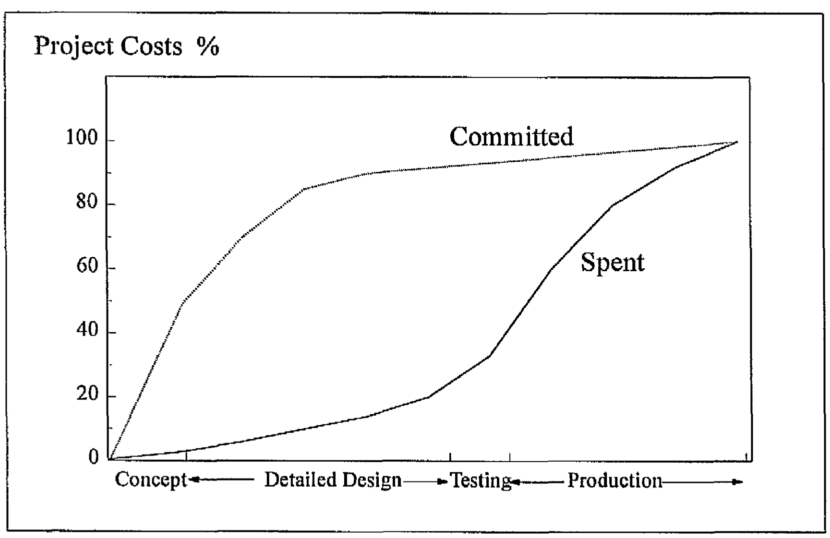


Fig. 1.3 Relationship between Committed and Incurred Costs

In the case of 'material intensive' products, as in aircraft production, design has an even greater influence on the final product cost. Figure 1.4 illustrates 'Design's True Impact' (Salomone 95).

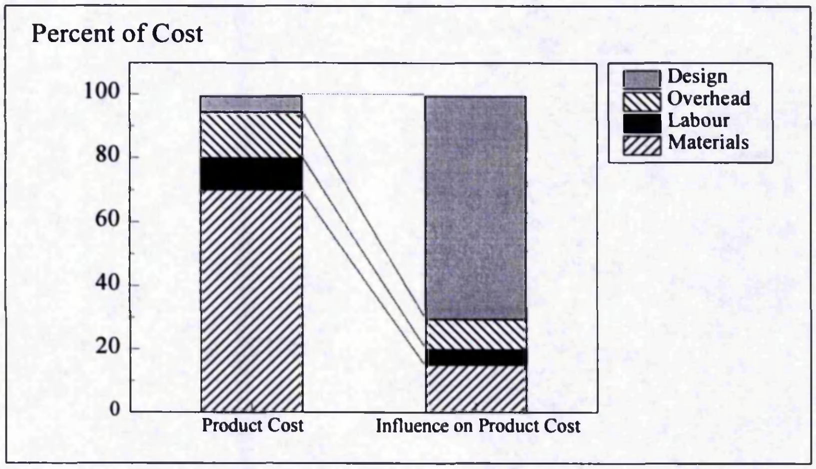


Figure 1.4 Design's True Impact on Material Intensive Products

1.2.4.2 Time

Trying to ensure manufacture and assembly issues are given thorough consideration within a design process is effectively introducing two additional aspects that need careful deliberation. This puts more work onto the design organisation. The company has to accept that additional work up front, will lead to far greater savings in the long run. It is sometimes difficult to get this message home, in the midst of the time pressures associated with both market entry (in the case of new product development) and customer deliveries (in the case of design changes made later in the product's life cycle).

1.2.4.3 Expert Knowledge

Even if a company shows its commitment to DFMA by ensuring the necessary additional design time is allocated, the 'type' of resource available is another factor that needs consideration. Many designers do not have the necessary manufacturing or assembly expertise to enable them to make proficient judgements on these matters. Designers may consider themselves to be sufficiently knowledgeable in this field, but in order to keep up to date with changes in technology, it takes either, a regular education/updating programme, or a dedicated resource assigned especially to this area to keep abreast of the latest developments. Having experts available for consultation ensures appropriate information is available for the designer, but it unfortunately adds another step or communication link to the design process.

1.2.4.4 Organisation

In order to (a) maintain realistic design lead-times and (b) ensure that the DFMA decisions are fed back to the designer and incorporated into the design, there has to be a fundamental change in the way the design process is organised. The traditional sequential approach has to make way for a concurrent approach, where all the elements of the Design for X Model are considered together. There are several ways this can be done.

In a survey conducted by Dean & Susman in 1989 on the organisational impact of DFMA, they discovered several organisational approaches which go a long way to overcoming barriers:

1. Production sign-off

Production engineers are given veto power over product design. The advantage of this approach is that unproducible designs are unlikely to reach the shop floor. The disadvantage however is its heavy handiness. It gives a club to production without providing for the creative interchange between the functions. Also, production system/process design still cannot begin until the product designs are complete.

2. The integrator

Integrators work with designers on producibility issues, serving as liaisons to the production group. Naturally, such a role requires individuals who can keep design and production perspectives in balance. An integrator who leans too heavily towards production will lose credibility with designers, and someone who leans too heavily towards design will simply not get the job done. Clearly the integrator approach is reasonably flexible. A single individual (or small team) can easily keep track of new capabilities in manufacturing, production engineers don't have to become more knowledgeable about design or designers become more expert in manufacturing. Rather the approach develops an expert in DFMA, who can become the focal point for company-wide efforts. The main disadvantage to this type of approach is the 'guru syndrome'. Since the integrator is there to worry about DFMA, no one else does. The organisation becomes very dependent on one or only a few individuals.

3. Multi-functional teams

At minimum they consist of a design engineer and a production engineer who work together throughout the whole process. The team meets regularly and may even be located in the same office. The production engineer becomes familiar with the design well before it is released and may even have a hand in creating it. The production process can be partially if not completely planned before the design is finalised. Friction can arise if designers begin to wonder why the company did not trust them to create efficient designs independently. However, the frequent interaction involved, permits people from the two functions to educate each other, thus enhancing capability for future effort. The inevitable tension stimulates greater creativity but the two functions still have separate hierarchies which helps members hold to their own respective missions.

These approaches are not cast in concrete or meant to seem exclusive of one another. Structures for organisations ought to accommodate the messy dilemmas managers face, so each organisation should customise its own approach. Whatever the chosen method, change in organisational structure will be necessary in a program to achieve a producible design.

1.2.4.5 Peculiarities of an Industry

Each industry has its own 'peculiarities' that distinguish it from other industries. These peculiarities are usually as a result of the nature of the product being made. In the case of aerospace industry there are certain features of the product that make the design process quite different to that in other industries, in terms of what it considers to be priority, for example, safety. These peculiarities influence how design decisions are arrived at, and hence how DFMA is considered. There needs to be a thorough understanding of how trade-offs are made for a particular industry before DFMA can be properly introduced. This aspect will be discussed further in Chapter 2 when discussing why there is a need for DFMA at Avro.

1.3 Feature-Based Design

The Concurrent Engineering Wheel model described in section 1.1 states that the product model should be able to interact with the life cycle decision support tools, for example, Computer Aided Process Planning tools, Design for Manufacture tools, Design for Assembly tools etc.. For this to take place without human intervention, the product model has to contain more information than simply geometric definition. The appropriate data must be extractable from the product model.

An emerging technology that enables the creation of a product model which contains much more than simply geometric data, is Feature-Based Design. The use of features in the modelling of a product is seen as key to the success of a fully integrated design environment.

Designers naturally think in terms of features, for example, a designer would think of a hole in terms of a diameter and a depth, and not as a negative cylinder.

"A feature is any geometric or non-geometric attribute of a discrete part whose presence or dimensions are relevant to the product's or part's function, manufacture, engineering analysis, use etc.. Typical features: hole, pin, flat, slot, spline, datum; typical feature attributes: diameter, depth, tolerance, orientation, used for (mating, fixing), mates with (feature **xx on part yy)." (De Fazio et al. (93)).

In today's Computer Aided Design systems three types of model are in common use: Wireframe, Surface and Solid. Although successful, these systems are built on the same "classic" foundations and remain purely geometric systems. This means that design is geometry driven, whereas geometry should only be considered as a tool to represent the intended object. Feature models are currently being widely investigated as an alternative basis of Computer Aided Design systems.

Much of the research done on Feature-Based Design has tended to concentrate on modelling individual parts using features that represent the part. In order to have a fully defined product model that can be used for all downstream analyses, the product model must also contain information relating the overall assembly not just the individual parts. The latest research into product modelling using features is focusing on 'assembly modelling'. This is the area that will be investigated by the Brite-Euram sponsored FEAST project.

Chapter Review

The purpose of this chapter was to review the literature on the extensive topic of design in order to determine the scope of this Eng.D. study. Initial surveys on the general topic of design revealed that:

- the trend in design over the last decade has been the adoption of Concurrent Engineering;
- Concurrent engineering is an extremely broad subject and the research associated with this field can be split into three groups:

  Organisational and Cultural Aspects;
  Life Cycle Decision Support Tools;
  A Fully Integrated Design Environment, in Particular Product Modelling and Integrated Systems Architectures.

Two of these elements were selected to be progressed further by this Eng.D. study: Life Cycle Decision Support Tools and Product Modelling, specifically, DFMA and Feature-Based Design respectively. Of these two topics, focus on DFMA will predominate.

The research into DFMA will focus on the practical application of qualitative rules and principles at Avro, and also the trial and assessment of quantitative DFMA tools. The research into Feature-Based Design will focus on using features for modelling assemblies, and will be done as part of the Brite-Euram sponsored FEAST project investigating feature based assembly techniques.

The next chapter examines the motivation behind the research into DFMA at Avro International Aerospace. It attempts to explain how the combination of external market forces and internal inefficiencies of the traditional aerospace design process have led to the need for improvements in the area of DFMA.

Chapter 2 Why Research DFMA at Avro?

Summary

Avro has been producing aircraft for many years, so why does a company that has been so successful in the past need to reassess its business processes? This chapter will explain the motivation for research into DFMA at Avro.

This need has arisen due to the combination of two factors: the external pressure of a fiercely competitive market, and a poor design philosophy. Firstly, the dramatic changes in the civil aerospace market over the past decade have led to a situation where aerospace companies must be able to produce aircraft, in less time, at lower cost, with fewer resources, if they are to survive and compete globally in the 1990s. This has put pressure on Avro to reassess and improve all its business processes. Secondly, the traditional approach of aerospace design has always been to focus on product safety, functionality and performance, rather than manufacture, assembly. This has resulted in a poor, inefficient design philosophy which has now been exposed, after the self examination forced on the company by the external market pressures.

Section 2.1 will describe the economic and political factors which have had a dramatic effect on the aerospace market over the past decade. Section 2.2 will describe some of the peculiarities of the aerospace industry which suggest that there are some significant differences from other manufacturing industries. It will then explain the traditional approach to design within Avro.

The issues presented in these sections will illustrate why there is a pressing need for Avro to reassess and improve all its business processes. One of the main themes within this activity will be DFMA.

2.1 Changes in Aerospace Market/Effects on Aircraft Manufacturers

2.1.1 The Avro RJ

Avro International Aerospace began life as the A.V.Roe Company which was formed on January 1, 1910 by Alliott and Humphrey Verdon Roe. In 1924, the factory moved from Didsbury in Manchester to Woodford aerodrome in Cheshire. In July 1935 the company became a subsidiary of Hawker Siddeley Aircraft Co. Ltd. The company underwent a further name change in April 1977 when it merged with the British Aircraft Corporation, and Scottish Aviation, and became BAe. Woodford, part of British Aerospace Plc. In 1993 BAe Woodford became Avro International Aerospace, still a subsidiary of BAe Plc., but treated as a separate business unit in readiness for a joint venture partnership.

Up until the 1950s the majority of the aircraft produced by Avro were military. In 1957 the Government declared there would be no more manned bombers for the RAF, forcing Avro to start to look towards the civil market. A replacement for the Dakota transport aircraft was required and the Avro 748 was born. The 748 (a 50 seat Turboprop aircraft) made its first flight from Woodford in April 1961, and before production ended in 1986, 380 were sold in 50 countries. In August 1986 the replacement for the 748, the ATP (Advanced Turboprop) made its first flight. In 1993 ATP production was transferred to BAe Prestwick in Scotland.

The aircraft currently in production at Avro is the "RJ", a 70-100 seat, four-engined, regional jet (see Figure 2.1 and Plate 2.1). The regional market can be defined by the needs of those airlines operating routes which connect one region to another region or to a major city. Regional operation characteristics are: stage length on average 350 miles, relatively low traffic levels, both large and small airlines and an aircraft capacity of typically 18-120 seats.

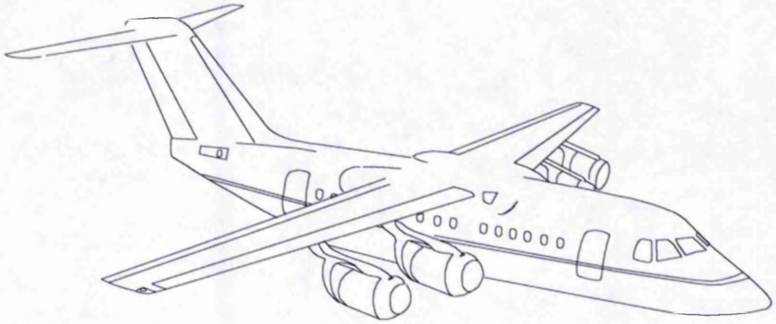


Figure 2.1 The Avro RJ

The RJ began life as the "146" which was designed at BAe Hatfield in 1971 and went into production at Hatfield in 1978. In 1988 a second final assembly production line was set up at Woodford. The roll out of the first 146 built at Woodford was on 29 April 1988. The 146 was relaunched as the RJ in 1992 with upgraded engines, an improved (CAT III) avionics system and a new 'spaceliner' interior. In 1993 after closure of BAe Hatfield, Woodford became the sole site for RJ production.

The RJ comes in three variants, the RJ70, RJ85 and RJ100 (see Figure 2.2). The difference between the variants is the length of the centre fuselage section. The numbers represent the number of passengers each variant can carry. The main performance features of the aircraft are: short take off and landing capability, rough runway capability, low noise emissions and four-engined reliability/safety.

Plate 2.1 The Avro RJ

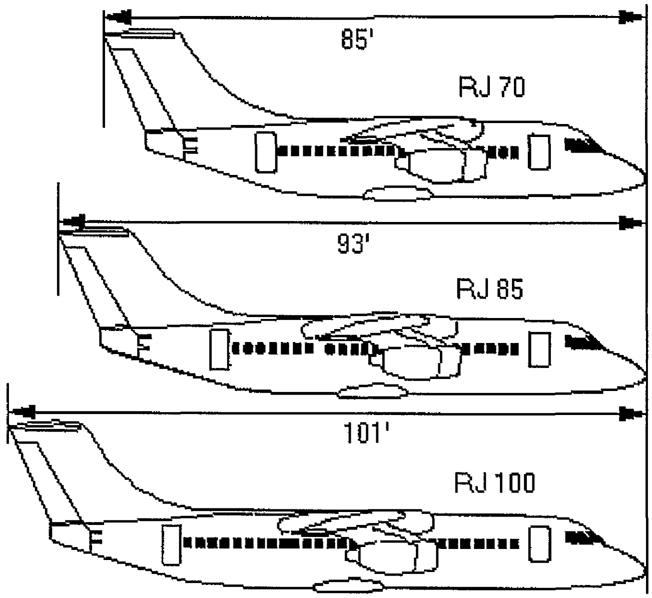


Figure 2.2 The RJ Variants

The RJ/146 has an extensive customer base, and almost 300 aircraft have been sold worldwide (see Figure 2.3).

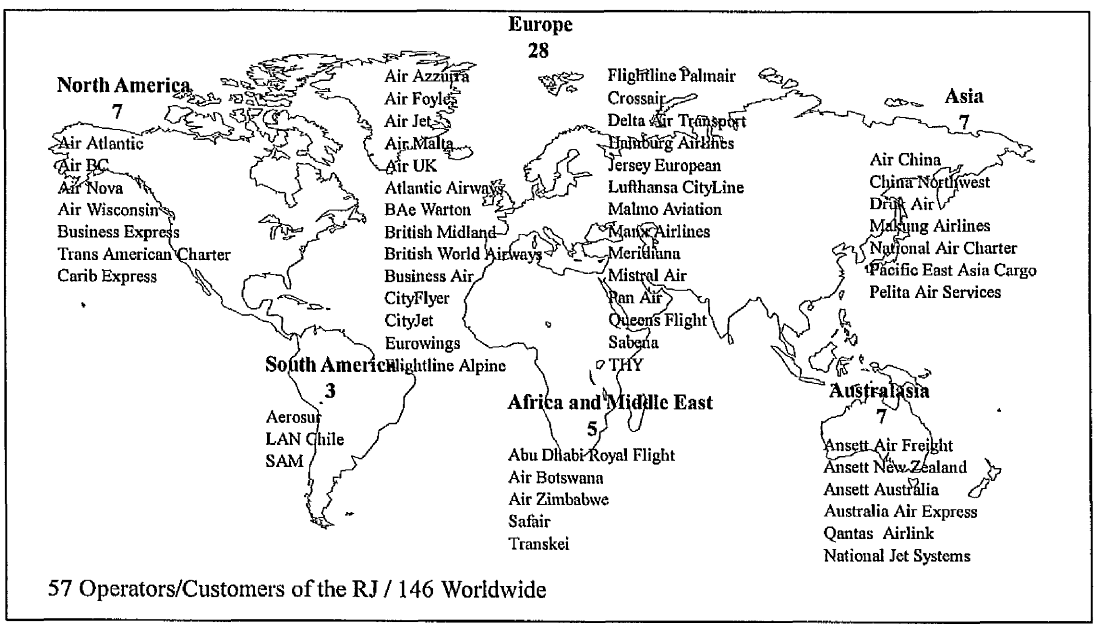


Figure 2.3 RJ/146 Customer Base

2.1.2 Recent Economic and Political Influences on the Aerospace Market

Growth in Gross Domestic Product (GDP) slowed worldwide in 1991, driven mainly by recession in Europe and the USA. As there is a close relationship between economic growth and airline passenger growth (see Figure 2.4), 1991 traffic reduced, compared to that of 1990.

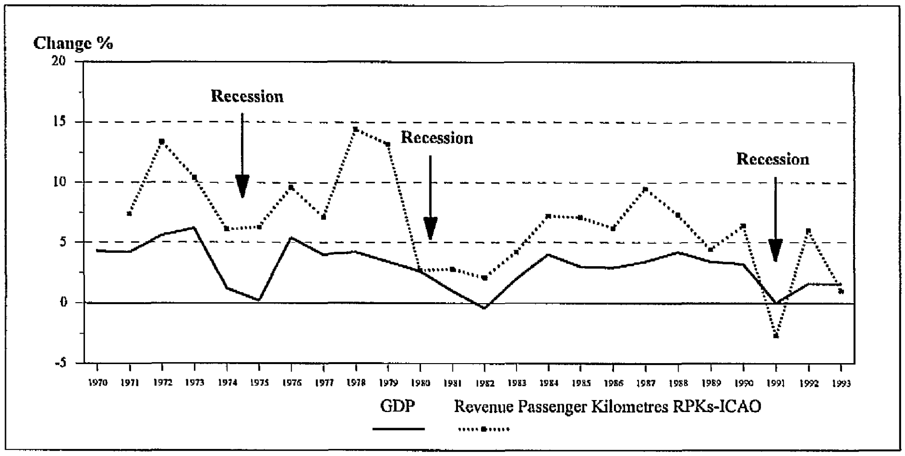


Figure 2.4 Correlation Between Economic Growth and Airline Passenger Growth (Source: Avro Marketing)

This situation was compounded by the invasion of Kuwait, which had a particularly negative effect on transatlantic traffic and, consequently, the regional feeder traffic associated with these flights. Leisure travel was affected by the reduction in disposable income that accompanies a recession, and business traffic also reduced in line with corporate travel budget cuts.

2.1.3 Effects on Aircraft Manufacturers

The resulting reduction in airline profitability has led to order cancellations and deferrals. The large number of aircraft deliveries in 1991, coupled with the decline in traffic, has resulted in industry-wide over capacity. IATA estimates that demand has slumped some 5% below capacity, equivalent to 400 Boeing 747s flying between New York and London every day. This has led to several major problems for manufacturers.

Since such a wide variety of aircraft are available, the market now dictates the selling price of the aircraft. If aircraft manufacturers are to make a profit, then at the simplest level they must ensure that the cost of building the aircraft is lower than the price the customer in the market place is prepared to pay. This means regional aircraft manufacturers have to be able to respond to the turbulence of market driven pricing policies.

Production rates are now having to be cut to match demand. Figure 2.5 illustrates the extent to which production has reduced, not just in the regional sector but right across the civil aircraft industry.

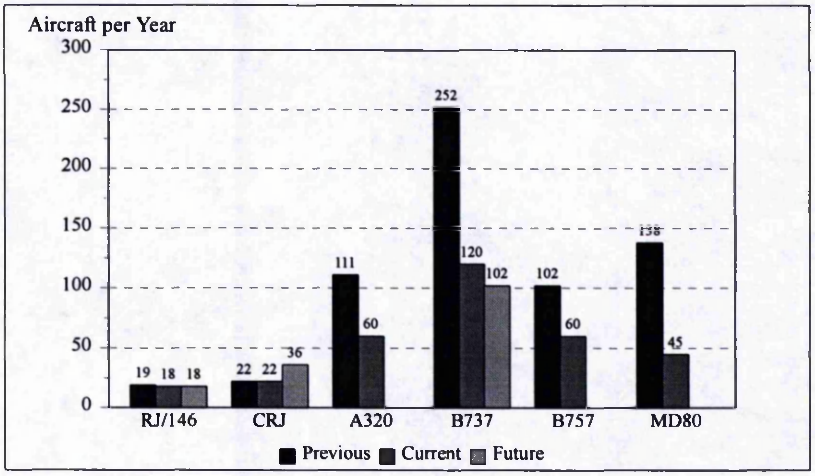


Figure 2.5 Production Rate Reductions (Source: Avro Marketing)

Over production, stocks of aircraft at leasing companies, and airline bankruptcies mean that large numbers of both new and used aircraft are readily available. All these factors influence the development of regional aircraft, as shown in Figure 2.6.

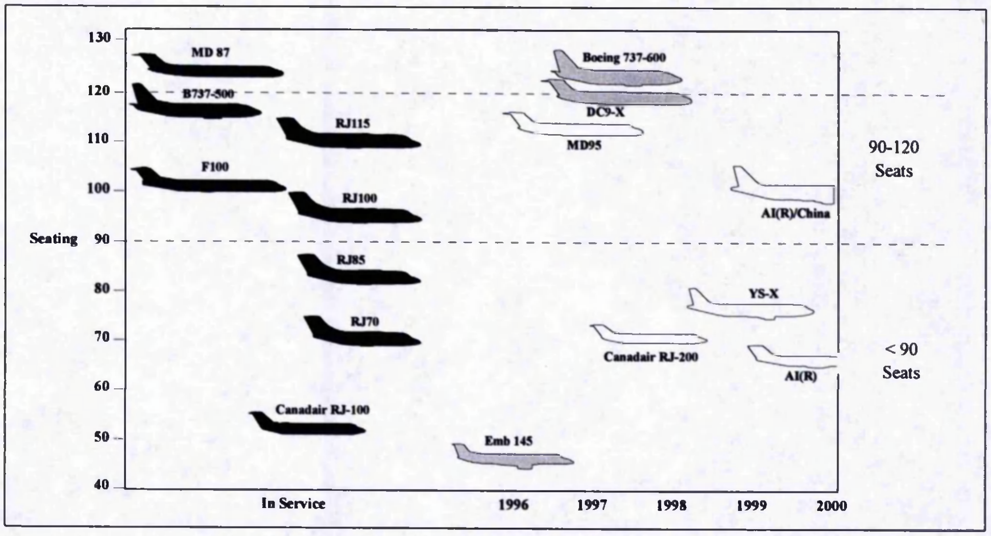


Figure 2.6 Development of Regional Aircraft

An additional complication for the smaller regional jet makers is the presence of the three large commercial aircraft manufacturers at the upper end of the market. Figure 2.7 lists the current civil aircraft manufacturers.

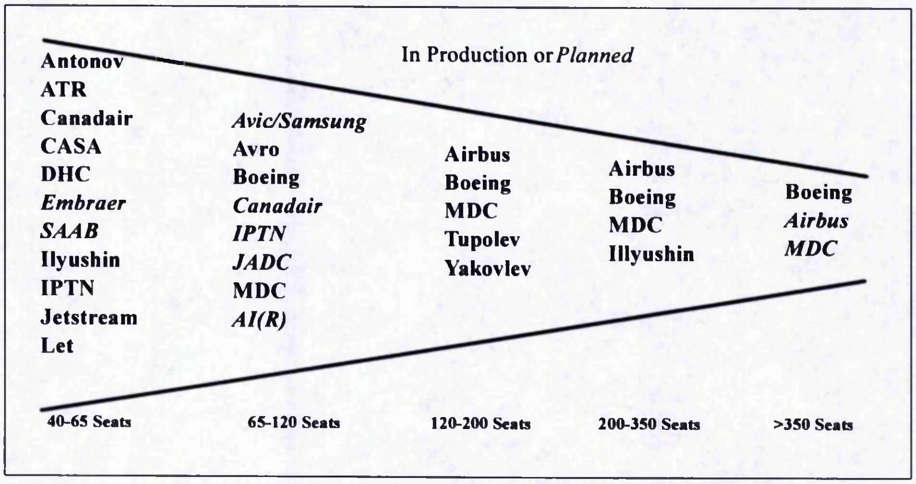


Figure 2.7 Current Civil Aircraft Manufacturers

At least nine manufacturers are still in the race to build regional aircraft in the 30 to 120 seat range, with another eight potential players from the former Eastern Bloc and the Pacific Rim. However, many within the industry believe there will be room for no more than three or four manufacturers in the regional aircraft market.

All this has led to acceleration of effort to rationalise the regional airliner industry, especially in Europe. Some consolidation has already begun. Bombardier of Canada absorbed Short Brothers of Northern Ireland, Canadair and more recently, de Havilland of Canada. Aerospatiale, the French aerospace company, and Alenia of Italy have also pooled their resources to form the ATR Consortium. The latest joint venture to be announced is that between British Aerospace and ATR. The new company AI(R), Aero International (Regional) will be based in Toulouse, France.

The general assumption is that major restructuring will continue worldwide and that an Airbus style consortium covering the 30 to 70 seat turboprop and the larger 70-120 seat turbofan market may be the way forward (Source: 'Rationalising the Regionals' Flight International 17-23 February 1993).

International collaboration is taking on a growing importance in developing new products and technologies. An International Aerospace and Defence survey conducted by Ernst and Young showed that virtually all Western respondents rejected the idea that a company could operate alone when developing new products and technologies in today's environment, and collaboration with foreign companies was seen as important for business development.

The first casualty in the fight for survival in the regional aircraft market was the Dutch aircraft producer, Fokker. The company went into receivership earlier this year.

2.1.4 Market Outlook

In spite of the current glut of aircraft in the market, transport of passengers by air remains a growth industry and, over the next 10 years, a sizeable market for regional aircraft will exist. World air traffic measured in terms of RPKs (Revenue Passenger Kilometres) is set to double by the year 2006 (excluding the CIS and China) (see Figure 2.8).

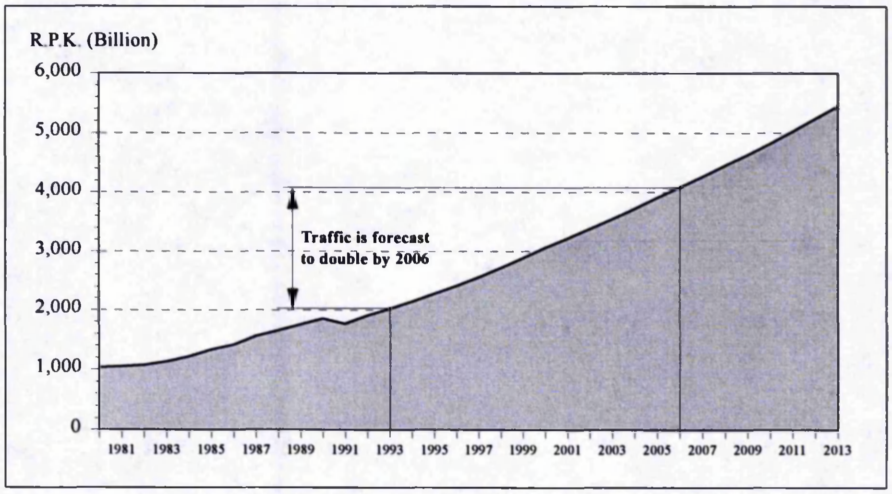


Figure 2.8 Future Traffic Forecast (Source: Avro Marketing)

Average growth between 1991 and 2011 will be 4.9% pa. This means that the fleet of aircraft in service will increase from 12,400 in 1991 to around 22,300 by 2011, an increase of 79%. During this period it is estimated that around 8,600 units will be retired from passenger airline service. Hence, a requirement will exist for in the region of 18,500 new jet and turboprop aircraft, representing around $77 billion in market value. Figure 2.9 shows the breakdown by aircraft type of the future annual deliveries.

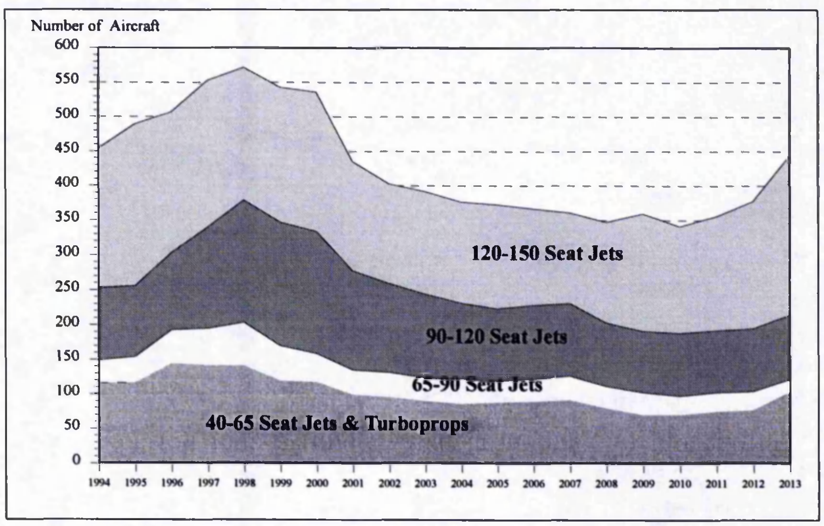


Figure 2.9 Future Annual Deliveries (Source: Avro Marketing)

2.1.5 Capturing a Slice of the Market

Companies which will be successful in capturing a large slice of this market amid global realignment of the aerospace industry, will be those which are best able to reduce the direct operating costs of their aircraft.

Although transport of passengers by air remains a growth industry, airline yields are decreasing at a faster rate than operating costs i.e. fares are declining faster than costs (see Figures 2.10 and 2.11).

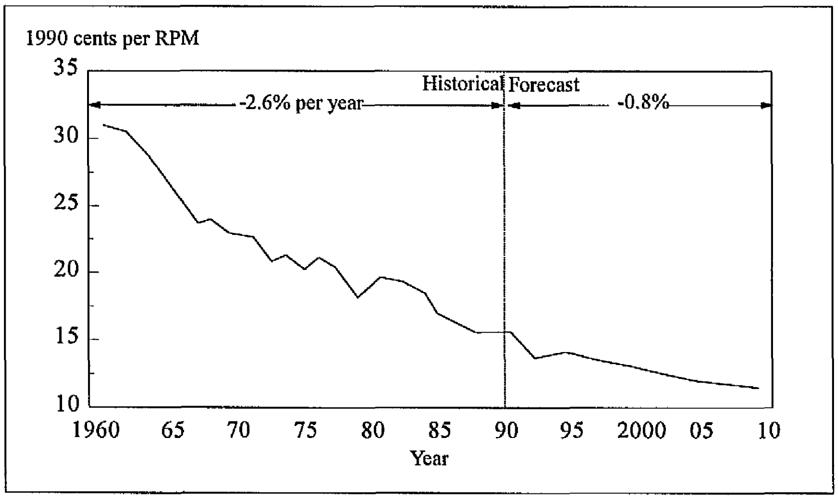


Figure 2.10 World Airline Yields (Source: Boeing's 1993 Current Market Outlook)

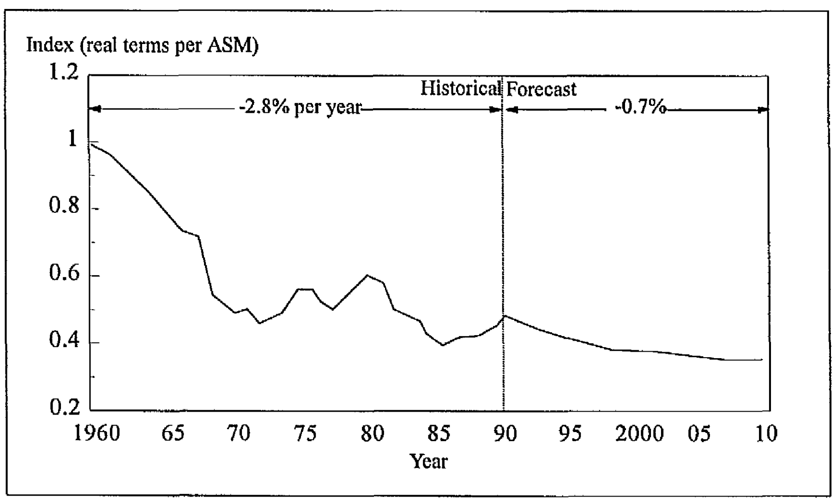


Figure 2.11 World Airline Total Operating Costs (Source: Boeing's 1993 Current Market Outlook)

With fierce fare wars breaking out as a result of continuing over capacity in the market at a time of increasing liberalisation, the need for airlines to minimise their direct operating costs has never been greater. Figure 2.12 shows the criteria on which airlines base their acquisitions. Economics (initial purchase cost plus operating costs) is by far the most important factor.

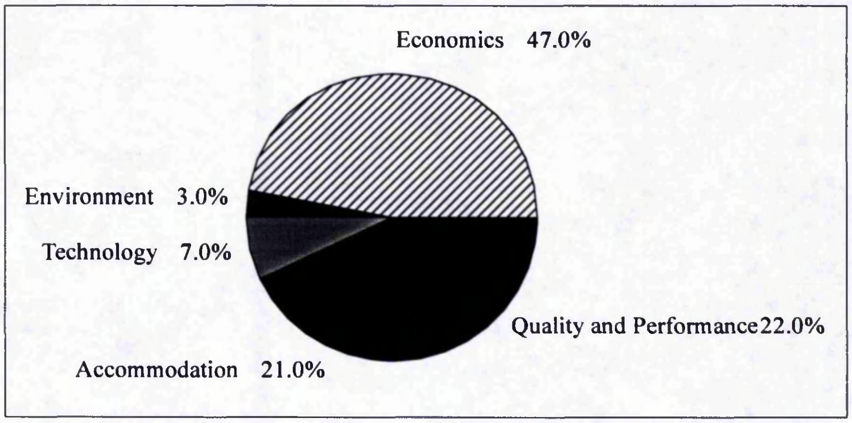


Figure 2.12 Airline Purchasing Criteria
(Source: International Aerospace & Defence Research Study, Ernst and Young, 1993)

Figure 2.13 shows the elements which contribute to aircraft economics, and it is clear that manufacturers have the capability and therefore the responsibility to influence up to 90% of these.

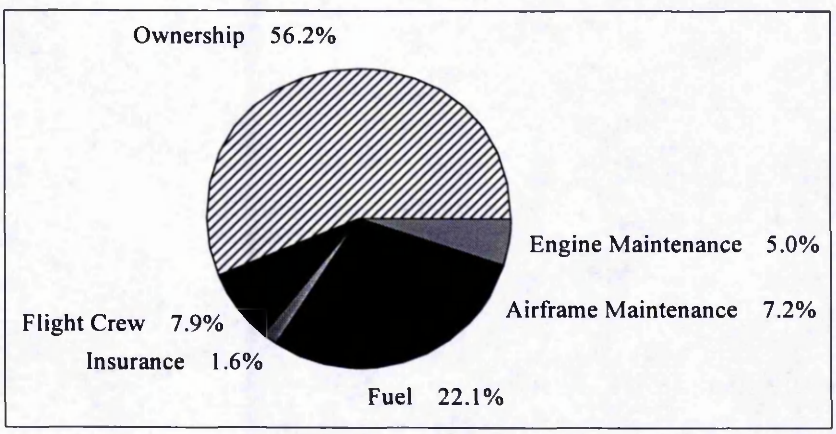


Figure 2.13 Elements of Direct Operating Cost (Source: BAe Marketing Survey 1993)

To survive the slump, maintain a profitable business and prepare for the coming upturn in air passenger miles, airlines have three basic requirements: Low initial purchase cost, 100% dispatch reliability (the aircraft leaving on time with no technical hitches), and minimum operating costs (e.g. fuel, crew, maintenance).

To maintain its competitiveness with the RJ aircraft, amidst these fierce market conditions, Avro must focus on cycle time reduction in order to achieve more competitive delivery targets.

Avro must also reassess its business processes in order to reduce the aircraft production costs and meet the market driven acquisition prices; the higher the aircraft production costs the higher the ownership costs.

2.2 Aerospace Design

This section will describe some of the peculiarities associated with aerospace design. It will then explain the traditional approach to trade-offs within aerospace design, and reveal how design at Avro has come to be lacking in the area of DFMA. The detailed interactions between the specialist functions within the design department during the aircraft design activity (see Bond and Ricci (92)), will not be described here, the purpose of the section is to highlight the peculiarities which have a major influence on trade-off decisions.

2.2.1 Peculiarities of the Aerospace Industry

Before the design process of a particular industry can be fully understood, the peculiarities associated with the product need to be investigated and an appreciation of how these peculiarities influence the design decisions needs to be developed.

The top level design process for the aerospace industry is no different to that of any other manufacturing industry (see Figures 2.14 and 2.15, Appendix 2 gives a more detailed account).

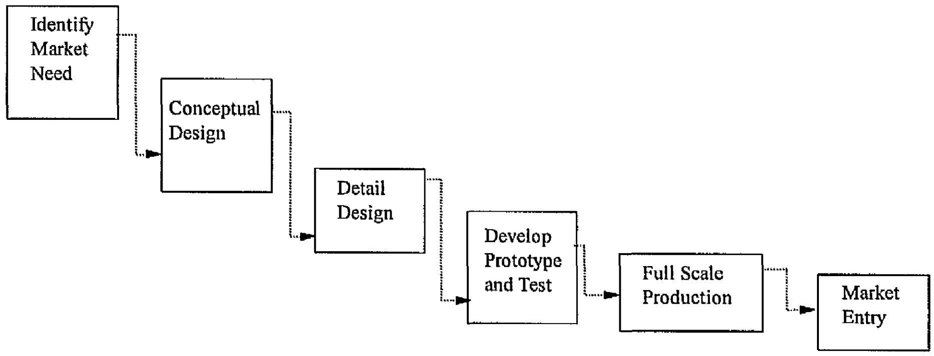


Figure 2.14 Top Level Model for New Product Development Design Process

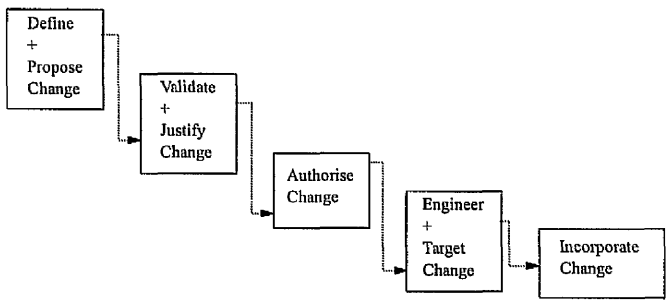


Figure 2.15 Top Level Model for Existing Product Design Change Process

However, at the more detailed level, there are peculiarities associated with every type of industry which differentiate one from another and which, once identified, offer an understanding as to how design decisions are arrived at. It is not within the scope of this project to investigate the peculiarities of all types of industry and then offer comparison. Only the peculiarities of the aerospace industry are of interest here.

The following aspects of the aerospace industry are the peculiarities that distinguish it from other manufacturing industries:

2.2.1.1 Stringent Industry Regulatory Authorities – Safety and Reliability

The aerospace industry is governed by regulatory authorities who apply stringent safety requirements in aircraft design. The CAA (Civil Aviation Authority) is responsible for standards in the UK, and the FAA (Federal Aviation Administration) is responsible for standards in the USA. These authorities produce strict guidelines for reliability and safety, which have to be adhered to by all aircraft manufacturers.

Before a new aircraft can be launched into the marketplace, it has to undergo 'certification', this is achieving approval from the relevant regulatory body. The regulatory authorities not only control the design at the development stage, they can also impose changes to the design for safety reasons, at any stage during the aircraft's life cycle.

Some of the issues associated with this peculiarity are:

1. Close dependency between reliability and safety

Unlike in other products, reliability and safety in aircraft design are to a significant degree dependent on one another; an unreliable aircraft cannot simply pull over to a lay-by if the engine fails.

2. Re-certification

If the producer wishes to modify the aircraft during its life cycle, then there may be instances where re-certification is required. This obviously depends on the nature and size of the modification. Re-certification costs can make design improvements economically infeasible late on in the product's life cycle.

3. Traceability

Within the aircraft industry, there are stringent traceability requirements. Information relating to all aspects of the production process needs to be available, from who fitted the part to the aircraft, to the actual batch of raw material from which the part was manufactured.

4. Approved suppliers

All companies within the supply chain have to be 'Approved Suppliers' i.e. they have to obtain approval from the relevant regulatory body (e.g. the CAA), before they can supply parts for use on aircraft.

5. Restrictions on the use of certain technologies

Restrictions imposed by the regulatory authorities can also have an impact on the benefits obtainable from certain technologies. An example of this is the use of *castings* on aircraft. Castings are components formed through moulding molten metal. The regulatory bodies do not allow castings to be used without a casting factor of x2 being applied, because they are not convinced that this manufacturing process can guarantee the stress requirements (regarding the grain structure of the metal after it has been cast). Therefore, the benefits that can be gained by reducing the part count through integrating a number of individual components into one cast piece, are surpassed by the imposed increase in the weight of the new casting. This effectively makes the use of castings somewhat prohibitive in aircraft design. Nevertheless, new casting technology is becoming much more advanced and reliable grain structures can now be formed. Work is underway to try to get the casting factor of x2 reduced.

2.2.1.2 Long Product Life Cycle

The typical life cycle of a regional aircraft is between 20-30 years. Some of the issues associated with this peculiarity are:

1. Inevitable design changes

Inevitable design changes throughout the life of the product can be attributed to one of the following reasons:

(a) Seeking performance improvements through technological advances.

Market demands change dramatically over a 20-30 year period, therefore it is inevitable that the performance of the product will have to be enhanced at some point during its life cycle. When new technologies are introduced, many industries take advantage by developing new products based on this technology. However, in the aerospace industry, the reverse of this tends to happen, new technologies are designed *into* old products. This is particularly true of the smaller aircraft companies.

(b) The role or usage of the aircraft may change. For example, on the RJ aircraft, the recent introduction of pannier tanks (extra fuel tanks) in order to increase the aircraft's range, and the introduction of an animal transportation bay.

2. No passage of experience

Regional aircraft producers generally only develop one aircraft at a time. It is difficult therefore, to learn from the experience of one development and transfer the knowledge on to the next, because most of the people who are involved in the first program are likely to be retired or have left the company by the time the next development begins.

2.2.1.3 Low Production Volume

Typically aircraft production volumes are low compared with other manufacturing industries. In some cases aircraft production can almost be viewed as a one-off project, depending on the diversity of the customisation requests.

The current production schedule at Avro is for 18 aircraft per year. This is small compared to Boeing's current 737 production rate of 120 units per year. However, both of these are minute when compared to the typical production rate of a car manufacturer, which runs into hundreds of thousands of units per year.

Some of the issues associated with this peculiarity are:

1. Tooling costs

(a) Should aircraft be designed with automation in mind, for example the use of automatic riveting machines, or does the low volume simply not warrant such extravagance?

(b) An ideal situation would be to have all the necessary component preparatory operations completed prior to the final assembly stage, for example, drilling off holes, so that the parts can simply be assembled and fastened during the final assembly stage. A pre-requisite to achieving this is to have accurate jigs and tooling fixtures. Is it cost effective to invest in 'state-of -the-art' tooling or is it better to struggle during the assembly process, ‘fettling to fit!’?

2. Impact on suppliers

(a) If the aircraft producer's business is only a small percentage of the supplier's turnover, then how much leverage do they have when it comes to demanding price reductions, design modifications and quality improvements?

(b) Minimum order quantity restrictions – cases may arise where even if the designer selects standard parts, a minimum order quantity constraint could negate the benefits.

(c) It is more difficult to use economies of scale.

2.2.1.4 Stringent Weight Limits

A major factor to consider in aircraft design is weight. Weight has significant impact on aircraft performance and consequently, airline profit and loss. The heavier the aircraft, the higher the fuel burn, the higher the direct operating costs for the airline. If the aircraft grows in weight throughout its life cycle, this can start to affect the passenger revenue; the heavier the aircraft becomes the fewer passengers and payload it is able to carry. Weight not only impacts on the cost of running the aircraft it can also hinder the route and runway capability.

2.2.1.5 Highly Political

As in most industries, business decisions are not simply based on economic reasons, politics play a major role. For example, aircraft producers may have to install equipment from a particular country of origin in order to stand a chance of capturing market share within that country.

2.2.1.6 Stringent Stress Requirements

All aircraft structural design decisions have to be approved from a stress point of view. Some of the issues associated with this peculiarity are:

1. Possibility of delays in the design process

Having to have Stress department approval on nearly every design decision adds an additional loop to the design process. At some stage the designer will have to submit his work for stress approval, before he can continue with the design; subsequently there is the potential for delay.

2. Fail safe or safe life?

Fail-safe is where a component is designed in such a way, so that if it fails, the overall system to which it belongs can still safely perform. Safe-life is where the component is designed in such a way that it has a specified life before failure will occur. When this time elapses the component must be replaced. The fail-safe philosophy inevitably leads to more robust and, therefore, heavier designs. The safe-life philosophy inevitably leads to higher replacement costs.

2.2.1.7 Product in Service

Some of the peculiarities associated with the aircraft in service are:

1. Strong emphasis on maintenance

The maintenance and testing in service aspect carries much more importance from a safety point of view in the aircraft industry than it does with many other types of industry. Maintenance is a large aspect of the product in service compared to say, cars, which only need to be serviced every 12000 miles with the odd check of the oil and water in between. In the case of aircraft, maintenance programmes are extremely rigorous and the intervals between the most basic checks are as low as in between flights. Therefore, ease of maintenance is vital.

2. Diverse operating conditions

(a) Differential pressure

An aircraft has to be able to function in an environment affected by changes in pressure. The design has to nullify the effects of this differential pressure.

(b) Temperature extremes

An aircraft has to operate in extreme temperature conditions, flying through cold air temperatures at 30,000 ft to reach a hot and humid airport in the tropics!

3. Airport infrastructure

Aircraft have to be designed to suit the airport infrastructure, for example, connection to jetways.

4. Noise pollution

Aircraft have to be designed to meet strictly enforced noise pollution restrictions.

2.2.1.8 High Cost of Parts

The requirement for Traceability and Approved Suppliers described in 2.2.1.1, is reflected in the price of aircraft parts. For example, a 6"x3" machined attachment bracket similar to that illustrated in Figure 2.16, costs £345. A simple 4"x2" Tee bracket similar to that shown in Figure 2.17 costs £53.

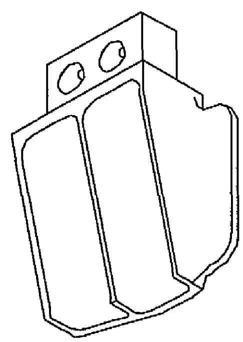


Figure 2.16 Attachment Bracket

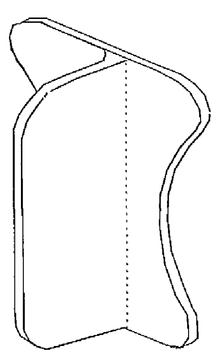


Figure 2.17 Tee Bracket

2.2.1.9 Product Complexity

Aircraft are extremely complex products. Aircraft production is building a structural shell and then performing complex systems integration. Complexity on this scale impacts many areas, for example:

- Design – understanding the impact changes in one area of the design have on another area. It is difficult to keep in mind all the possible 'knock on' effects;
- Finance – it is difficult to accurately monitor all aspects of cost for example, man-hour spend, parts' costs etc..

2.2.1.1.0 Lack of Competitor Information

A common practice in other industries is to perform *tear down* analysis on competitor products. This is where the product is purchased then taken apart for analysis. Obviously this is not practical in the aircraft industry; detailed, technical competitor information, is more difficult to come by.

2.2.2 Trade-Offs in Traditional Aerospace Design

Trade-off evaluations are an integral part of any design process, understanding the impact changes in one area have on other areas is the fundamental conundrum. This section will explain how Avro has ended up with a poor design philosophy through the traditional approach to aerospace design.

Aircraft have always and will always be designed principally with safety in mind. There are no trade-offs with the safety aspect of the Design for X model, all other aspects are effectively secondary considerations.

In the traditional approach to aircraft design at Avro, after safety, aircraft functionality and performance were the next priority. Reduction of fuel consumption and increasing the range of the aircraft by focusing on weight and drag reduction were considered to be the key factors for market success; manufacture and assembly came a poor second.

The traditional design trade-off model within Avro never had to have cost as a principal element. This is because all aircraft designed at Avro have been subsidised either directly (military business), or indirectly (on the back of the military business) by the Government. Therefore, stringent budgets and cost targets have never really been used. Since Avro no longer carries out military work, it no longer has Government backing. The company now has to hold its own in the regional aircraft market.

In trying to maintain its competitiveness with the RJ aircraft, amidst fierce market conditions, the focus has had to turn to cycle time reduction (in order to achieve more competitive delivery targets) and cost reduction (in order to meet market driven pricing) unfortunately it is only now that the neglect of manufacture and assembly issues during the early stages of the aircraft development is coming to light.

Section 7.3.1 of Chapter 7 will attempt to highlight the complexity of today's trade-off model which is based on the peculiarities associated with aerospace design.

Chapter Review

This chapter described the motivation for research into DFMA at Avro.

In summary:

- over capacity in the market place has led to fierce fare wars and subsequent falls in airlines' yields. The falls in airlines' operating costs have not kept up with the decline in fares, and the impact this has had on aircraft manufacturers is that they need to improve the efficiency of their production processes so they can meet the new, lower, market driven aircraft acquisition price;
- as Avro seeks to produce its current aircraft faster and cheaper, and looks to the next generation regional jet development, one of the main stumbling blocks is lack of DFMA in the design process This has arisen because the traditional design process was protected by military subsidies. Safety, reliability and product performance were priority, manufacture and assembly came a poor second.

The next chapter examines how the Eng.D. study has had to adapt in order to stay in line with changes in Avro's company strategy and maintain its relevance.

Chapter 3 Eng.D. Research Project Methodology and Path

Summary

This chapter will explain how the subject of DFMA was investigated, applied and assessed. It will also briefly explain how the research into Feature-Based Design was conducted.

A feature of the Eng.D. program which distinguishes it from the traditional Ph.D. is that the research topic has to have industrial relevance for the sponsoring company. It is therefore not surprising to find that the research path is sensitive to changes in company strategy which occur over four years, particularly in periods of rapid change as experienced in the early 90s. The purpose of this section is to explain how the path of the research into DFMA had to adapt during the course of this project in order to stay in line with company strategy and maintain its relevance. A detailed account of how changes in Avro's strategy influenced the path of the research will be given.

3.1 Research Methodology for DFMA Activity

In chapter 1 two of the elements of the research into Concurrent Engineering were selected for further progression by this Eng.D. study, these were: DFMA and Feature-Based Design.

The research into DFMA will predominate and will adopt the following methodology:

1. The practical application of qualitative DFMA rules and principles.
2. The trial and assessment of quantitative DFMA tools.

3.2 Research Path for DFMA Activity

3.2.1 Original Direction of DFMA Research at Avro

A feature of the Eng.D. program which distinguishes it from the traditional Ph.D. is that the research topic has to have industrial relevance for the sponsoring company. It is therefore not surprising to find that the research path is sensitive to changes in company strategy. Section 2.1 of Chapter 2 described how the aerospace industry has undergone monumental changes over the past decade. This has resulted in many changes in Avro's company strategy over the period of the Eng.D. project. In order for the research to maintain its relevance within this very turbulent environment, its direction had to change in line with the company strategy.

At the start of the Eng.D. project in October 1992, Avro's company strategy was as it had been for many years. The company employed just over 3000 people, the organisation was primarily functionally based and the main business activities were: RJ and ATP production, flight testing, and new product development.

The company was embarking on the conceptual design stage of a new aircraft development; the RJX, a new twin-engined regional jet. From the practical application of qualitative DFMA rules and principles and the trial of quantitative DFMA tools on the RJ, any potential improvements would primarily be fed into the new product development activity. Effectively the RJ was to be the 'trial' vehicle for idea generation and the RJX was the intended 'exploitation' vehicle.

The first task undertaken was to set up a team consisting of designers, engineers and shop floor operators and research new ways for aircraft nose assembly by studying how the RJ nose assembly was designed and built. The plan was to apply qualitative DFMA rules and principles in order to generate suggestions for improvement.

At the same time investigations into the mechanics of the commercially available quantitative DFMA tools began.

3.2.2 Changes in Company Strategy

As the increasingly turbulent market forces began to influence Avro's business, the company's priorities began to change. In 1992 Avro followed the inevitable track of so many aircraft manufacturers, and made moves towards finding a joint venture partner. The phenomenal costs (>£1billion) associated with new aircraft development made this activity prohibitive to Avro in isolation. BAe Plc. were not prepared to make the necessary investment, and so a joint venture partner was the only hope of any kind of long term future for the company. In readiness for joint venture discussions, Avro announced that the company's core activity would be RJ production and new product development. To this end, ATP production was transferred to BAe Prestwick, where it joined the Jetstream 31 and 41 to complete the turboprop family. The first set of discussions with a joint venture partner began in 1992 with the Taiwanese Aerospace Industry.

Unfortunately, the Taiwanese joint venture discussions broke down in 1993 and at the same time, due to increasing market pressures, the company found itself in a worsening situation. Although at this point in time, Avro had a healthy order book, it was still a loss making business (the company was losing approximately £1million per week). BAe Plc. could no longer subsidise Avro in the way it had in the past, so in the midst of major organisational restructuring, headcount reduction and improvement drives to make the company attractive to a joint venture partner, Avro was also under threat of closure from its parent company.

During this period Avro's company strategy changed again. Focus shifted from long term development to short term issues that would improve the efficiency of RJ production. The emphasis turned to streamlining the production activity (see Appendix 3 for an overview of the RJ's production activity) in order to: (a) reduce production cycle times and gain more flexibility, and (b) reduce production costs. The RJ production activity was to be streamlined in three ways:

- by improving the way the aircraft was physically assembled both through re-engineering and more efficient assembly planning;
- by improving the efficiency of the logistics system through closer working relationships with key suppliers;
- through focusing on any potential physical design changes to the aircraft that could ease production.

3.2.3 New Direction for DFMA Research

As a result of this RJ production streamlining activity, the new aircraft development program was scaled down, and eventually the RJX activity was put on hold. Consequently, the direction of the Eng.D. research had to change; the exploitation of the ideas generated by the DFMA research was now much more targeted at the RJ rather than the next generation aircraft.

The principal task at this stage in the Eng.D. research was to understand the sources of Avro's current design activity. Appendix 1 describes the various sources of design activity at Avro. From this investigation the customisation design activity was seen to have most influence on the efficiency of the RJ's production process, and was therefore selected for further investigation. It was felt that improving the customisation activity with respect to DFMA, would ensure that the Eng.D. research remained relevant and contributed to the topical company initiative with maximum effect. At the same time the knowledge gained as a result of this research, could be carried forward into ensuring the next generation regional aircraft is customised with manufacture and assembly in mind.

The Eng.D. research into the customisation area began with a familiarisation exercise. Investigations revealed that the most troublesome area of the customisation activity was in fact galley installation. Therefore this was the area selected for improvement. Chapter 4 presents an extensive account of how qualitative DFMA rules and principles were applied to this production easement exercise.

3.2.4 The DFMA Research Activities Placed in the Overall Context of Avro's Break-Even Drive

3.2.4.1 The Business Plan Improvement Programme ("BPIP")

This section will set the DFMA research into the overall context of Avro's break-even drive by explaining how the research ties in to the Avro's Business Plan Improvement Program, ("BPIP") initiative.

In 1995 BAe Plc. appointed a new Chief Executive Officer ("CEO") at Avro with instruction to achieve financial break-even by 1997. Although, moves were already afoot within Avro to improve the business, it was apparently felt by the new CEO that a more rigorous and structured approach was needed. To this end, a major cost focused, disaster driven recovery plan was instigated. This initiative was called BPIP, and its purpose was to provide a framework to monitor and control the significant operational efficiencies that were being sought across the business.

BPIP is made up of seven themes focusing on cash, profit and business enablers:

- Build to Order;
- War on Waste;
- Cost Management Journey;
- Customer Focus;

- Maximise Opportunities for Revenue Enhancement;
- Avoid Cost, Reduce Overdraft;
- Performance Through People.

3.2.4.2 Qualitative DFMA Research and the Build to Order ("BTO") Theme

It has already been mentioned that within the production environment, significant improvements in efficiency had been achieved. Through re-engineering, headcount reduction etc.. Following the instigation of the formal BPIP initiative and the drive for even more improvements in the area of production efficiency, the production contingent of the organisation saw opportunities to turn this already developed capability into a real competitive advantage.

The order winning criteria in the aerospace market at this time was customer delivery response time, price, and standard of interior accommodation. Further improvements in production efficiency meant that Avro could confidently and overtly start using responsive delivery time, and flexible configuration in the RJ's sales campaigns. This signalled the start of the Build to Order initiative ("BTO").

The essence of Build to Order is quite simple, it is about matching supply to demand and consequently minimising the company's exposure to financial working capital (a more detailed explanation of the Build to Order initiative is given in Appendix 4).

BTO became one of the main themes within BPIP and it effectively became the focal point for all production activity improvements. BTO raised cycle time as a key business objective and hence any initiatives that would impact this area were given priority.

The qualitative aspect of the research into DFMA is concerned with improving Avro's customisation activity, this therefore links into the BTO theme. A more detailed explanation of this contribution is given in section 4.6 of Chapter 4.

3.2.4.3 Quantitative DFMA Research and the Cost Management Journey Theme

The Eng.D. research into quantitative DFMA tools links into Avro's Procurement organisation's BPIP theme known as the Cost Management Journey.

The aim of this theme is to contribute to improving the efficiency of the RJ's production process by seeking reductions in material costs. In July 1995 an exercise aimed at reducing the costs of the RJ's passenger and service doors through re-design was instigated by the Procurement department. This exercise was to be done in conjunction with the door supplier and the design changes were to be sought by using one of the DFMA software tools being investigated as part of the Eng.D. research. The exercise is described in detail in section 5.3.2 of Chapter 5.

3.2.4.4 Avro's Current Position

Today, Avro employs approximately 1800 people and is very much a process based organisation. The company is split into three groups: the Customer Process, the Product Process, and the Supply Process.

In 1995 a joint venture partnership was signed between Avro, BAe Prestwick, Aerospatiale of France and Alenia of Italy. The joint venture company is called Aero International (Regional), (AI(R)) and the headquarters will be based in Toulouse in France. As a result of the ATR joint venture, Avro's strategy is now very firmly focused on becoming an efficient, world class final assembly site. The ultimate aim is to become the final assembly site for the new regional jet, which will be developed in Toulouse through the Joint Venture.

3.3 Research Methodology for Feature-Based Design Activity

The research into Feature-Based Design was specifically focused in the area of the identification and exploitation of assembly features and was to be conducted through the Brite-Euram sponsored FEAST project (number BRE2-CT94-1015).

In 1994 Avro's Information Technology Department submitted a proposal to the Brite-Euram Commission for funding of a project which was to investigate the possibility of identifying and exploiting assembly features in product modelling for use in future CAD systems. The project called FEAST is a joint research initiative between BAe, Aerospatiale, Alenia, CASA, Dassault Aviation, University of Parma, and University of Valenciennes. This project provided the opportunity for the Eng.D. study to become involved in research that contributes to the progression of the Product Modelling aspect of Concurrent Engineering, as described in Chapter 1.

The FEAST project is broken into eight subtasks:

- Task 1 – Definition of business requirements:
  Definition of Industrial Requirements,
  Survey of Emerging Technologies;
- Task 2 – Identification of Feature Requirements;
- Task 3 – Definition of Features;
- Task 4 – Development of Demonstrator;
- Task 5 – Specification of Assembly Modeller;
- Task 6 – Development and Testing of Prototype Modeller;
- Task 7 – Consolidation of Results;
- Task 8 – Liaison with STEP.

The Eng.D. study was primarily involved with Task 2 of this research. The FEAST project is still ongoing and is due to finish in 1997.

Chapter Review

This Chapter has given an overview on how the research into DFMA and Feature-Based Design fits into Avro's overall business initiatives. It has described the methodology for the research and explained how changes in Avro's company strategy influenced the path of the study into DFMA.

To summarise:

- the original methodology adopted for DFMA research was to use the RJ aircraft as a 'trial' vehicle for idea generation from both application of qualitative DFMA rules and principles and trial of quantitative DFMA tools. Any ideas for improvement that were generated were to be exploited on the next generation regional jet, the RJX;
- as Avro's Company strategy changed, and new product development was put on hold, focus shifted more onto improving the efficiency of the RJ's production process and so the research path shifted in line with this. Although the methodology remained intact i.e. the practical application of qualitative DFMA principles and the trial and assessment of quantitative DFMA tools, the exploitation vehicle for the improvement ideas became the RJ aircraft;
- it was still envisaged that the knowledge gathered throughout this study would be fed into the new product development activity wherever and whenever this was going to happen;
- the research into Feature-Based Design was to be conducted through a Brite-Euram sponsored project with other European partners, co-ordinated by Avro.

The next chapter discusses in detail the first part of the Eng.D. research into DFMA; the practical application of qualitative DFMA rules and principles.

Chapter 4 Practical Application of Qualitative DFMA Rules and Principles – The "Four Corners" Project

Summary

This chapter describes the main element of the Eng.D. study at Avro; the practical application of qualitative DFMA rules and principles.

This chapter will describe how qualitative rules and principles such as simplification, modularisation, part count reduction, and standardisation were applied to a production easement exercise aimed at improving galley installation; one of the most troublesome aspects of Avro's customisation activity.

The project came to be known throughout the company as the "Four Corners" project. The name Four Corners comes from the positioning of the galleys on the aircraft. There are effectively four possible locations for galleys to be installed, two at the front of the aircraft and two at the back, hence the title Four Corners.

Section 4.1 describes how Avro will benefit from improvements to its customisation activity. In addition, it outlines how research in this area was worthwhile for the Eng.D. study. Section 4.2 describes Avro's marketing and sales strategy with respect to the RJ's cabin facilities, and it attempts to explain why the customisation activity is not as straight forward as it first appears. Section 4.3 explores some of the problems associated with customisation design. This critique will begin to highlight why improvements were deemed necessary. Section 4.4 describes how galley installation has become the area in most need of improvement and defines the scope of the galley installation problem. Section 4.5 sets out the improvements that were implemented and outlines the progression of the Four Corners project. Finally, section 4.6 presents the actual savings and benefits to Avro as a result of the project.

4.1 Introduction

Avro's production activity, as described in Appendix 3 is split into two distinct areas; Structural Build and Completions. One of the main activities within the Completions area is customisation. Customisation involves modification of the aircraft to meet the customer's specification. In theory, an airline could request modifications to any of the systems and equipment in the aircraft. However, the majority of the customisation work is attributed to changes in the interior decor, seating and, cabin facilities such as galleys, toilets, attendants' seats and stowage units.

When an airline orders an aircraft, particular emphasis is placed on fleet commonality. This is especially the case with larger airlines. They are keen to ensure that equipment used on their entire fleet of aircraft is similar both from an operating point of view i.e. cabin crew familiarity, a passenger point of view i.e. offering a consistent standard of service, and from a maintenance point of view i.e. interchangeability of equipment. Therefore, most airlines request specifications that continue their fleet commonality, and the more involved these requirements are, the greater the amount of associated design work for Avro.

Since Avro's business strategy no longer includes new product development, the main constituent of the company's design activity is now customisation. The customisation requests from each new customer can require anything between 10,000 and 30,000 man-hours of design effort to complete. Galley installation alone can take approximately 4,000 man-hours.

A more responsive and efficient customisation process will enhance Avro's business in two ways: ability to win orders and contribution to profit.

1. Ability to win orders

As the airlines demand ever shorter delivery lead-times, so the pressure on Design to complete the customisation modifications escalates. In recent sales campaigns the importance of speedy customisation has become evident. Short delivery lead-time was a key factor in Avro's two most recent sales campaigns in which significant orders were secured from Lufthansa and Sabena. In the case of Sabena, Avro was the only regional jet manufacturer who could supply the first aircraft within 82 days of the order being placed. Avro now needs to further improve on its capability to deliver aircraft in ever shrinking lead-times. A responsive customisation process is needed.

2. Contribution to profit

In Appendix 4 the concept of Build to Order is described. The main aim of this initiative is the elimination of white tail aircraft (unsold, finished aircraft) and the subsequent inventory cost penalties. The key to Build to Order is having the ability to rapidly customise the aircraft. Therefore, anything that can improve the responsiveness of the customisation activity will contribute to Avro's successful implementation of the Build to Order philosophy, and hence, ultimately, improve the business's profitability.

Including the Four Corners project as part of the Eng.D. research will ensure that the Eng.D. project:

- makes a contribution towards improving Avro's main design activity i.e. customisation, with respect to DFMA;
- is linked to an important, topical, company initiative, namely, Build to Order. This ensures the research effort is immediately relevant and effective;
- makes a contribution towards improving the business' bottom line by achieving real savings.

4.2 The Selling Strategy of RJ Cabin Facilities

4.2.1 Description of Cabin Facilities

Within the passenger cabin of the aircraft there are specific areas designated for the installation of cabin facilities. The following notation is used: 1R, 2R, 3R, 4R, 1L, 2L, 3L, & 4L, see Figure 4.1. The cabin facilities that have to be located in these areas are: galleys, galley stowage units, wardrobes and toilets.

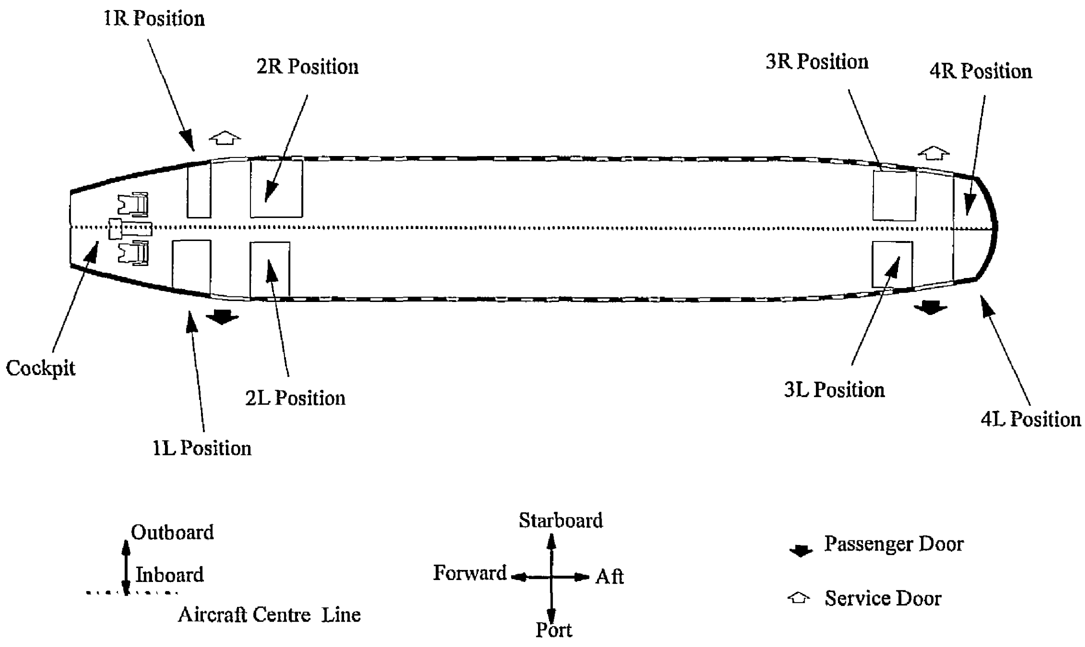


Figure 4.1 Areas Designated for Cabin Facilities

4.2.1.1 Galleys

The prime purpose of a galley unit is simply to house ovens, hot water dispensers and catering trolleys. The rest of the space within the unit is given over to miscellaneous items such as waste bins, work surfaces and stowage cupboards. Figure 4.2 shows a typical galley unit.

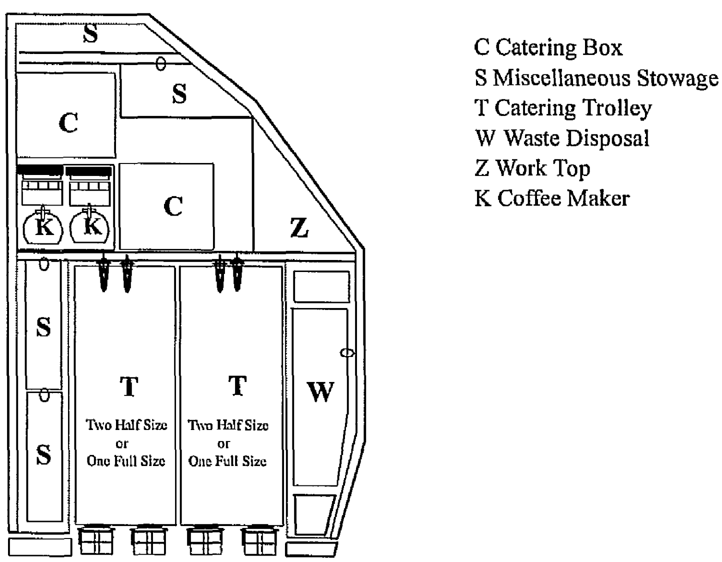


Figure 4.2 Typical Galley unit

A photograph of a typical galley unit (without equipment) can be found in Appendix 5 (see Plate A5.1).

Catering on an aircraft is all to do with trolleys, meal boxes, and ovens. An assessment of the number of passengers, the level of service, and the size standard of catering equipment used by the airline, for example ATLAS, KSSU, will dictate how many trolleys and ovens are required, which will then dictate how many or how big the galley units need to be.

The items that fit into the galley above the work surface are called inserts and include coffee makers, waste bins, storage boxes etc.. A typical galley unit can weigh anything up to 1200 lbs. when fully laden, and can cost up to £30,000.

Avro is not responsible for the design or manufacture of the RJ galleys. This is done by external suppliers. There are currently two galley suppliers for the RJ; Rumbold Ltd of Great Britain and Bucher of Switzerland. The basic structure of the galleys manufactured by Rumbold, consists of lightweight non-metallic sandwich panels which have a Nomex honeycomb core with uni-directional glass cloth skins. The galleys supplied by Bucher are manufactured from aluminium extruded sections and aluminium skins.

4.2.1.2 Toilets

The toilets on the aircraft are modular units which are manufactured and assembled by an external supplier.

4.2.1.3 Stowage Units

Stowage units can either be used to store additional catering trolleys and boxes or they can be used as wardrobes. The figure below shows the front and side view of a typical stowage unit.

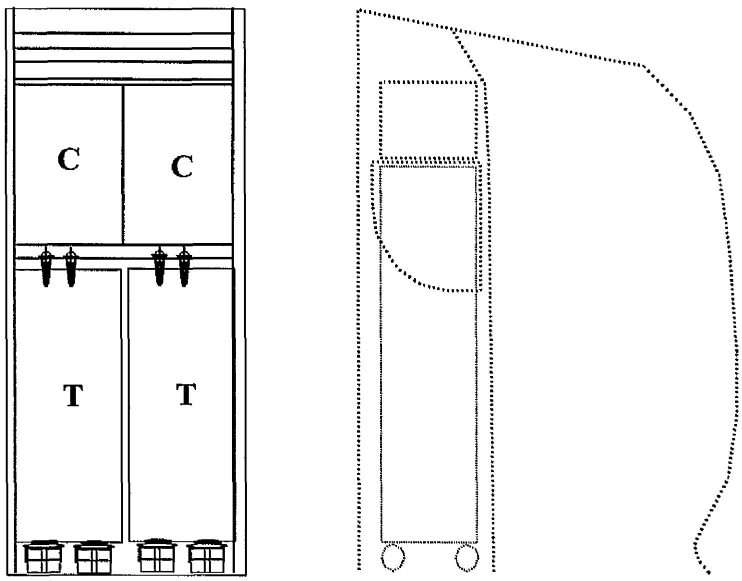


Figure 4.3 Typical Stowage Unit

4.2.2 Selling Strategy

Prior to the Build to Order initiative, RJs were built regardless of whether they had been allocated to a customer. Any unallocated aircraft were built to a Basic specification, which was for a complete and operational aircraft, with basic cabin facilities, which could be introduced into revenue generating service simply by adding seats.

The Sales discussions with regard to cabin facilities could be viewed as a three tiered activity. Sales began each campaign by offering the Basic specification aircraft. With respect to cabin facilities, the RJ had two galleys as Basic, at positions 1R and 4R (see Figure 4.4). These galleys incorporated coffee makers, catering boxes, catering trolleys and miscellaneous stowage units to provide a cold meal and hot beverage facility. Also fitted as Basic were toilets at the 1L and 4L positions. If airlines were not happy with the level of equipment on the basic aircraft, Sales would then offer an alternative to the basic options. Again with respect to cabin facilities the alternative or Standard options as they were referred to were: galleys fitted with ovens at the 1R and 4R position to provide a hot meal service capability, two additional galleys fitted at the 2R and 3R positions and stowage units at the 2L and 3L positions (see Figure 4.5).

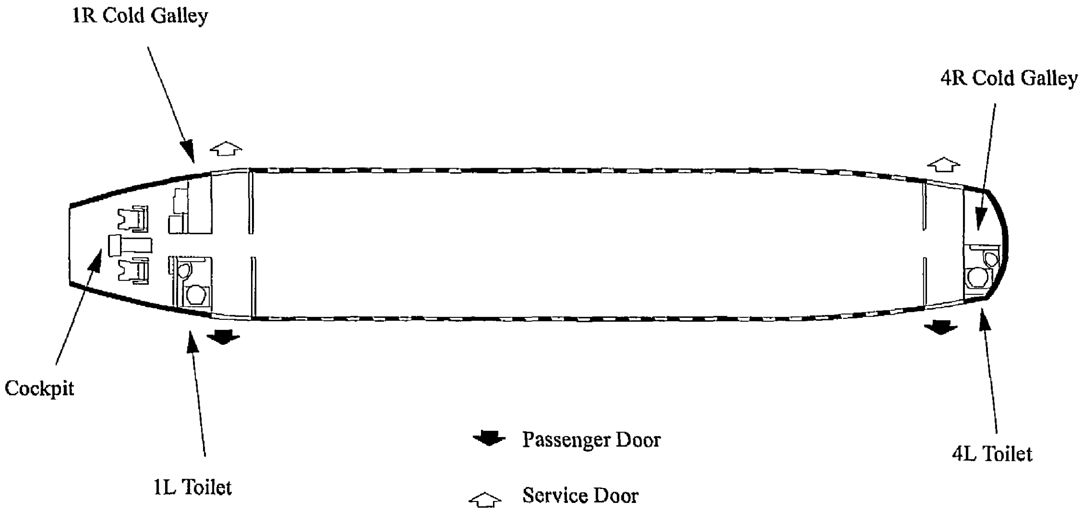


Figure 4.4 Layout of Cabin Facilities on a Basic Specification RJ

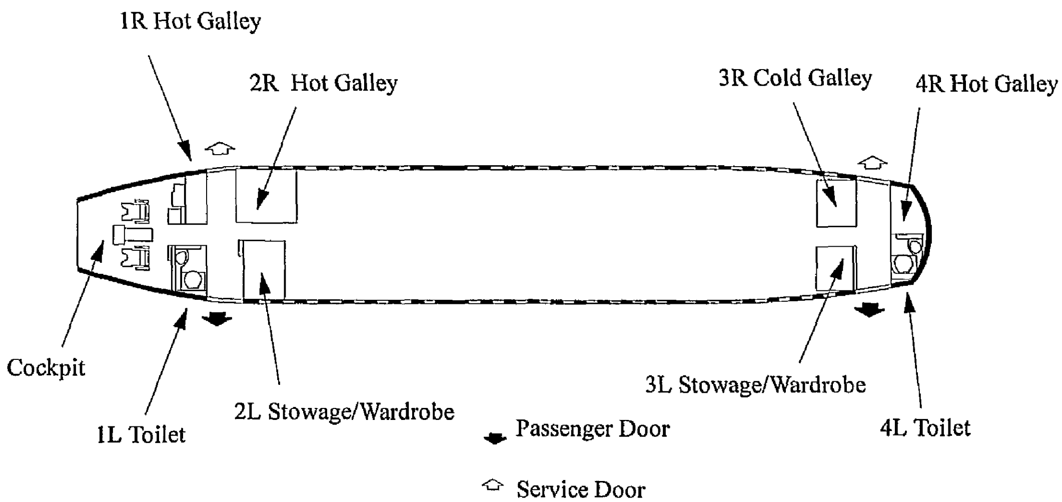


Figure 4.5 Layout of Standard Option Cabin Facilities

If Basic or Standard options were selected, no additional work was needed. The drawings and engineering for such options already existed, and a simple processing exercise was all that was required. The selected options were loaded onto the AMD (Aircraft Master Definition) for that particular aircraft, the work packages (operations) were loaded onto the production system in the usual way, and the parts manufactured and delivered against the build schedule as normal.

If neither the Basic or Standard options were sufficient to meet the airlines requirements, Sales would then look at Customer Special options. Customer Special options were special requirements that the airline insisted on having, and which could not be met by the Basic or Standard options.

Customer Special options could involve minor changes to an existing Basic or Standard option, or they could be major changes, for example, an entirely new piece of equipment or a request for equipment to be installed in a non-standard position.

If a Customer Special option was requested, the processing was much more involved. By definition, this option is Special i.e. specific to a particular customer and as such there would be no drawings or engineering in existence to support this request. A design would have to be amended or created, new engineering would have to be prepared, and new parts procured. Customer Special options are the source of many of the problems experienced within the customisation process.

4.3 Customisation Design Issues

The following section explores the problems associated with customisation design.

It could be argued that by its very nature customisation is *fluid*; it cannot be predicted and therefore will always be an ongoing, isolated design activity throughout the life of the product. However, it could also be argued that it *is* possible to predict the future customisation requirements of a product, and therefore it should be possible to prepare all customisation design at the original design stage. This debate is explored further in section 7.1.3 of Chapter 7. Customisation design on the RJ is an isolated activity; it was not done in conjunction with the original design of the aircraft, and subsequently this has led to several problems. The model below is used to explain how these problems arise.

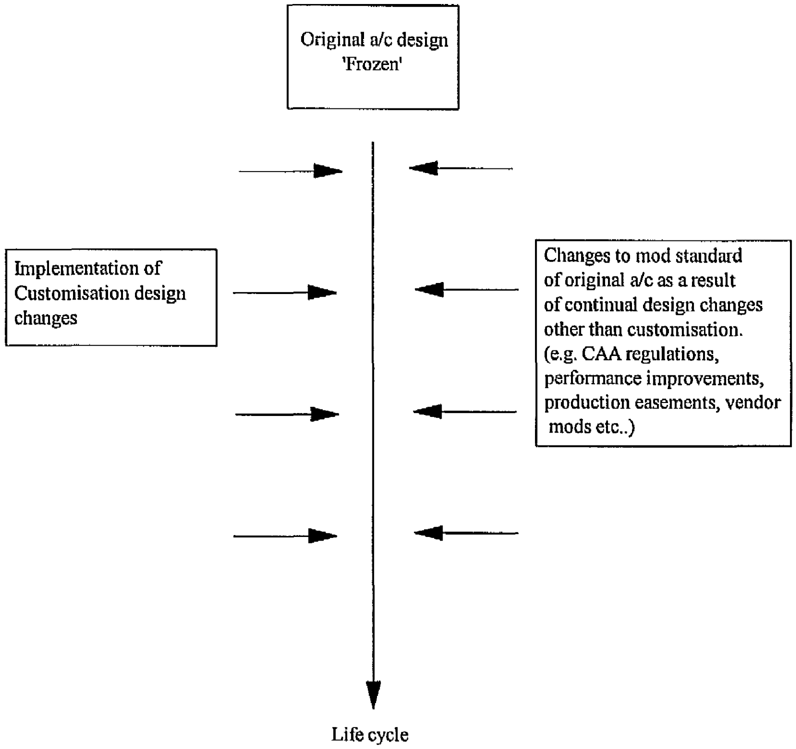
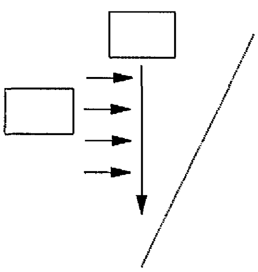


Figure 4.6 Design Change Model

Scenario 1.



First of all consider the scenario where the only design changes to the aircraft are as a result of customisation. In other words the original design remains, 'frozen' apart from customisation. The following problems occur:

1. Complex shaped designs

If the customisation request requires that a new piece of equipment, whether it be structure or piping, needs to be introduced, then there is a high chance that this new equipment will clash or collide with the existing equipment in the frozen design. Collisions obviously need to be avoided and sometimes this can only be done through the use of complex shaped designs. This has led to a proliferation of parts as the opportunity to standardise parts becomes extremely difficult.

2. Re-work, scrap and further re-design

If a collision is unavoidable the existing equipment (i.e. in the frozen design) will have to be removed, possibly scrapped and a new item designed; this is before the specific customisation design can even begin.

3. No opportunity to learn

Due to the unlimited variation that Avro allows in *Customer Special* options, customisation effectively becomes unique from one order to the next. Therefore, the shop floor operators lose the opportunity to learn. Each customisation work package effectively becomes a prototype.

The *time* constraint associated with the RJ's "customise as you go" philosophy, not only compounds the problems described in the first two points above (i.e. no time to fully appreciate the existing equipment, so the chance of collisions occurring in production will increase), thereby increasing the cost inefficiency of customisation, it also contributes to inefficiencies in the following areas:

1. Weight

The Stress Department often have to make over the top stress allowances, because they have to be sure the factors they apply are sufficient to do the job. There is no time to refine designs for weight savings.

2. Functionality of the design

Designers do not have time to explore other possible solutions and select the best for the functional requirement. There is only ever time to create one off solutions within customisation.

3. Standardisation

The opportunity to standardise parts becomes even more remote.

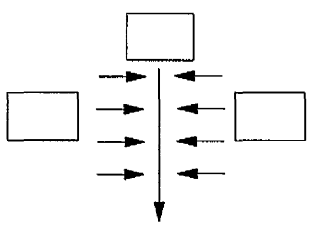
4. Manufacturing

(a) Details are often manufactured with advanced information before the final drawings are issued. Obviously, the components are not released by the sub-contractors until they receive the final documentation, but this 'short-cutting' exercise can sometimes lead to parts being manufactured that later have to be amended or even scrapped because of last minute design changes.

(b) Following on from this, there is rarely time to have design visual examination on the first manufacturing run; the complete batch is usually manufactured at once.

(c) There is no time to ensure that a part has been designed in a way that best suits the intended manufacturing process.

Scenario 2.



Now consider the scenario that occurs in reality, i.e. where the customisation design changes are trying to be introduced on an aircraft that is continually undergoing design modification due to other reasons.

The problems described in scenario 1 are further compounded, and there is the added possibility of a situation where multiple design solutions have to be created to meet the same customisation request. The continual modification of the aircraft, resulting from design changes other than customisation, has led to the situation where the mod standard (see Appendix 2 for explanation of mod standard) of the basic aircraft can differ from one aircraft set to the next. Unfortunately, establishing the actual mod standard of an aircraft is time consuming and not always straight forward. The situation can arise where a design is created that does not take into account the different mod standards. Thus a customisation design can be applied to the first aircraft of a customer order, say, and work perfectly well, but when the same design is applied to the second aircraft, it may suddenly collide with an existing piece of structure. This inconsistency of aircraft mod states can lead to multiple designs having to be created in order to meet the *same* customisation requirement on different aircraft sets.

An example of this was experienced on Avro's recent Lufthansa order. The customisation request for attendants seats at the 3R position ran into difficulty when the design of the underfloor structure to support these seats, had to be done around two different mod standards of existing structure. Lufthansa allocated aircraft, set 246, was different to their sets 256 and 253. A mod replacing fabricated beams with machined beams was targeted for introduction on set 244 and subsequent aircraft (according to the official change control documentation). However, set 246 still had fabricated beams. So the design solution which worked on set 256 and 253 did not work on set 246. This example also illustrates that even if the designer does have time to look up the mod standard of each aircraft allocated to a customer, the information he finds may not even be accurate.

Obviously this 'multiple design solution' problem resulting from inconsistent mod standards, does not only affect customisation design changes; the problem can arise with the introduction of any type of design change.

In a perfect world the designer should have been clear about the mod standards before starting the design. However:

- the time constraints may have made this impossible (checking the mod standard is not that simple. Time is allocated for drawing the job, not doing the preparatory groundwork as well);
- even if the designer had checked the mod targeting documentation, there is no guarantee that it is correct;
- even if the designer had physically looked at the aircraft this is still no guarantee, because aircraft sets can be re-allocated to different customers whilst the customisation designs are being done.

From the model presented here, it is clear that customisation design solutions are rarely the most efficient design solutions. The problems described are pertinent to all areas of customisation, but the area that would benefit most from improvement was perceived to be galley installation.

4.4 Why Choose Galley Installation?

Within the production environment, galley installation was viewed as the most disruptive and inefficient part of the customisation activity. This section explains why.

4.4.1 Impact of Galley Variation

When the RJ was designed in 1971 the basic specification included only one galley. The reason for this was that the standard of airline catering at that time, on short haul routes was somewhat basic; passengers were served drinks and sometimes cold snacks. However, airlines soon began to realise the marketing benefits of being able to offer a seamless service i.e. the same level of service and passenger comfort on their short haul flights, as on their long haul routes. Levels of service became more sophisticated and this led to a fundamental change in the cabin facilities Avro had to supply on the RJ. Today most RJ customers want three, sometimes four, galleys on their aircraft.

Every airline has its own version of the standard of service it wants to offer its passengers. Unfortunately for Avro as an aircraft producer, this standard of service is invariably only met by Customer Special options. It is important to realise that each airline not only requires varying numbers of galleys, but that the design of the galley units themselves differ from airline to airline. Consequently, galley installation is an area that continually undergoes substantial design modification.

The impact that this continual variation had on Avro's customisation activity could only be fully appreciated after considering how the galley units were actually attached to the aircraft. The CAA stipulate that any equipment supported inside an aircraft has to be able to withstand the loads generated in a 9g crash case. Therefore the method of galley attachment on the RJ entailed more than a few simple nuts and bolts through the floor panels. The galley was in fact attached to a complex network of underfloor structure which transferred the loads to the necessary dissipation points. Consequently, any significant change in the design of the galley unit invoked a stress re-assessment of the underfloor support structure. If the support structure was inadequate then a new one had to be designed. This task involved substantial design and engineering effort. A detailed description of the design of a typical underfloor support structure is given in the next section.

In an attempt to quantify the scale of galley variation, an investigation was carried out by the author, looking at the different types of galleys that had been fitted to the RJ over the past six years.

The results of this investigation were alarming (see Appendix 6). At the 1R position, eight different galley units had been fitted and at 4R, nine different units had been fitted. The differences between the units at these positions were only slight, and therefore, the impact on the underfloor support structure was minimal. There had only ever been two galley footprints at both the 1R and 4R positions (a galley footprint refers to the longitudinal and lateral positions of the galley attachment or 'pick-up' points located on the bottom of the galley, which attach to the brackets already fitted to the underfloor support structure). At the 2R and 3R positions the history was somewhat different. At 2R, seven different galley units had been fitted resulting in seven different footprints. At 3R, five different galley units had been fitted resulting in five different footprints. The design of the galley units both at 2R and 3R varied immensely. Consequently, this led to creation of twelve underfloor support structure designs.

This variation was responsible for significant design effort on Avro's part in designing a new underfloor support structure each time the galley changed. Along with these changes came another dose of the problems described in the previous chapter.

4.4.2 Method of Galley Installation

This section will describe the general structural philosophy used on the RJ, and then the design of a typical underfloor support structure. It will explain how a galley unit is physically installed onto this underfloor structure, and then highlight the problems associated with the galley installation operation.

4.4.2.1 RJ General Structural Philosophy

Before describing a typical underfloor structure used to support the galley unit inside the aircraft cabin, it is necessary to briefly explain how the overall aircraft is structurally configured.

The fuselage is of a conventional semi-monocoque construction using fail safe principles. It consists mainly of light alloy frames and stringers, which support rolled and stretch formed skin panels (see Figure 4.7).

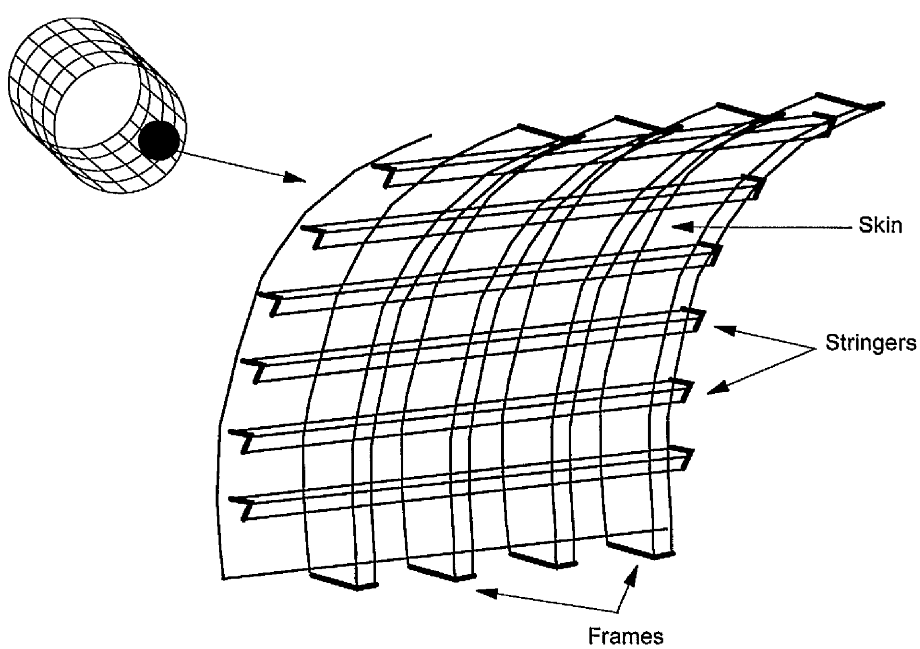


Figure 4.7 Schematic of RJ General Airframe Structure

The fuselage comprises of:

1. Nose section. Frame 1 to 19 plus the radome.
2. Centre section. Frame 19 to 33.
3. Rear section. Frame 33 to 44.
4. Tail section. Frame 44 to 50 plus the airbrake.

Figure 4.8 below shows the frame positions for the RJ85. The RJ100 and RJ70 are different lengths to the RJ85 and therefore each have a different number of frames.

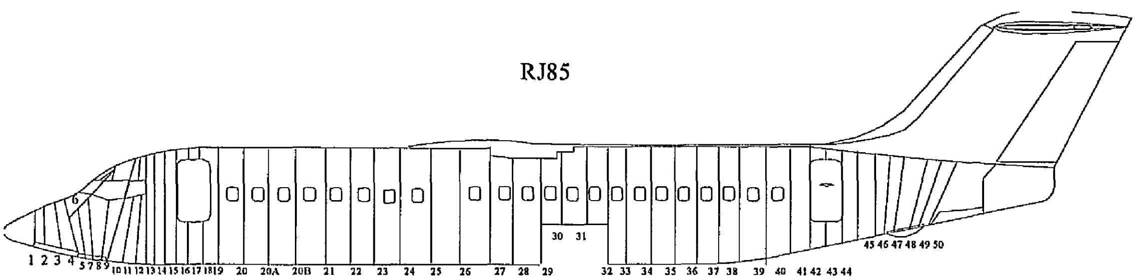


Figure 4.8 Fuselage Frame Positions

The pressurised area of the fuselage is located between frame 4 (front pressure bulkhead) and frame 44 (rear pressure dome). This includes the flight deck, cabin and whole underfloor area, with the exception of the wing centre section box and the nose and main landing gear cut-outs. The vertical stabiliser is attached to the tail section at frames 45 and 50 and is supported by reinforcing longerons and cross beams.

The cabin floor is supported by lateral beams and longitudinal intercostals and has two sets of seat rails running parallel down the length of the cabin (see Figure 4.9).

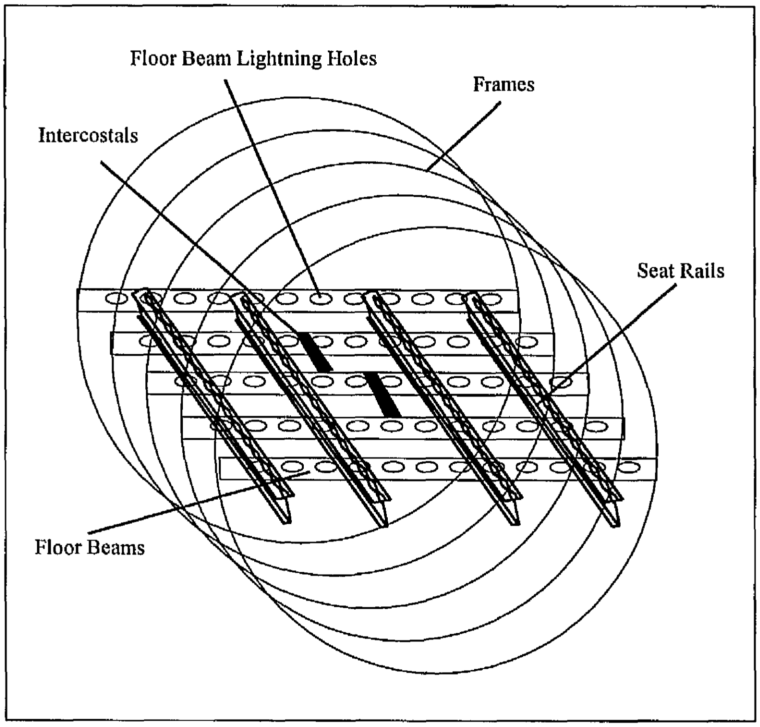


Figure 4.9 RJ Cabin Floor Structural Philosophy

4.4.2.2 Underfloor Support Structure – Design Philosophy

The construction of the cabin floor is analogous to the floor structure in a house. The lateral beams and longitudinal intercostals in the aircraft are similar to joists in a house, and the Nomex floor panels are placed on top of the beams and intercostals in a similar manner to the way floor boards are placed on joists.

Unlike in a house where a cupboard, for example, can simply be placed on top of the floor board, the galley in an aircraft cannot simply be placed on top of the floor panel. The first reason for this is because in the normal operation of an aircraft any equipment not securely fastened will soon move. Secondly, it has already been stated that the equipment has to be able to withstand the 9g crash case, therefore, the equipment not only has to be fastened down, but the chosen attachment method has to be substantial enough to withstand the crash case.

The galley cannot be attached solely to the floor panel using simple nut and bolts, because the panel is not strong enough to support the type of loads that would be generated in the galley in the crash condition. Therefore, underneath the floor panel, directly below the galley attachment points, there has to be additional support structure which would act as a flow path to transfer the loads to the relevant dissipation points, within the main aircraft structure.

The design of a typical underfloor support structure consisting of a series of intercostals (beams), angle brackets and support plates is shown in Figure 4.10. The intercostals were the main load bearing items. The angle brackets were used to attach the intercostals to the floor beams or the seat rails (depending if they were running longitudinally or laterally), and the plates were used to provide the required strength and stiffness.

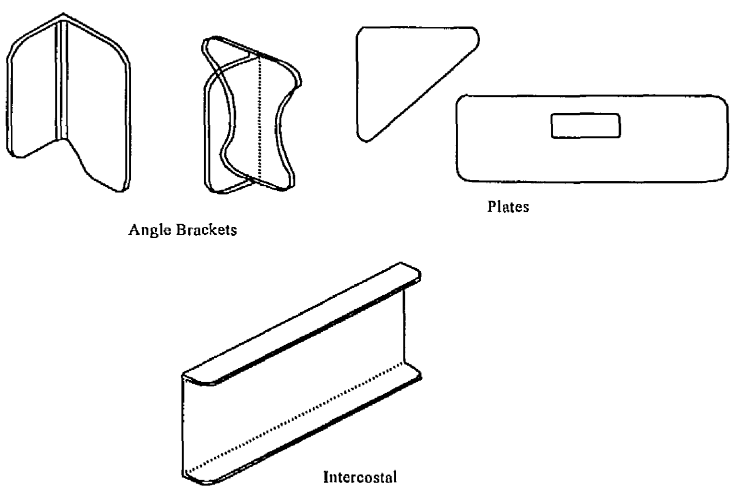


Figure 4.10 Typical Items Which Make Up Underfloor Support Structure

These items collectively formed a network of sub-structure, installed in between the aircraft's main floor beams and seat rails (see Figure 4.11). The cost of the parts for a typical galley underfloor support structure is in the order of £4,000.

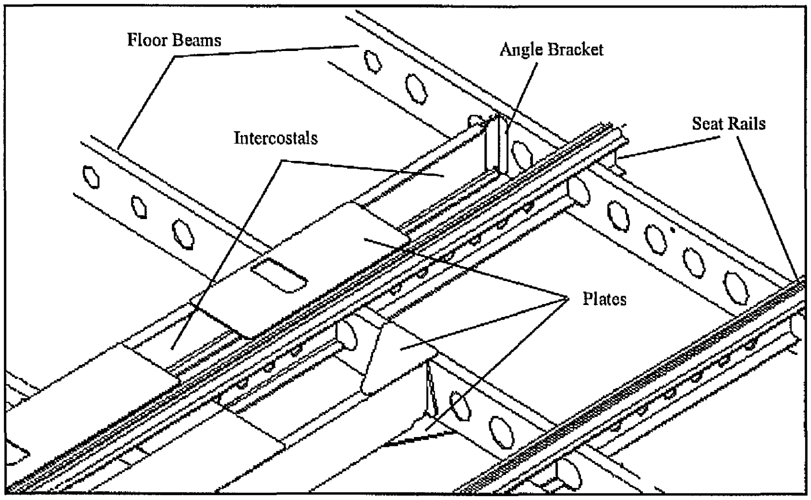


Figure 4.11 A Sample of Typical Underfloor Support Structure

The *threaded insert* type attachment used to attach the galley unit to the underfloor support structure were in the main, integral with the intercostals (see Figure 4.12). However, in some cases, in order to accommodate the galley footprint, special brackets had to be designed for attachment directly to the floor beams or seat rails.

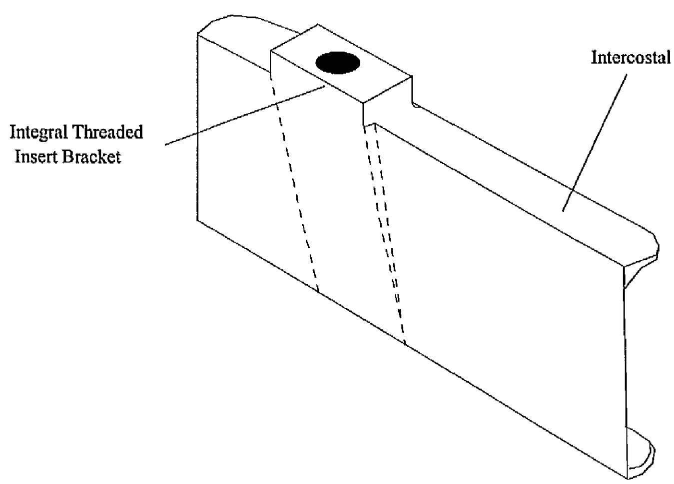


Figure 4.12 Integral Threaded Insert Attachment

The covering floor panels were fastened down using quarter turn Camloc fasteners. Holes were already cut into the floor panels in order to provide access to the floor fittings (see Figure 4.13).

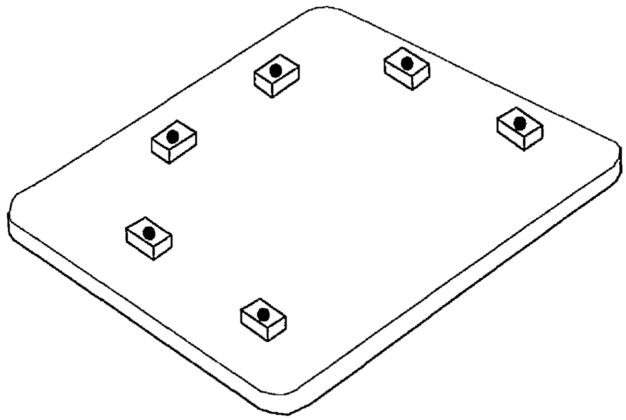


Figure 4.13 Final Installation of Floor Panels Around Galley Attachment Fittings

The design of this underfloor support structure seems rather elaborate. It is difficult to establish why the intercostal/bracket design philosophy was chosen over a structural floor panel, for example, or attaching the galley units directly to the seat rails. The designers responsible for the first design of underfloor support structure at the 2R and 3R positions no longer work at Avro, and the reasons *why* particular design solutions were chosen were rarely documented. Consequently, one can only speculate as to the reasons why this type of design philosophy was adopted.

It has already been mentioned that the original aircraft only had one galley. Therefore, when a request for galleys at the 2R and 3R positions was made, perhaps the Design department thought that this would be a one off request which, consequently, did not warrant any special effort into developing a design that could easily be adapted to accommodate any future variation in galley design at these positions. If they did not envisage much call for galleys at 2R and 3R, then it would not be deemed necessary to spend time pre-empting them, or perhaps it was simply because, as is often the case, there was not enough time to step back and think about the wider implications..

Questions also arise regarding the actual efficiency of this design solution with respect to DFMA:

- why did the angle brackets, which attached the intercostals to the floor beams, have to be separate items?

This goes against one of the fundamental principles of DFMA, namely, part count reduction. Why couldn't the intercostals simply have integrated flanges? It is believed that the use of separate attachment angle brackets was necessary to overcome the inconsistencies of distance between floor beams from one aircraft set to the next, which arose as a result of the type of tooling used to assemble the main structure of the aircraft. Basically, the exact distance between floor beams cannot be guaranteed, so a degree of float was needed during final assembly; separate angle brackets offered this. It could also have been cheaper to manufacture straight intercostals and simple angle brackets rather than complicated intercostals with integrated attachment flanges;

- why were expensive machined angle brackets used instead of simple pressed parts? The machined angle brackets produce a great deal of re-cyclable material, but this operation is preferable to using pressed angles because the pressing operation on material that is 0.1" thick would result in an unacceptably high bend radius. There is a better chance of picking up existing rivets if the bend radius is kept tight; this can be achieved through machining.

In summary, the intercostal/bracket philosophy for underfloor support structure, though elaborate in terms of part count and final assembly effort, was a simple structural concept that had been tried and tested and entailed no risk. Therefore, it was selected for what was probably thought to be a one-off situation. Unfortunately, galleys at 2R and 3R became the norm, and the design department just accepted the impact the continual galley variation had on the overall customisation activity. No one ever stopped to question this variation, until now.

4.4.2.3 Galley Attachment and Sealing Operation

Once the underfloor support structure and floor panel had been installed the next stage was to physically attach the galley unit. Stainless steel rails were first of all fastened to the attachment brackets. Then, a laminate "drip tray" (used to ensure that spillage from the galley unit did not leak into restricted areas) was placed over the galley rails. The galley unit was then placed on top of the drip tray/galley rails. Before the galley could be fastened in position, it had to be aligned; packers (washers) were used to achieve this. Figure 4.14 shows how a typical galley unit was attached.

The alignment procedure was not always straightforward. Each time a packer had to be inserted, the galley had to be removed. The upper profile of the galley unit also had to be trimmed before the galley could be fastened in position. Again this involved the continual removal and re-fitting of the unit.

After the galley and drip tray were installed, the final sealing and trimming of the galley unit and surrounding areas took place. The lower part of the unit and surrounding vestibule areas were then trimmed using "bird's beak" (a plastic extrusion with a profile which resembles a bird's beak).

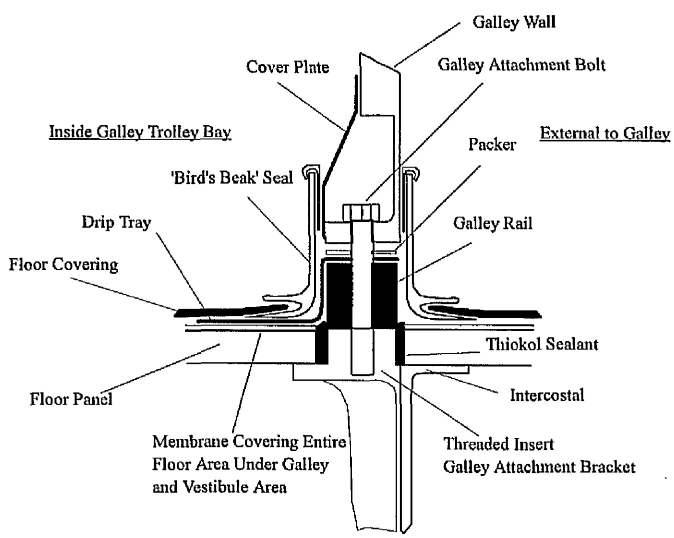


Figure 4.14 Galley Attachment and Lower Sealing Method

The profile gap between the upper galley unit and the aircraft was trimmed using a 'P' seal (see Figure 4.15).

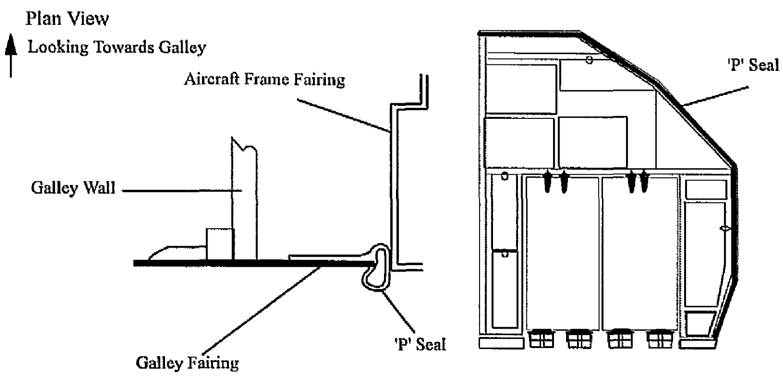


Figure 4.15 Trimming the Upper Galley Profile with 'P' Seal

The installation method illustrated in Figure 4.14 is for the galleys produced by the RJ's main galley supplier. The galleys produced by the other supplier are attached in a slightly different way. Galley rails are fitted to the galley attachment brackets in the floor, and then an extruded profile on the bottom of the galley unit is slotted into the rail. The galley is then held in position by closing plates as shown in Figure 4.16.

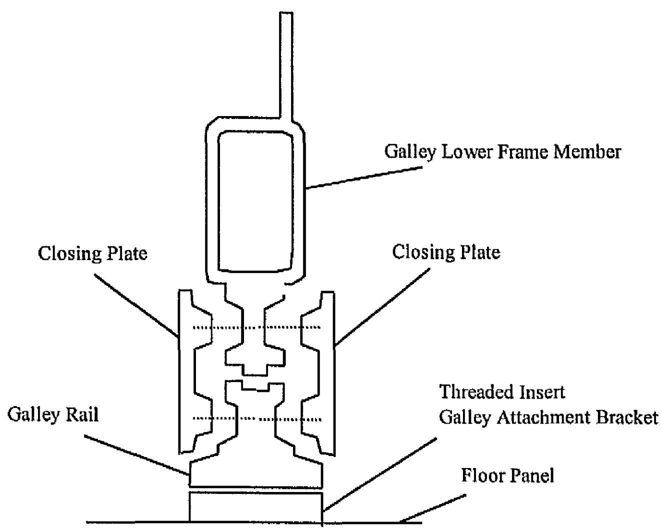


Figure 4.16 Galley Attachment Method for Second Galley Supplier

4.4.2.4 Problems Associated with Galley Attachment and Sealing Operation

Variation in galley design and the impact this had on the underfloor support structure, was not the only cause for concern in the realm of galley installation. The actual method of galley unit attachment and sealing described above was also troublesome. A survey of the shop floor operators and observations of the task itself, revealed that the main causes for concern were as follows:

- the threaded insert style bolts being used for galley attachment provided no amount of float for picking up the thread through several layers, thus sometimes prolonging the bolt up operation;
- unnecessary proliferation in the types of bolts that were being used for galley installation (23 types used);
- the simultaneous installation of the galley unit and the drip tray led to excessive damage and sometimes even scrapping of the drip tray, as the galley was aligned and trimmed. The continual removal and fitting of the galley unit prolonged the overall galley installation operation considerably;
- the use of birds beak and P seal for the method of sealing and trimming, was messy and consequently never really gave an acceptable aesthetic finish. The condition of the birds beak became unacceptably worse after the wear and tear of only a few months in service.

The findings of the investigation into galley variation, and the results of the survey into the problems experienced during galley installation, initiated the launch of the Four Corners project. The uncontrolled variation in galleys from airline to airline had to be restrained, and the physical method of galley attachment and sealing had to be improved.

4.5 Four Corners Project Improvements

This section will describe in detail the improvements introduced as a result of the Four Corners project. In section 4.4.1, it was explained how the galleys at the 2R and 3R positions were the ones mostly affected by variation. The 2R and 3R positions were therefore given priority in this project. The 1R and 4R positions were to be dealt with at a later stage.

The team formed to work on the project, consisted of representatives from all areas of the business: Design, Stress, Engineering, Procurement, Sales and Marketing, and Production. As the Four Corners project became part of the Build to Order initiative, it became a high profile activity within the company. Appendix 8 shows a company newspaper report outlining the project, along with a photograph of the core team members.

The improvements introduced as a result of the Four Corners project can be summarised as follows:

- design improvements to the physical method of galley attachment and sealing;
- design improvements to the underfloor support structure;
- production build sequence changes for galley underfloor support structure, galley attachment brackets and galley units;
- improvements to galley Sales and Marketing strategy;
- improvements to Avro/Galley Supplier interface.

4.5.1 Design Improvements to the Physical Method of Galley Attachment and Sealing

The physical method of galley attachment and sealing was improved in the following ways:

- the threaded insert galley attachment brackets (which were integral to the intercostal) were changed for barrel nut galley attachment brackets as shown in Figure 4.17. The use of barrel nut fittings for this type of application is industry standard; Airbus and Boeing use similar brackets. The installation of the bracket to the underfloor intercostal is carried out using screws (see Figure 4.18). The galley unit to galley bracket installation was also changed. The use of barrel nut brackets involved slight modification to the design of the galley units themselves. Figure 4.19 shows the bolt-up operation using the new brackets. The barrel nuts give more 'float' in the bolt up operation and, therefore, makes it easier to catch the thread. As the galley fittings now sit above the floor panels, it allows the airline to remove the barrel nuts if corrosion or damage occurs, without having to remove the galley itself;

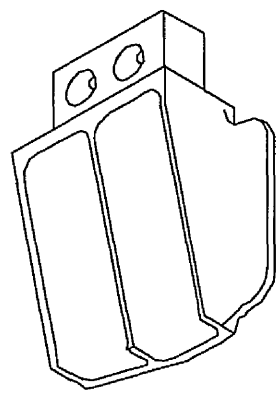


Figure 4.17 New Barrel Nut Galley Attachment Brackets

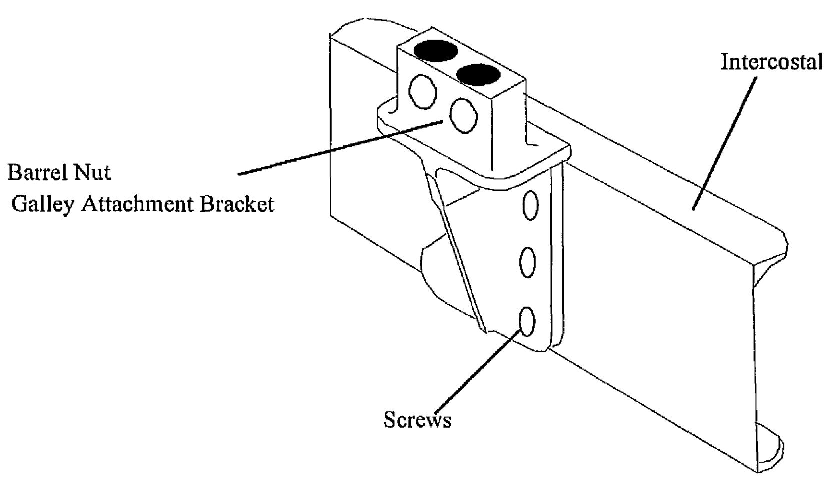


Figure 4.18 Barrel Nut Galley Attachment Brackets Attached to Intercostal

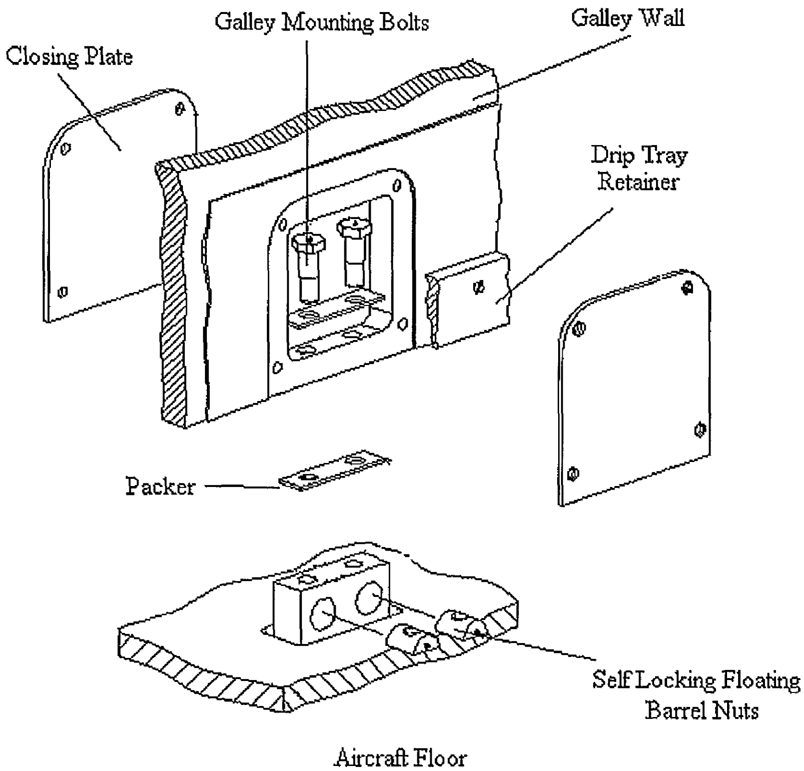


Figure 4.19 Bolt-Up Operation With New Barrel Nut Attachment Brackets

- the number of different types of bolts used for galley installation has been reduced from 23 to 2 (depending on which galley supplier is used) by using five washers that fit either between the galley and the floor fitting (acting as alignment packers), or between the galley and the bolt head when not needed for alignment. This allows the same length bolt to be used each time;
- the old style drip tray, that had to be fitted simultaneously with the galley, has been replaced. A drop in drip tray is now used which can be 'dropped in' after the galley unit has been fitted. The drip tray is held in place by a Tufnol retainer strip, attached to the galley wall with countersunk screws. This means that the drip tray is fitted right at the end of galley installation and, therefore, minimises the risk of damage (see Figure 4.20);

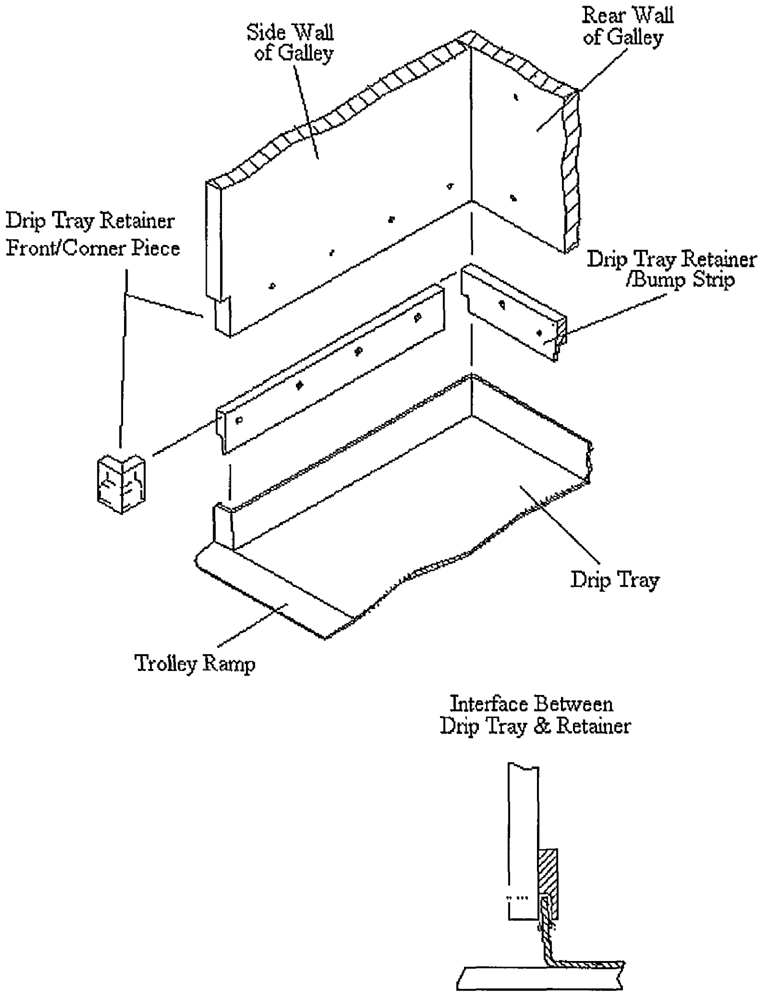


Figure 4.20 New Style 'Drop In' Drip Tray

- the messy bird beak sealing inside the galley bay has been removed. The floor covering is now simply trimmed and lies on top of the drip tray. A bead of sealant is then put around the edge (see Figure 4.21);

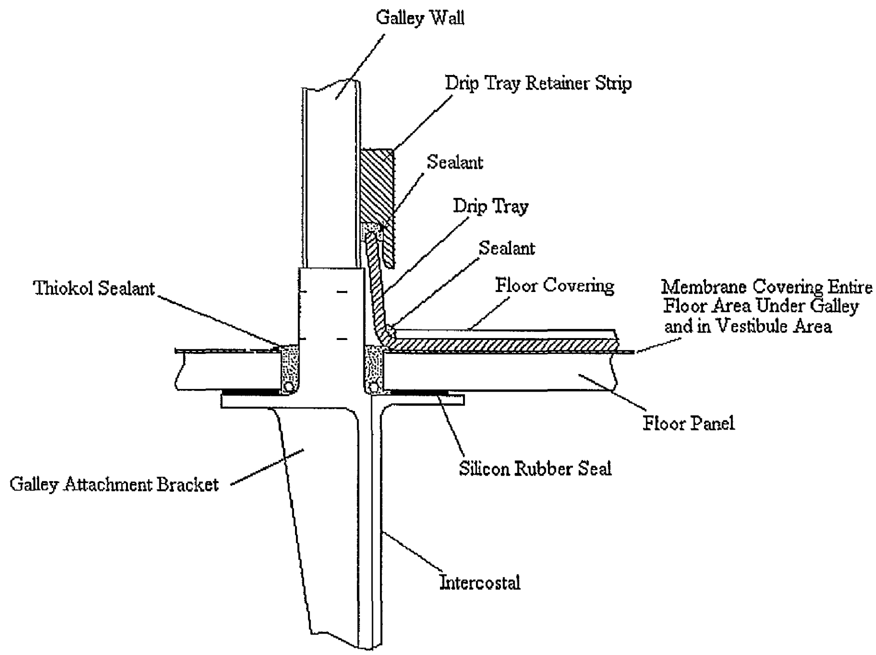


Figure 4.21 New lower Galley Sealing/Trim Philosophy

- the P seal that was used to fill the gap between the galley profile and the aircraft wall/ceiling has been replaced with a 'flipper' seal which covers the gap instead. This means that the galley unit no longer has to be precisely trimmed and consequently no longer has to be moved in and out of position (see Figure 4.22).

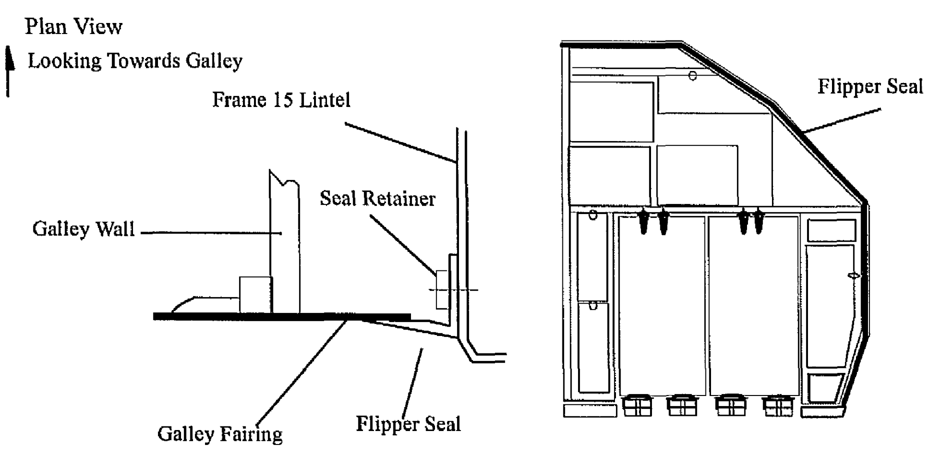


Figure 4.22 New Upper Galley Trim Philosophy

4.5.2 Design Improvements to the Underfloor Support Structure

The principal aim of the Four Corners project was to reduce the impact that galley variation was having on the customisation activity, due to continual re-design of the underfloor support structure. It was obviously impossible to completely restrict the Customers in their choices of galley units, but it was believed that some degree of restriction could be introduced. This would then allow Avro to develop an underfloor support structure design, for both the 2R and 3R positions, that was capable of accommodating all galley variants within this restriction. By having the design and engineering in place, this would mean that for each new Customer, there would no longer be any additional design or engineering work. This would amount to significant savings for the business.

4.5.2.1 The Selected Galley Options

The first step in achieving such a design solution was to determine which galley variants should be catered for within this restriction. The Marketing Department were asked to put forward a selection of galley units and locations for both the 2R and 3R positions, which they felt would cover the majority of potential RJ Customers' service levels and preferences.

The galleys that were chosen were:

At the 2R position

Galley A – A galley with 3 full size trolleys .....(same style as Rumbold old Standard option galley unit) (see Figure 4.23).

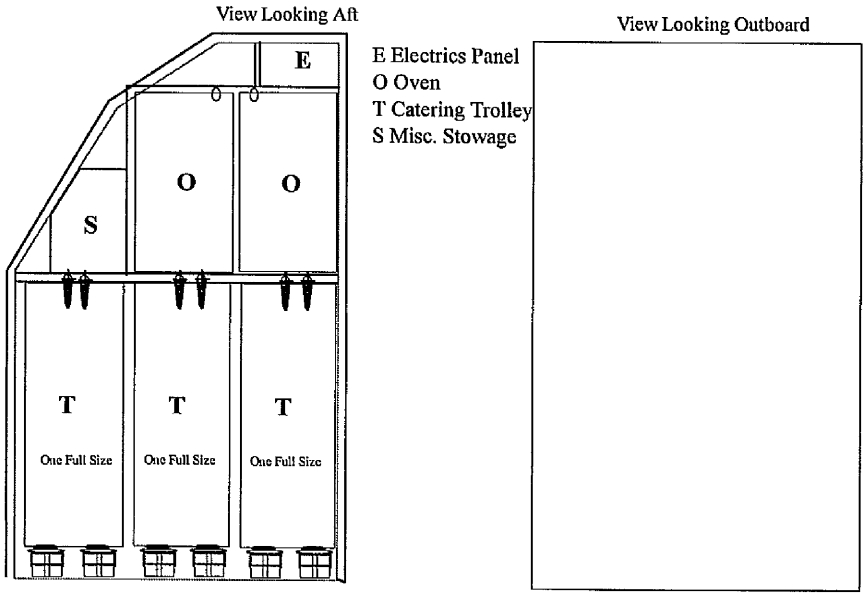


Figure 4.23 Galley A

Galley B – A galley with 3 full size trolleys ..... (same style as Rumbold Lufthansa galley unit) (see Figure 4.24).

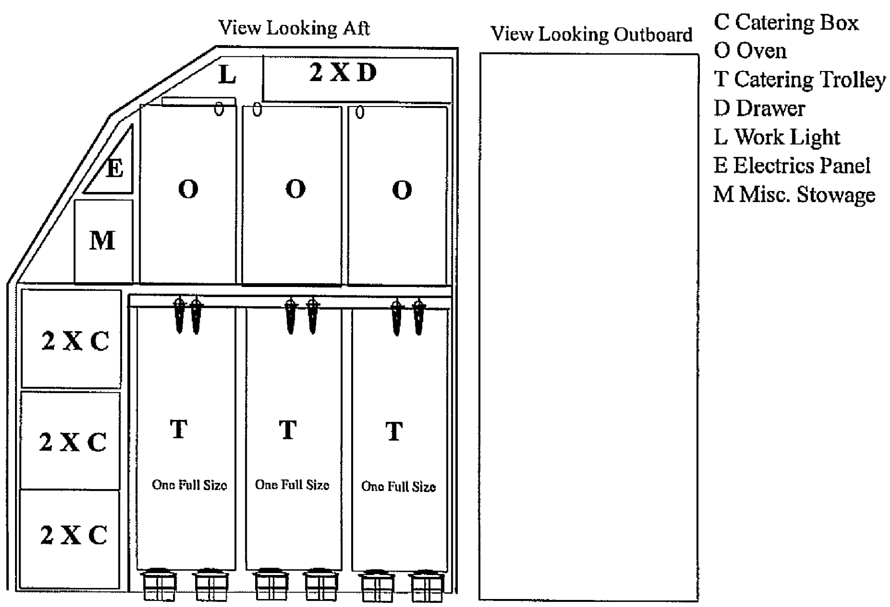


Figure 4.24 Galley B

Galley C – A galley with 3 full size trolleys ..... (same style as Bucher Crossair galley unit) (see Figure 4.25).

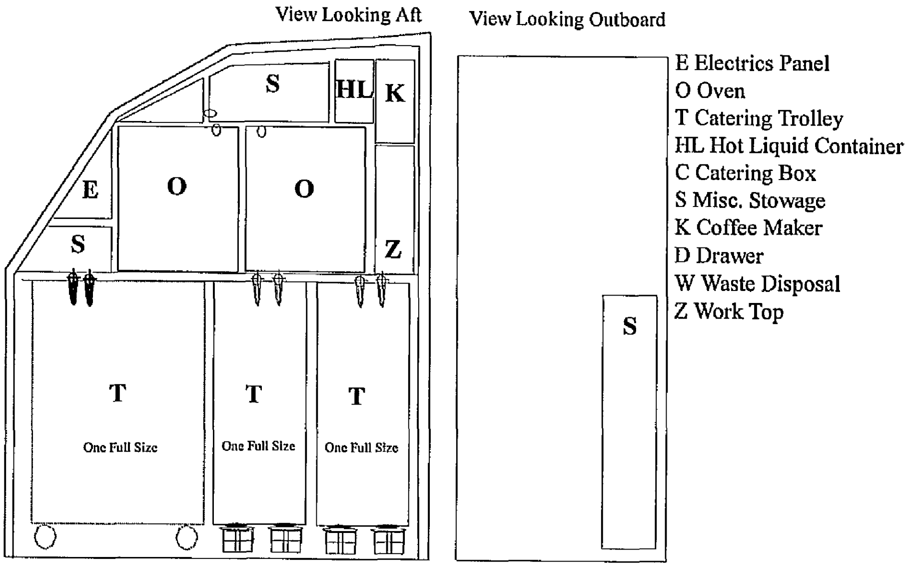


Figure 4.25 Galley C

Galley D – A galley with 2 x two thirds size trolleys and 1 half size trolley.....(same style as Bucher Sabena galley unit) (see Figure 4.26).

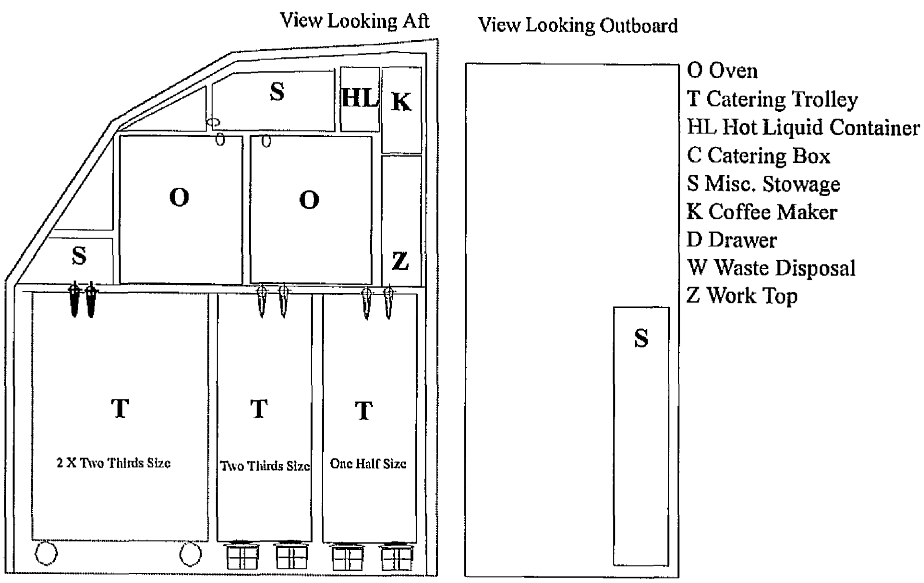


Figure 4.26 Galley D

Options for the 2R position

Option A – Galley A at the Ax 220.70 forward position

Option B – Galley A at the Ax 223.55 forward position

Option C – Galley A at the Ax 227.15 forward position (gives 40" space in serving area)

Option D – Galley A at the Ax 230.79 forward position (gives 40" space in serving area when there is an ATLAS size oven in the 1R position)

Option E – Galley B at the Ax 220.70 forward position

Option F – Galley B at the Ax 223.55 forward position

Option G – Galley B at the Ax 227.15 forward position (gives 40" space in serving area)

Option H – Galley B at the Ax 230.79 forward position (gives 40" space in serving area when there is an ATLAS size oven in the 1R position)

Option I – Galley C at the 220.70 position (only on the RJ100)

Option J – Galley D at the 220.70 position (only on the RJ85)

In summary, at the 2R position, a rationalised floor structure had to be designed to cater for 3 galleys in 8 locations on the RJ100, and 3 galleys in 9 locations on the RJ70/85.

At the 3R position

Galley A – A galley with 4 half size trolleys .....(same style galley unit as Rumbold old Standard option galley unit) (see Figure 4.27).

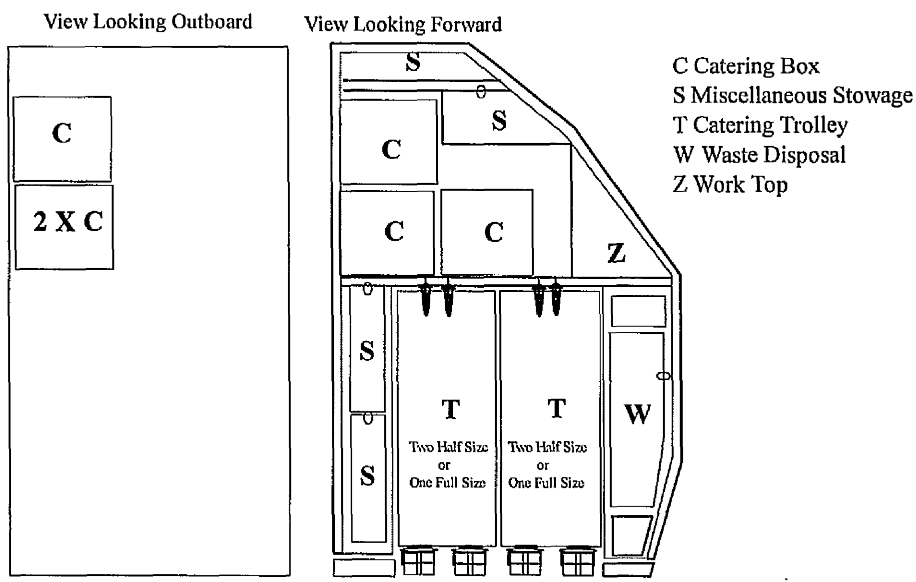


Figure 4.27 Galley A

Galley B – A galley with 4 half size trolleys .....(same style galley unit as Rumbold Air Malta) (see Figure 4.28).

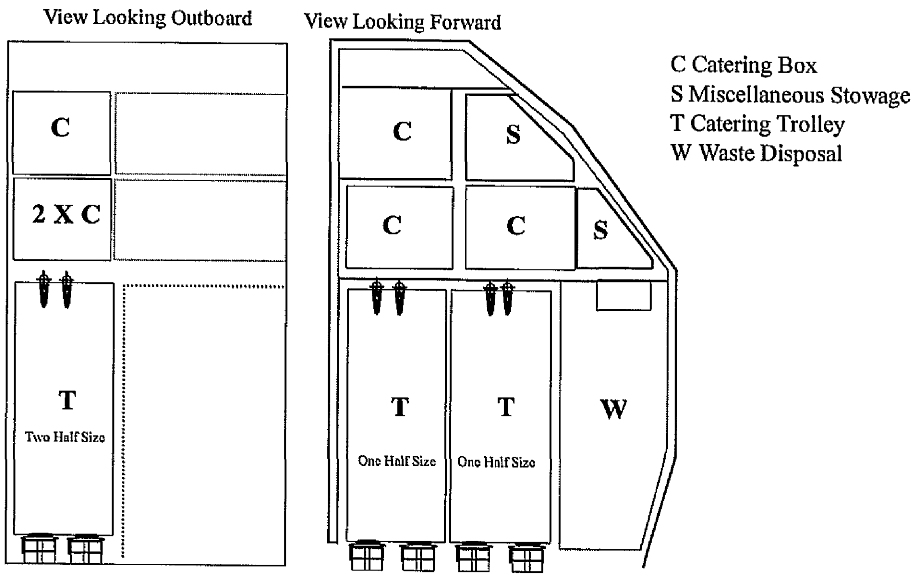


Figure 4.28 Galley B

Galley C – A galley with 3 trolleys .....(same style galley unit as Bucher Crossair/Sabena) (see Figure 4.29).

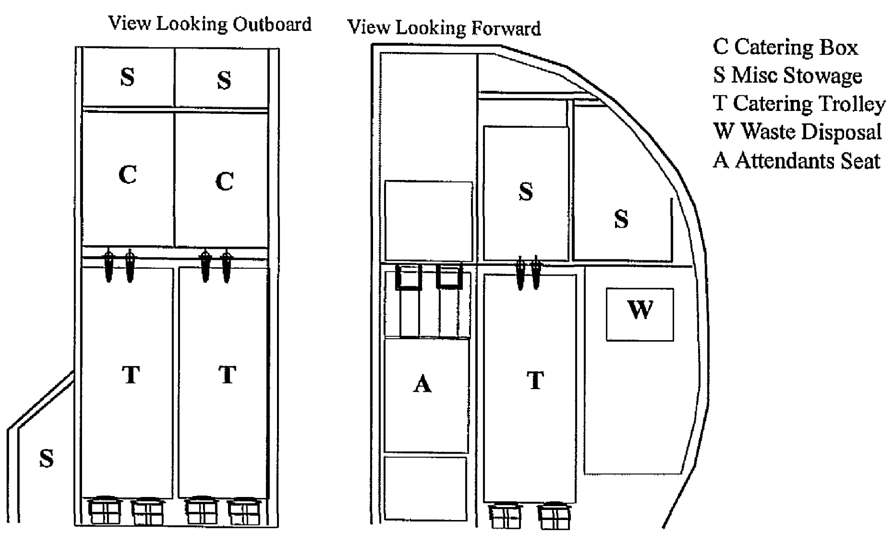


Figure 4.29 Galley C

Options for 3R position

Option A – Galley A at the Ax 784.81 rear position.

Option B – Galley B at the Ax 784.81 rear position.

Option C – Galley C at the Ax 782.51 rear position.

Option D – Galley B at the Ax 772.26 rear position (gives 40" space in serving area).

The galley units selected above for both the 2R and 3R positions were not new designs, they were chosen from the various galleys that had been previously installed on the aircraft. However, some of the locations indicated above for these galley units were in fact new and had been requested in the Sales and Marketing wish list.

There is a fundamental structural difference between the 2R and 3R positions that meant that each area had to be treated quite separately when developing the new underfloor support structure design. The 2R position spans the "boxing joint" i.e. the joint between the nose section (built at Avro) and the centre fuselage section (built at BAe Filton), but the 3R position is fully contained within the rear fuselage section (built at BAe Chadderton). This means that at the 3R position a truly "modular" support structure could be developed, whereas at the 2R position a "kit of parts" approach was needed. These concepts will be explained in more detail shortly.

4.5.2.2 Decision on the Design Philosophy for the New Underfloor Support Structure

Although the original design philosophy (i.e. using intercostals etc.) of the underfloor support structure was not the most efficient, it is important to realise that it was not the philosophy that was the main cause for concern. It was the variation in galleys that led to the re-design of this structure every time there was a new customer, and the actual method of galley attachment and sealing that caused the main problems. If the galleys had been the same from one aircraft to the next, then the use of intercostals etc., although rather elaborate, would have been tolerable.

However, since the Four Corners project was seen as an opportunity to rectify *all* the inefficiencies associated with the galley installation activity, it was felt that a trade-off study should be performed, to see if any other design philosophies would better suit the support structure application. Various options were considered:

- structural floor panel – a reinforced floor panel that can have attachment holes drilled into it at any location. The galley unit would then be attached directly to the floor panel. This concept eliminates the need for underfloor support structure;
- attaching galleys to seat rails – the seat rails could possibly be utilised for galley attachment in a similar fashion to the way seats are attached i.e. fittings that slide up and down a groove until they are located and then simply locked into position;
- original philosophy i.e. using a network of underfloor support structure made up of intercostals, brackets and plates.

The results of this trade-off study are summarised as follows:

- the use of a structural floor panel was considered to be too drastic a design change considering the resource and time constraints. Even if the time and resource was available to develop a structural floor panel design, the fact that it would effectively be a re-design done within the constraints of the existing aircraft structure would lead to unacceptably high weight penalties;
- attaching the galleys directly to the seat rails was unacceptable from a stress point of view because the design of the seat rail section was not strong enough to support the galleys in the crash case condition. To re-design the seat rail was again too drastic a change at this stage in the aircraft's life cycle. Also, the pick-up points on the chosen galley units would have to be moved to coincide with the seat rail positions. This would involve major modification to the galley units themselves, which would in turn lead to costly re-certification;
- due to the Four Corners project timescale and resource level, it was decided that the traditional, 'safe' design philosophy for support structure i.e. using intercostals, brackets and plates would be continued, but this time qualitative DFMA principles

such as part count reduction, standardisation, modularisation and simplification would be more rigorously applied.

4.5.2.3 3R Position "Modular" Design

The spread of the pick-up points of the galleys on Sales and Marketing's 'wish list' for the 3R position were clustered in such a way that they were all contained within the rear fuselage section of the aircraft. It was, therefore, possible to design a floor structure that could be considered as modular, i.e. one design that could accommodate all sets of pick-up points with minimum redundant structure. Figure 4.30 shows the pick-up point locations for the RJ70/85/100. (NB. The rear fuselage frame pitches for the RJ70, 85 &100 are identical, therefore the same underfloor structure design can be used on all series).

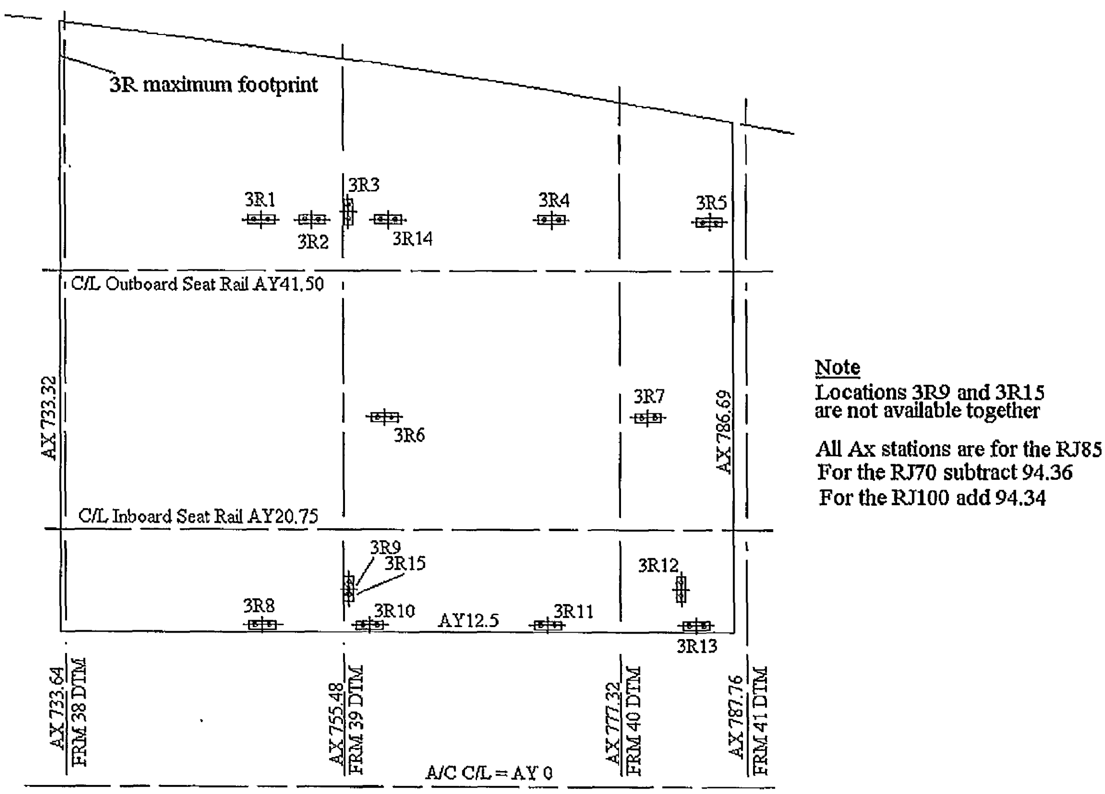


Figure 4.30 Pick-Up Point Locations at the 3R Position for the RJ70/85/100

Figure 4.31 shows the footprints of the galleys selected at the 3R position.

If Option A is selected pick-up points 3R2,3R5,3R10,3R13 are used.

If Option B is selected pick-up points 3R3,3R4,3R5,3R9,3R11,3R13 are used.

If Option C (with new style attachment method) is selected pick-up points 3R14,3R4,3R6,3R7,3R15,3R12 are used. (An explanation of the meaning of 'old style/new style' attachment method relating to Option C is given shortly).

If Option D is selected pick-up points 3R1,3R4,3R8,3R11 are used.

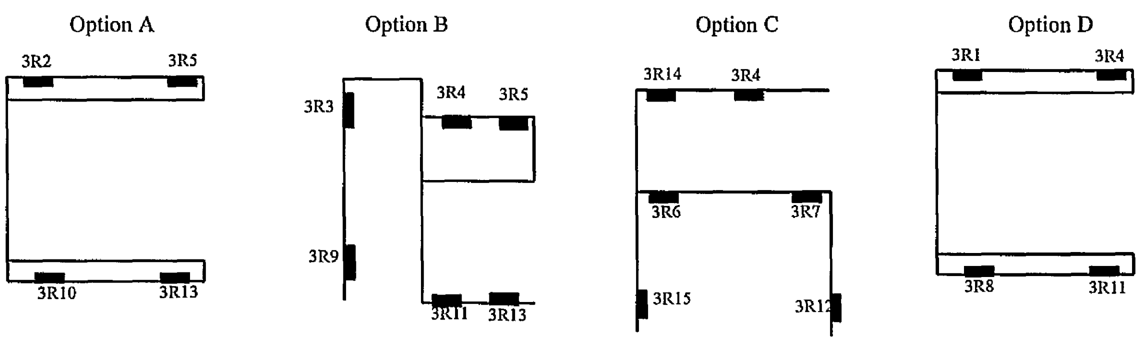


Figure 4.31 Galley Footprints at the 3R Position

Figure 4.32 shows an isometric view of the new 3R modular underfloor support structure (the galley attachment brackets are not shown). A photograph of this structure installed on the aircraft can be found in Appendix 5 (see Plate A5.2). A photograph showing the galley attachment brackets in place for Option C can also be found in Appendix 5 (see Plate A5.3).

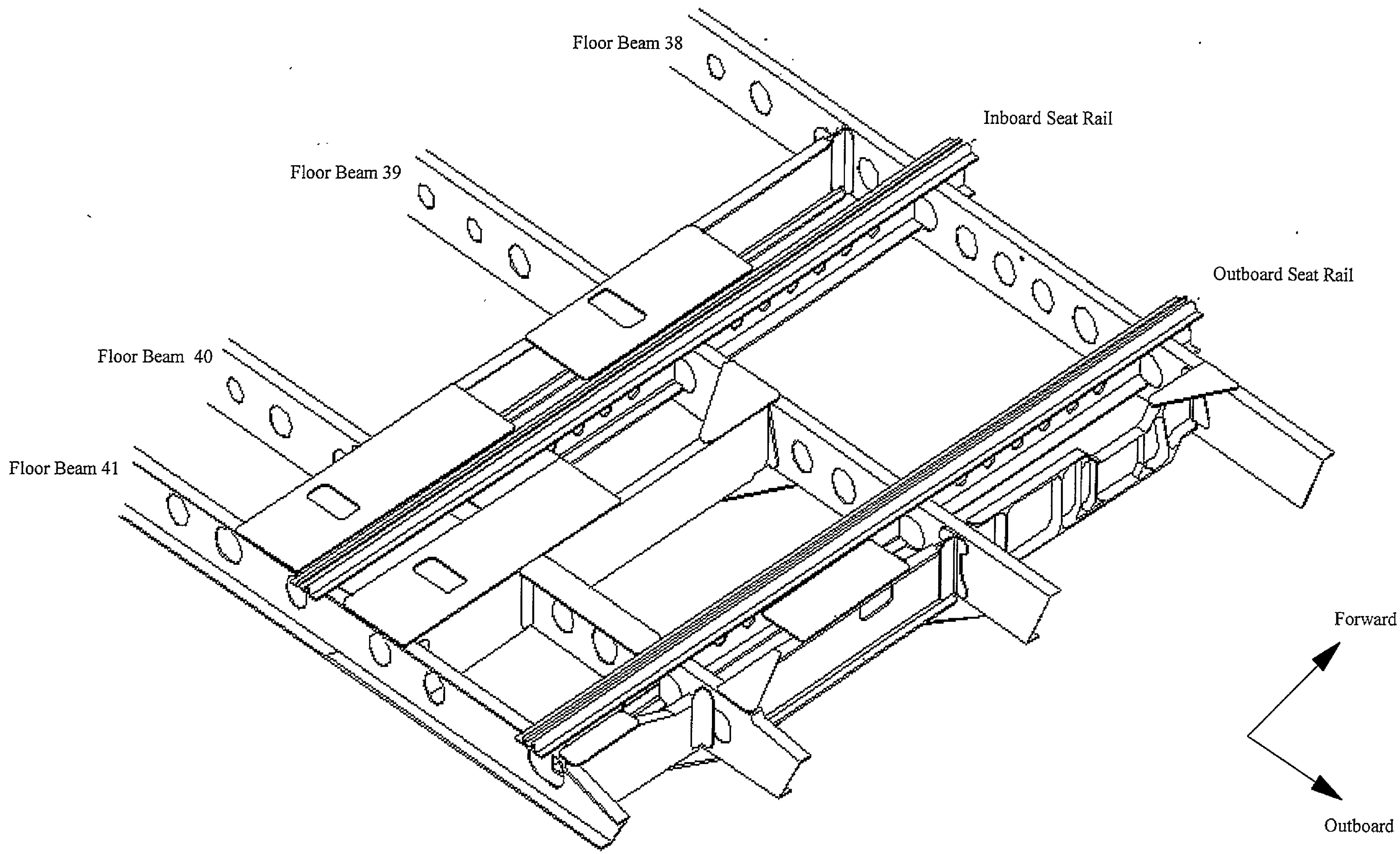


Figure 4.32 3R Galley Modular Underfloor Support Structure

This new design accommodates three of the galley units described earlier without any modification; Option A, Option B and Option D. Option C was manufactured by the second galley supplier, and accommodating this option proved to be slightly more complicated. The complication arose from the preferences of Avro's current customers who had already selected Option C.

It is important to remember that the Four Corners project was not just about changing the design of the underfloor support structure, it was also about changing the way the galleys were physically attached to this structure (i.e. moving from threaded insert type attachment brackets to barrel nut attachment brackets). The two galley suppliers each had their own peculiar method of attaching the galley unit to galley attachment brackets, as illustrated in Figures 4.14 and 4.16 (see section 4.4.2.3).

Unfortunately, the airlines have considerable influence over the way the galleys are attached. The airline which had already taken delivery of some of their aircraft with the 'old style' attachment method preferred to keep it the same for their remaining aircraft. The other airline had yet to take delivery of any aircraft, and they agreed to a modification of the galley units so that they could use the 'new style' attachment method. (These modifications refer to both the method of attachment and to the actual location of the pick-up points. The pick-up points in the outboard position had to be moved further outboard so that they coincided with the structure which was in place for the other three options).

The fact that one of the airlines refused to allow Avro to carry out Four Corners improvements on their galleys caused concern, since at this time, this airline was one of Avro's main customers. Therefore, the continual changing from installing old style galleys (and hence floor structure) and new style galleys would have had an unacceptable disruptive effect on the production activity. The compromise for Avro was to look at the 3R design proposal and include at least as much structure as possible that could be used to accommodate the pick-up point positions for the old style Option C galley. (Remember the new style Option C was already going to be catered for).

The Four Corners team decided to put in some structure that could be used to support the central attachment brackets for the old style Option C (see structure between seat rails in Figure 4.32). The inboard brackets could use the same structure that was in place for the other options. Unfortunately, the outboard structure used for the other options, will have to be removed, when the old style Option C galley is fitted, because the original fittings for this galley in the outboard position are attached directly to the seat rails and would, therefore, clash.

The issue of an airline not wanting to change how the galley is attached to the floor structure may appear to be somewhat trivial, but it developed into a major political issue during the course of this project. The implications of trying to introduce design changes to the aircraft, part way through a customer order, are discussed further in section 7.1.2 of Chapter 7.

4.5.2.4 2R Position "Kit of Parts" Design

Unlike the galley units that Sales and Marketing wanted to accommodate at the 3R position, the spread of the pick-up points, for the chosen units at the 2R position restricted the use of similar modular design for three reasons:

- if all the necessary support structure was installed as one design, then there would be lots of redundant structure when each individual galley unit was chosen. This is because for every pair of longitudinal pick-up points moving inboard, there has to be a separate intercostal;
- since at the 2R position the frame pitch is different between the RJ70/85 and RJ100, different length intercostals would have to be used for each series;
- the existing structure located in the area of 2R, for the RJ70/85 and RJ100 is different. The main difference is the location of a 'g' weight on the flying control cables. Therefore, 'collision avoidance' fixes had to be incorporated in some parts of the design.

After investigation into the pick-up points at the outboard position it was clear that with minor modifications to some of the galley units, the lateral co-ordinates of the outboard pick-up points could be made to coincide. This was possible both on the RJ70/85 and on the RJ100. This meant that the outboard portion of the overall design on each series could in fact be considered as modular i.e. the same outboard design could be used for every galley option without any redundant structure.

For the 2R position a kit of parts approach was adopted, whereby, the design would effectively be split into two parts. The outboard pick-up points for all the galleys would be covered by one design and each inboard set of pick-up points would have a separate design. (NB. This would apply to the RJ70/85 and RJ100 separately). Therefore, when customers select their 2R galley, the same design would be used for the outboard structure but a specific design would be used for the inboard structure.

Figures 4.33 and 4.34 show the final spread of the pick-up points at the 2R position for the RJ70/85 and RJ100 respectively.

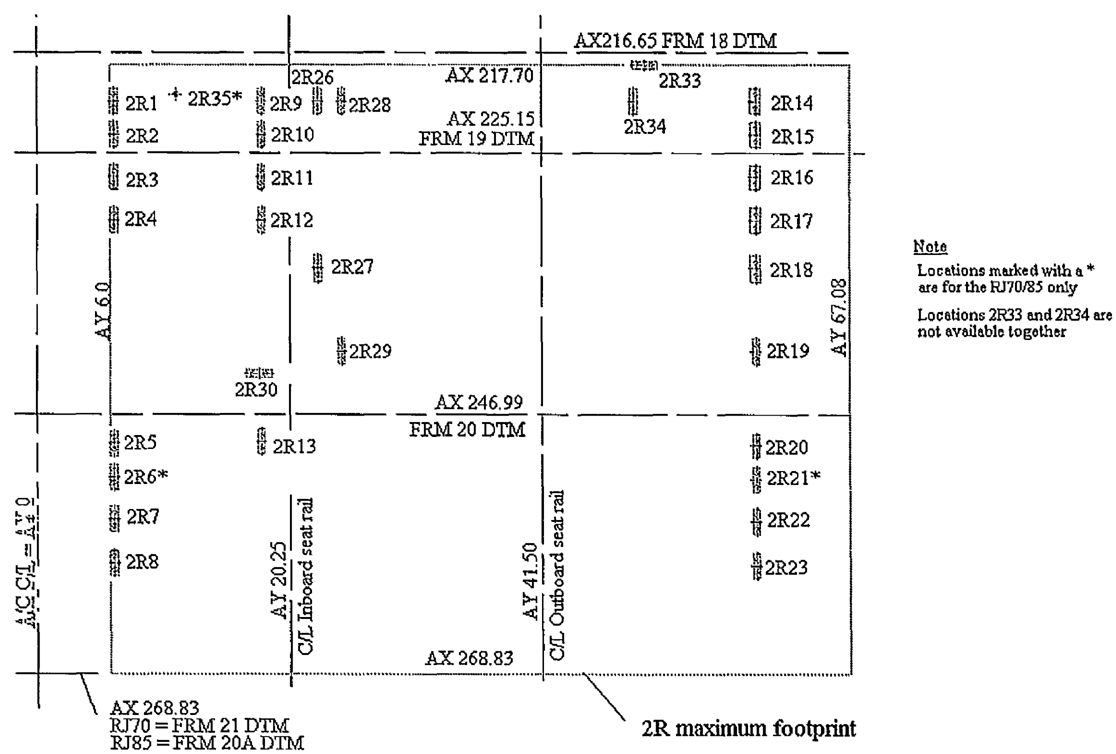


Figure 4.33 Pick-Up Point Locations at the 2R Position for the RJ70/85

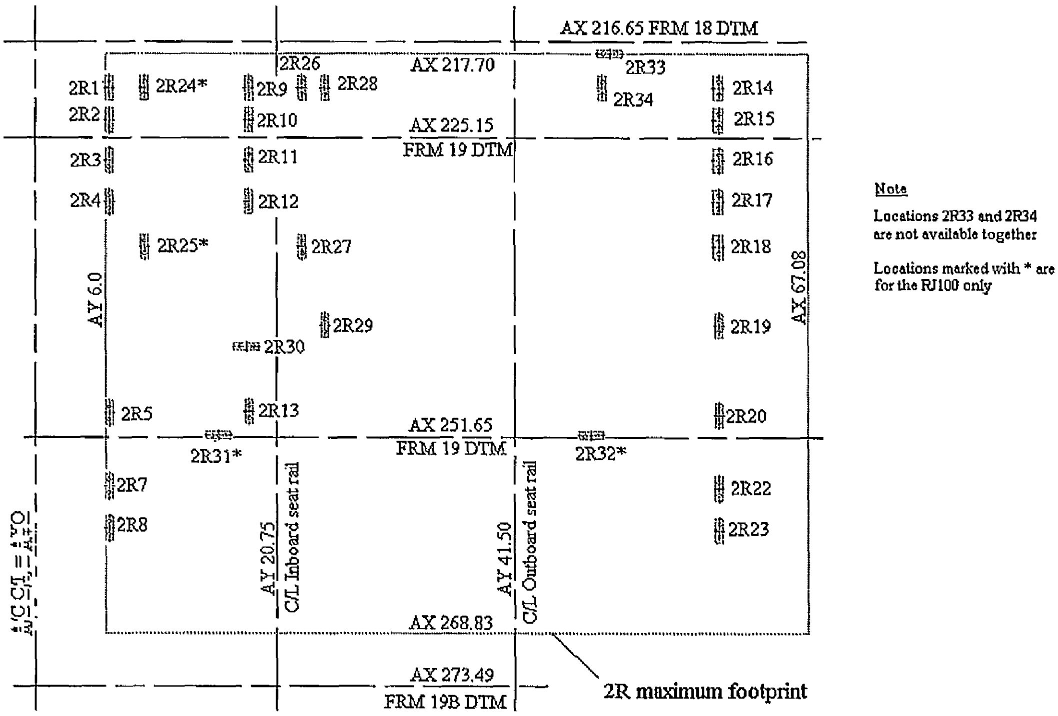


Figure 4.34 Pick-up Point Locations at the 2R Position for the RJ100

Figure 4.35 below, shows the footprints of the galleys selected at the 2R position.

If Option A is selected pick-up points 2R9,2R14,2R13,2R20 are used.

If Option B is selected pick-up points 2R10,2R15,2R13,2R21 are used.

If Option C is selected pick-up points 2R11,2R16,2R13,2R22 are used.

If Option D is selected pick-up points 2R12, 2R17, 2R13, 2R23 are used.

If Option E is selected pick-up points 2R1,2R14,2R5,2R20 are used.

If Option F is selected pick-up points 2R2,2R15,2R6,2R21 are used.

If Option G is selected pick-up points 2R3,2R16,2R7,2R22 are used.

If Option H is selected pick-up points 2R4,2R17,2R8,2R23 are used.

If Option I is selected pick-up points 2R24,2R26,2R34,2R14,2R25,2R27,2R18, 2R31,2R32 are used.

If Option J is selected pick-up points 2R35,2R28,2R33,2R14,2R30,2R29,2R19 are used.

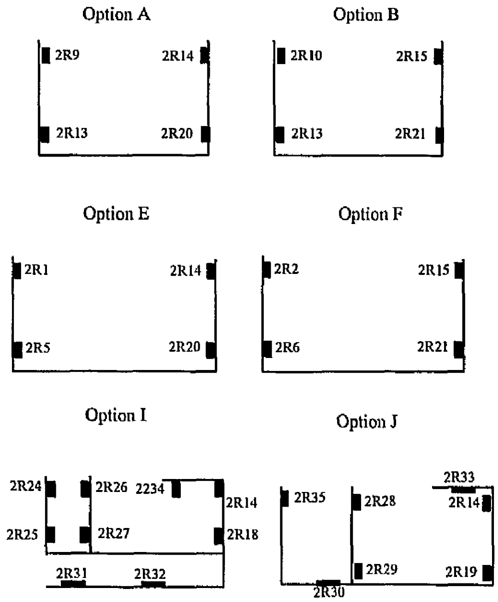


Figure 4.35 Galley Footprints at the 2R Position

Figure 4.36 shows a schematic plan view of the associated intercostal locations at the 2R position for the RJ70/85 and RJ100.

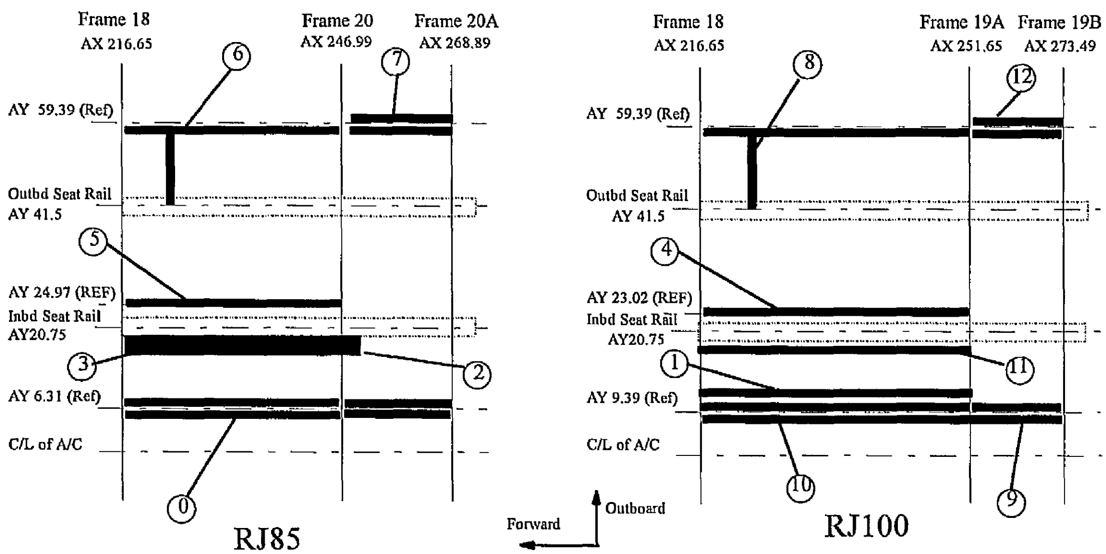


Figure 4.36 Intercostal Locations at the 2R Position for the RJ70/85 and RJ 100

Figures 4.37 to 4.46 show the isometric views of each of the new structural items identified in the figure above.

At the end of the previous section it was explained how one of Avro's customers was reluctant to allow the incorporation of the Four Corners improvements on their galley at the 3R position. Not surprisingly, the situation was the same at the 2R position. However, because of the kit of parts nature of the new 2R underfloor support structure, there was no way a partial solution could be reached i.e. incorporating at least some structure for the old style galley, as had been done at the 3R position. Therefore, on the remaining aircraft, for this particular customer at the 2R position, the old underfloor structure had to be installed.

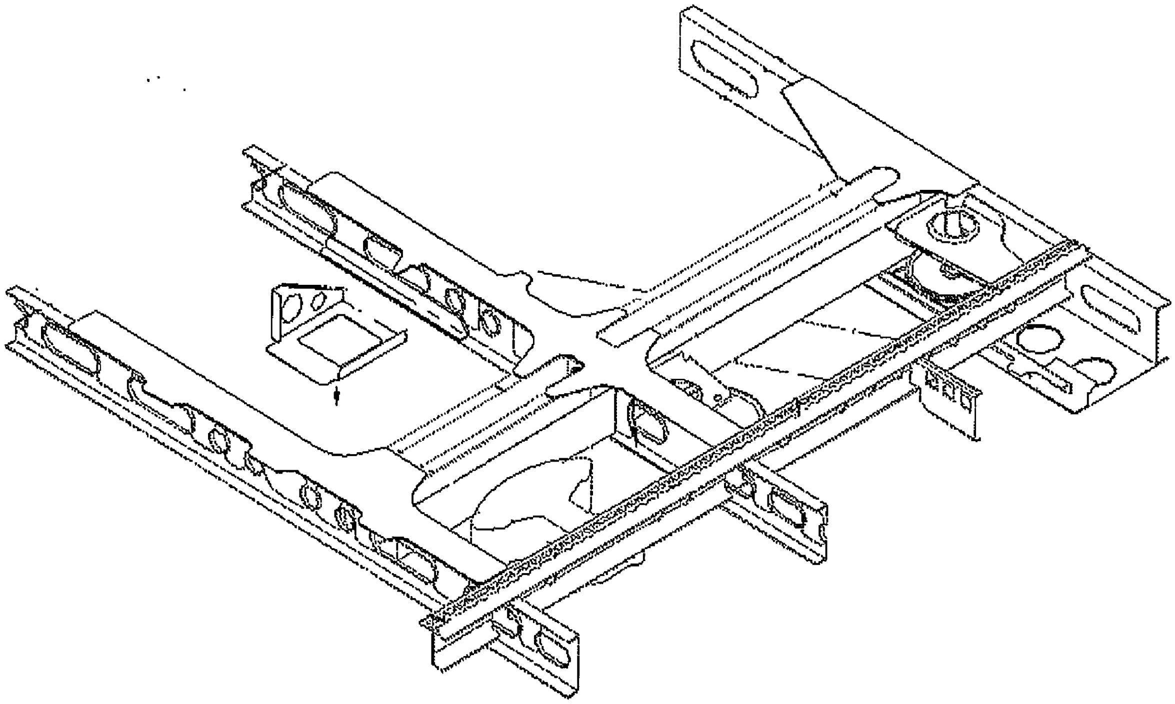


Figure 4.37 Structure at AY 6.31 Balloon Reference 0

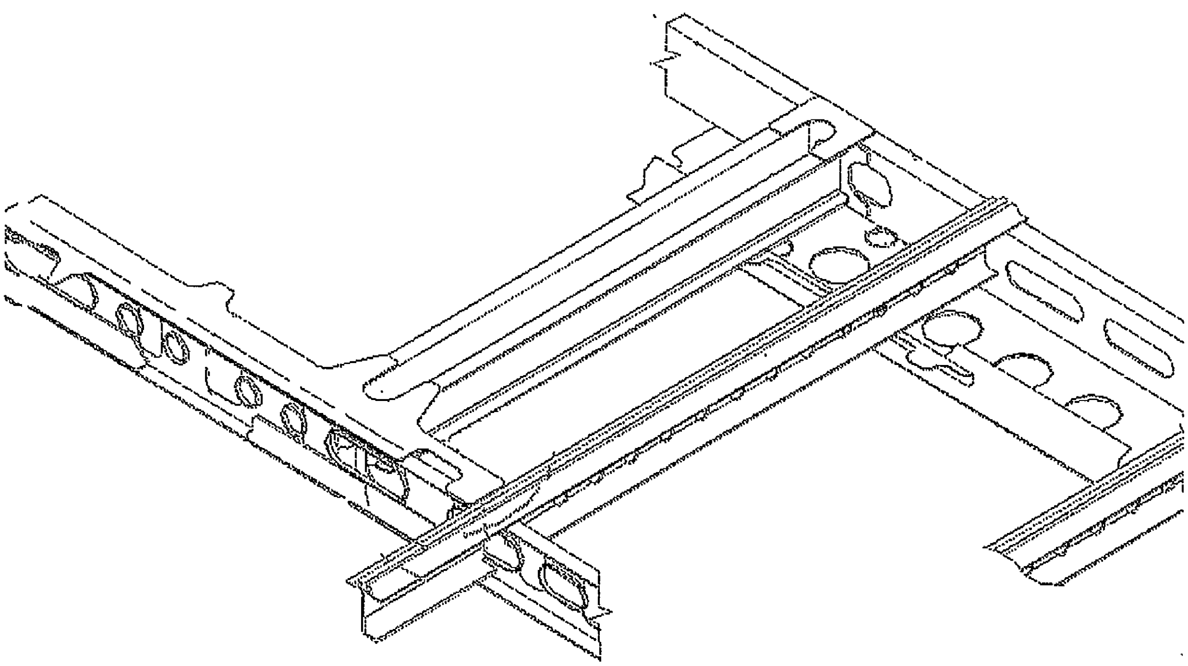


Figure 4.38 Structure at AY 9.39 Balloon Reference 1

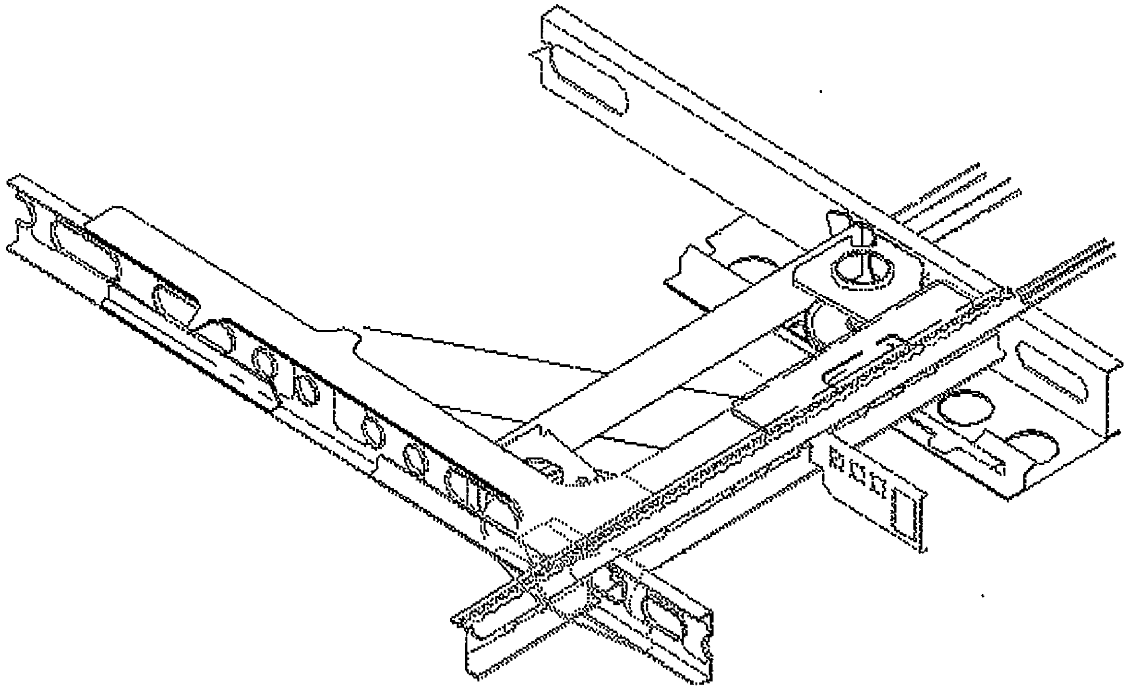


Figure 4.39 Structure at AY18.38 Balloon Reference 2 & 3

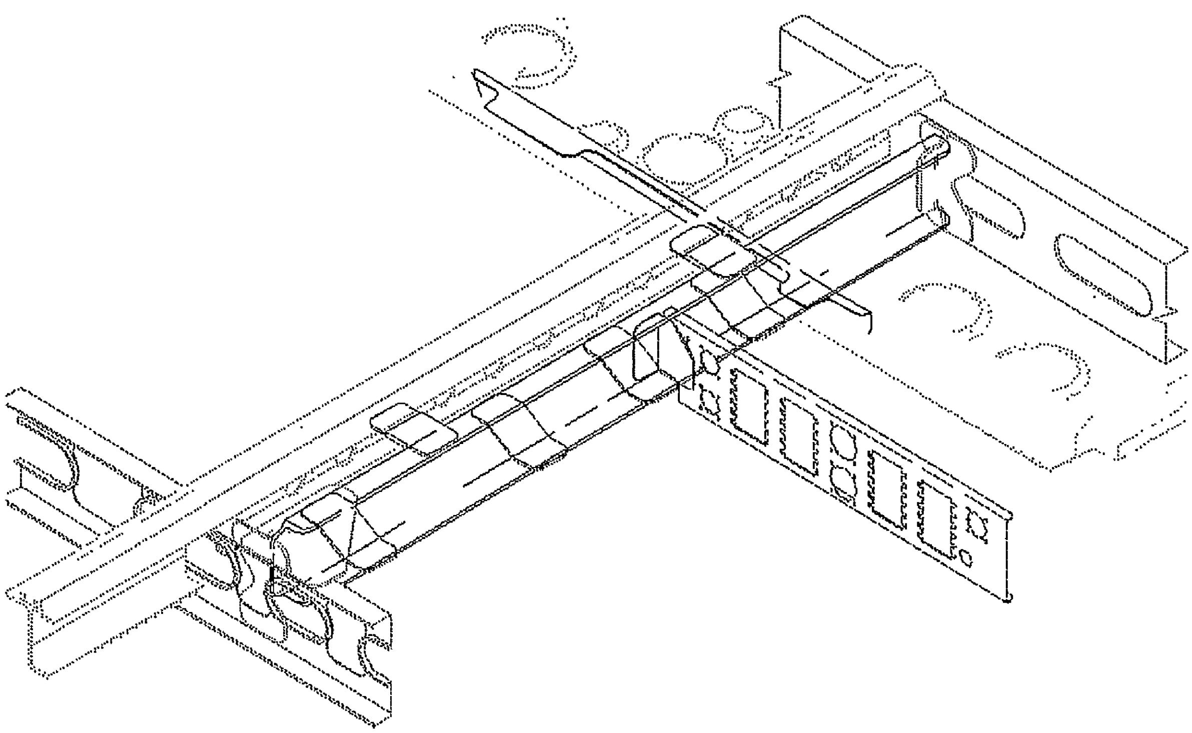


Figure 4.40 Structure at AY 23.02 Balloon Reference 4

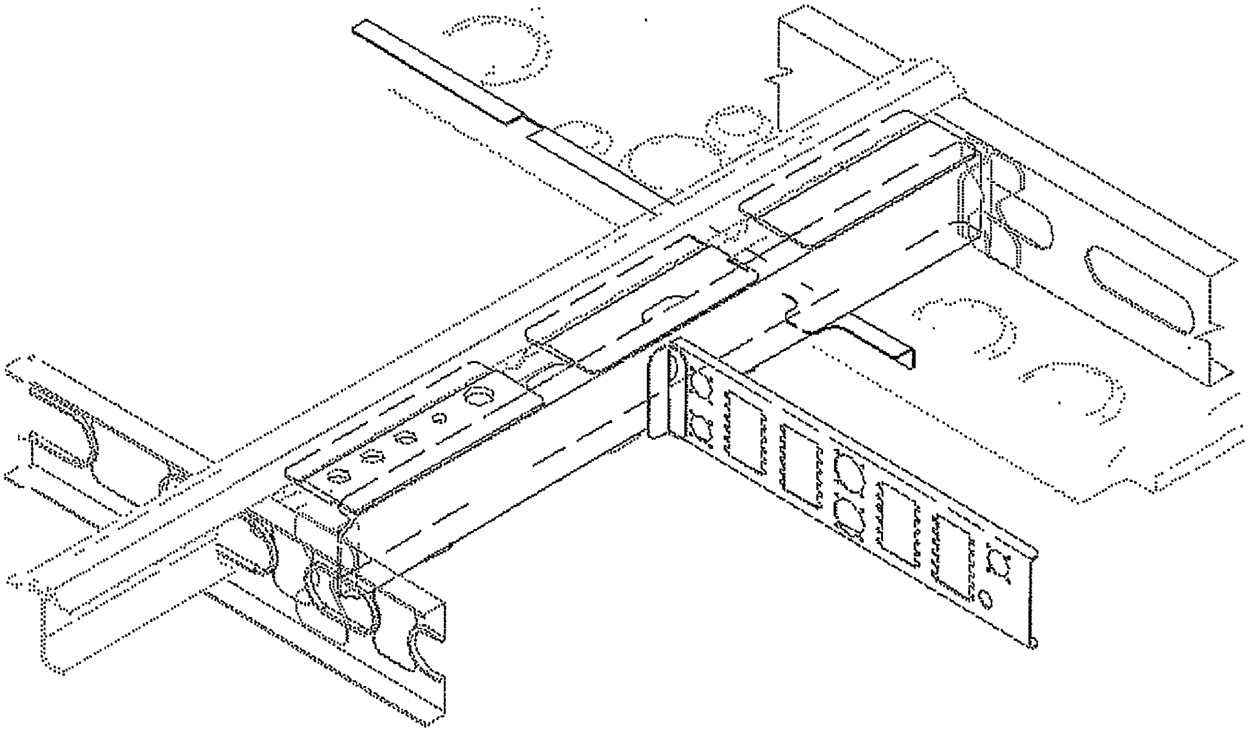


Figure 4.41 Structure at AY 24.97 Balloon Reference 5

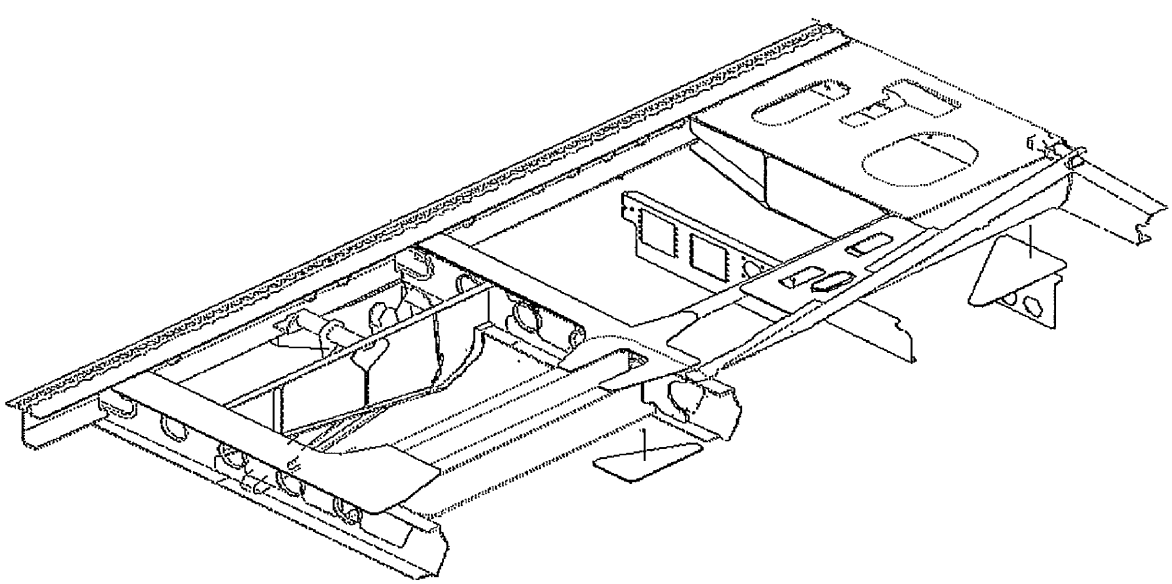


Figure 4.42 Structure at Outboard Position Balloon Reference 6 & 7

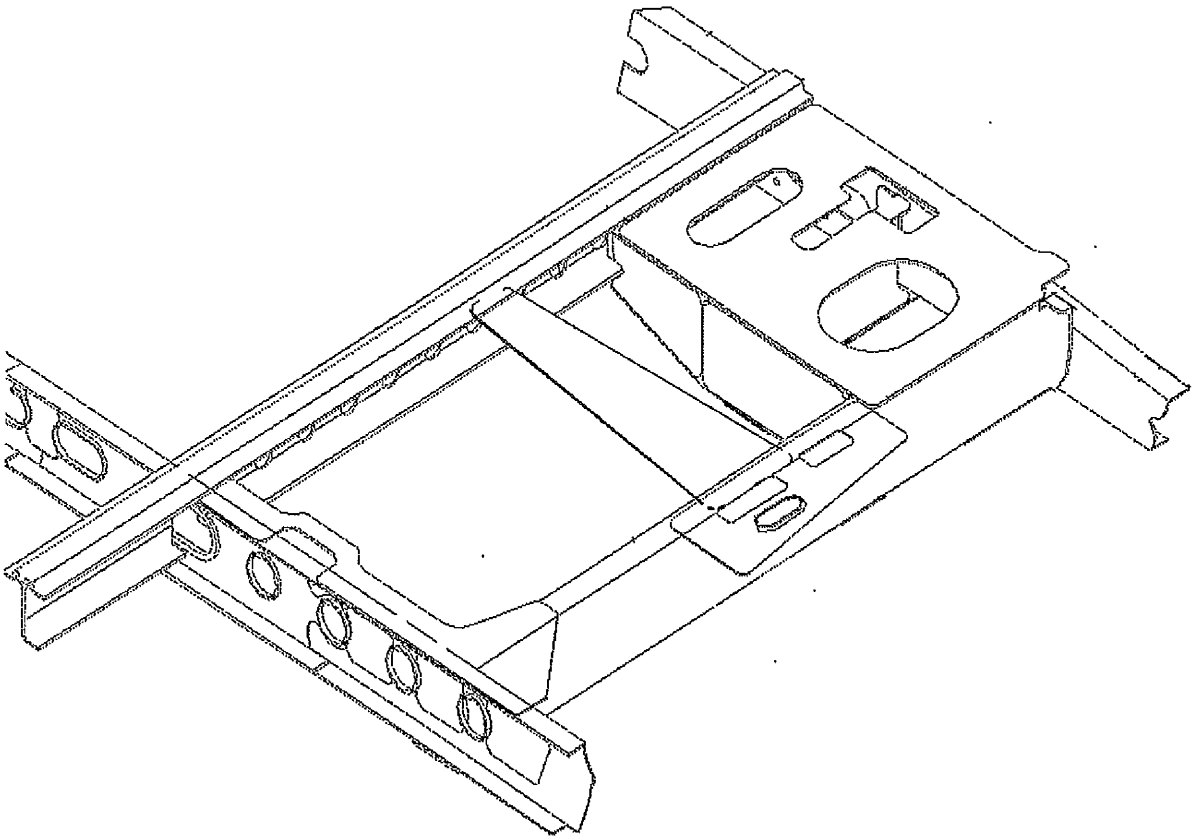


Figure 4.43 Structure at Outboard Position Balloon Reference 8

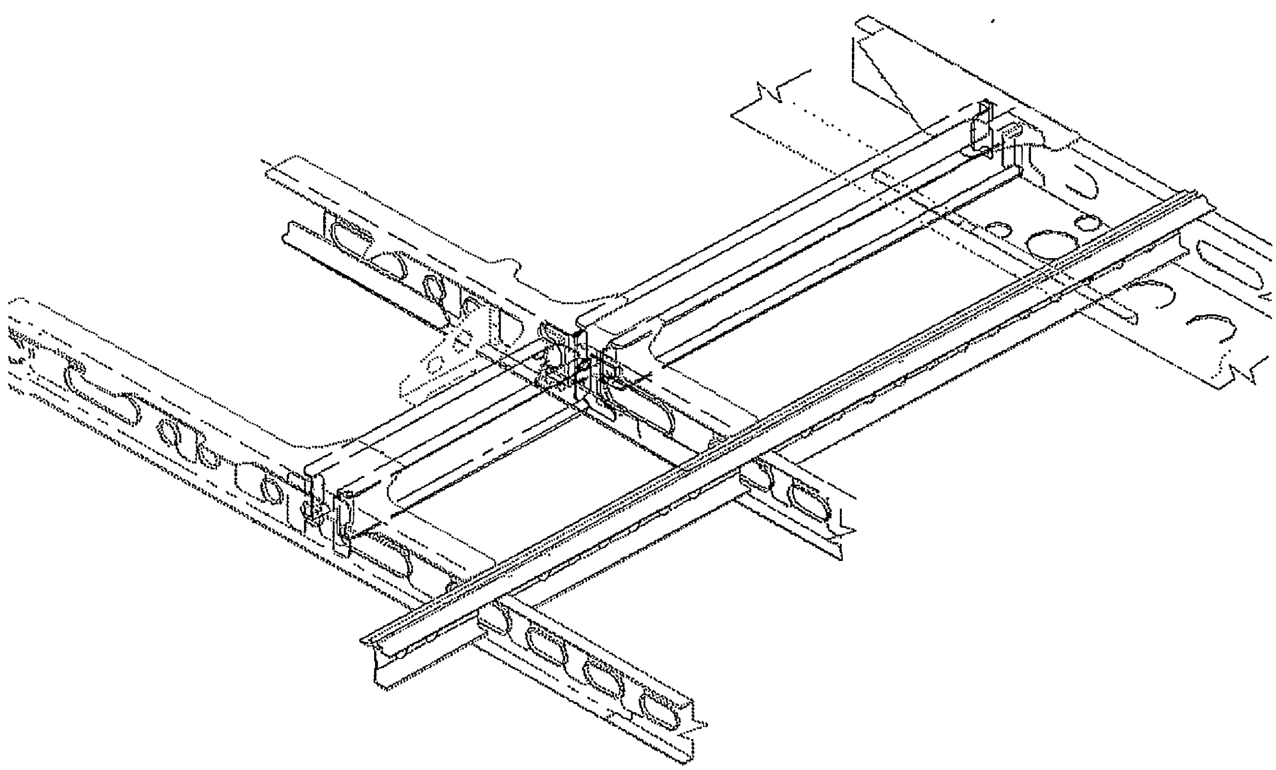


Figure 4.44 Structure at AY 6.31 Balloon Reference 9 & 10

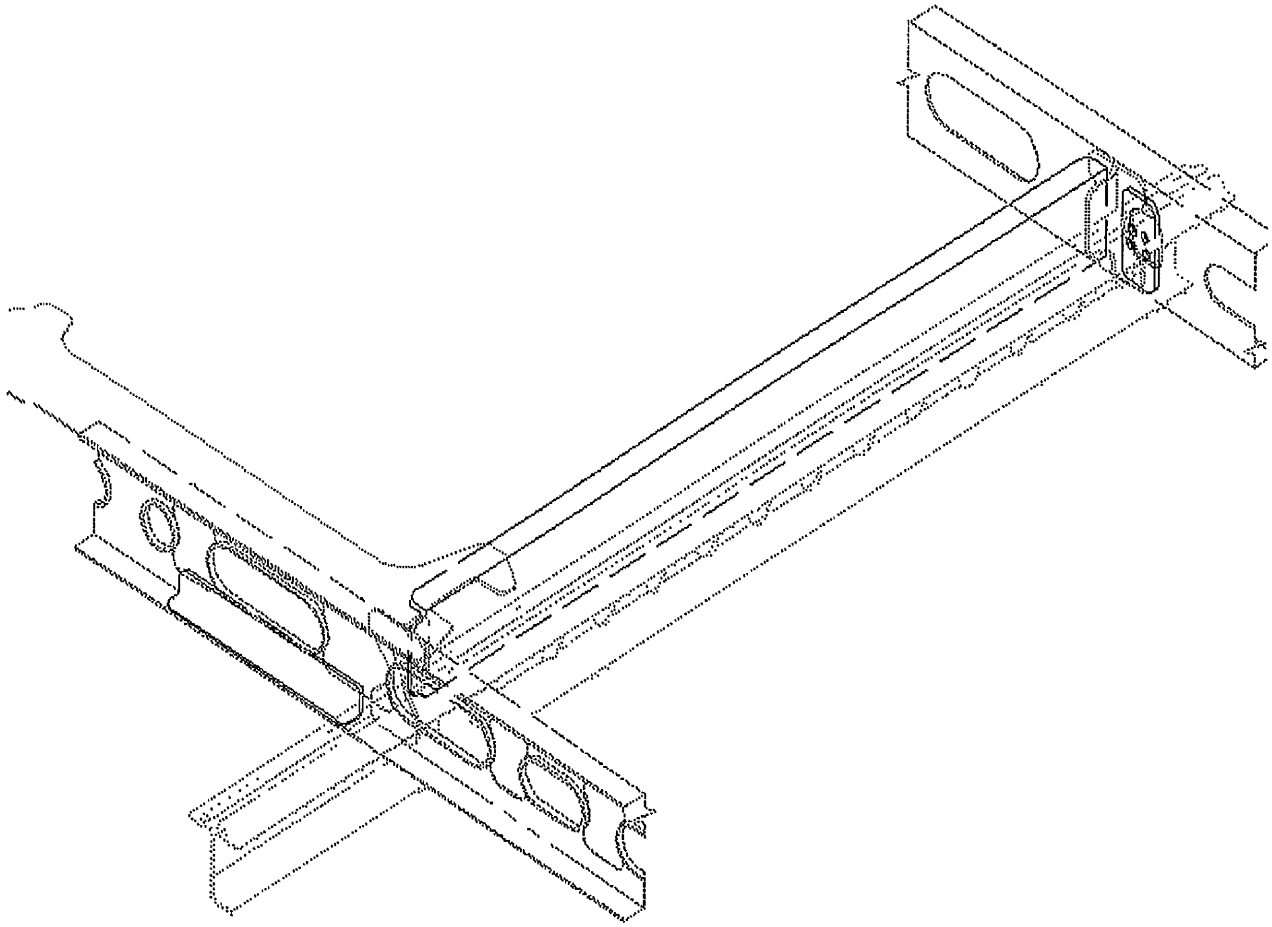


Figure 4.45 Structure at AY 18.38 Balloon Reference 11

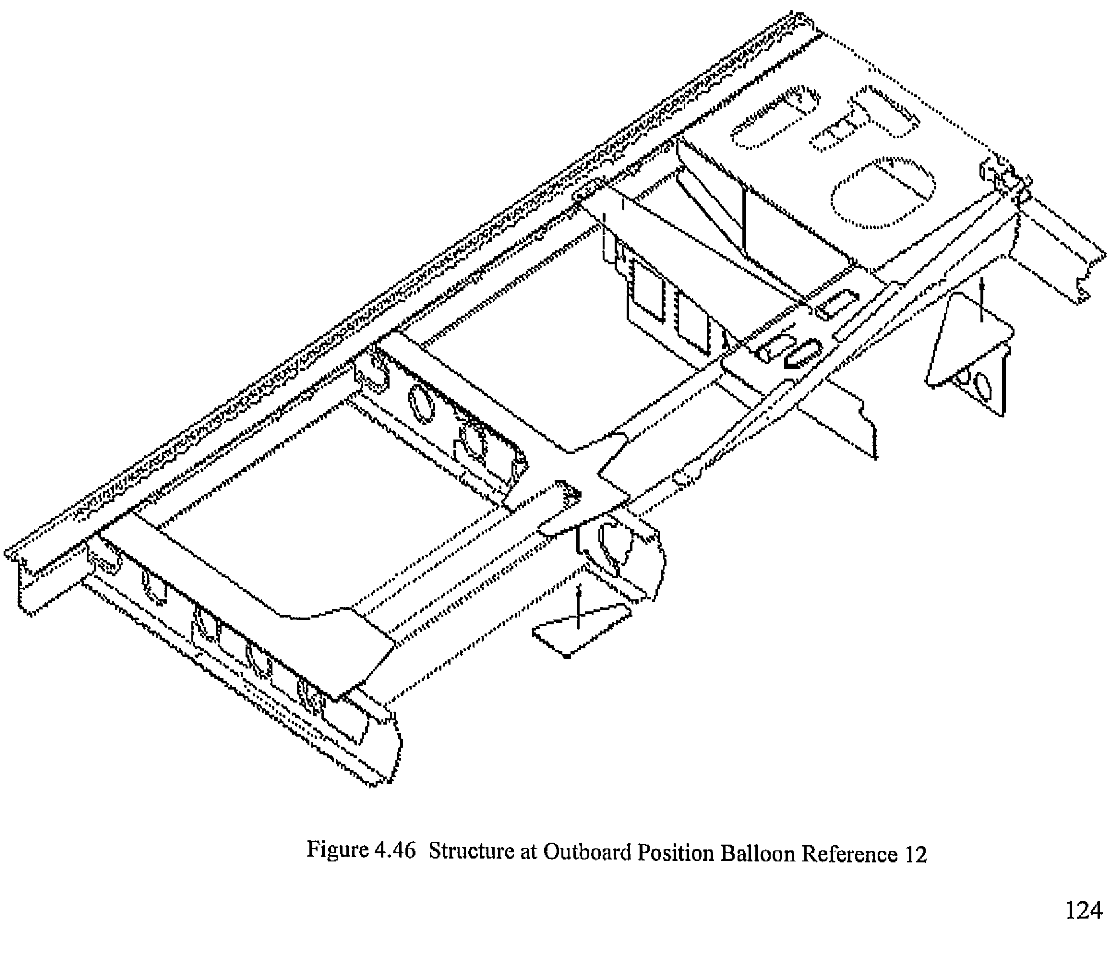


Figure 4.46 Structure at Outboard Position Balloon Reference 12

4.5.3 Production Build Sequence Changes for Galley Underfloor Support Structure, Galley Attachment Brackets, and Galley Units

4.5.3.1 Original Build Sequence

In section 4.2.2 it was explained how the RJ had Standard option galleys at the 2R and 3R positions. This meant that the rear fuselage section had the 3R Standard option galley underfloor support structure built in at BAe Chadderton. So if an airline did not choose the Standard option galley at 3R (which unfortunately, was often the case), this structure had to be removed and scrapped when the centre fuselage reached Avro, in order to make way for the new support structure. If an airline did not want a galley at 3R, the support structure would stay in place and effectively become a weight penalty for the customer. It was not cost effective for Avro to remove it.

The situation at the 2R position was slightly different. Since the 2R position spanned the boxing joint, this meant that the underfloor support structure had to be installed in the Completions stage at Avro. However, by the time the aircraft reached Completions, it would have been allocated to a Customer and the galley selection at the 2R position would be known. Therefore, there was never any need to remove and scrap underfloor structure at 2R; it was never installed unless it was needed.

4.5.3.2 New Build Sequence

As a result of the Four Corners project, the following concepts regarding the build sequence of the installation of the underfloor support structure, the galley attachment brackets and the galley units themselves were adopted:

For the 3R position

A decision was made to have the new modular support structure installed at Chadderton (as before like the old Standard option structure). However, this time, since the intended customer could still not be guaranteed until the centre fuselage reached Avro, and therefore the specific galley selection would still not be known at Chadderton, the specific galley attachment brackets would not be installed with the support structure at Chadderton. They would be installed as a separate operation at Avro. In an attempt to integrate as much of the trivial, none high cost item operations upstream of Completions, it was decided that the galley attachment brackets for 3R would be best fitted during the IAS stage of Structural Build and not in Completions.

There is no advantage to having the underfloor support structure fitted at Chadderton other than it *still* ensures that a large work package stays 'outside' Avro's final assembly process. The main benefits come from fitting the attachment brackets during the IAS stage: (a) there will no longer be any need to scrap unwanted brackets because they will not be fitted until it is confirmed that they are definitely needed; (b) it keeps another operation out of the critical Completions stage of the final assembly process.

In the case of airlines who choose not to have a 3R galley, the 'weight penalty' or 'removal' trade-off will still have to be made as before. However, an important point to remember here is that many of the aircraft are leased to customers. If and when leased aircraft are returned, the new customers may require a galley in this position. Therefore, it may be wise to leave this structure in after all.

The galley units themselves would still be installed during the Completions stage, for access and inventory reasons.

For the 2R position

The new underfloor support structure at the 2R position still spanned the boxing joint and therefore it could not be installed before IAS. The same reasoning with the 3R position also applied here; the installation of both the underfloor structure and the galley attachment brackets should be kept out of Completions, and so both would be fitted during IAS, and the galley units would be installed during Completions.

4.5.4 Improvements to Galley Sales and Marketing Strategy

The key to the success of the Four Corners project is the ability of the Sales negotiators to convince the customers that one of the galley options that has been catered for within this project will sufficiently accommodate their requirements. The Four Corners project has given the Sales and Marketing organisation a clear insight into the impact their marketing strategy can have on the overall customisation process.

In an attempt to assist in sales negotiations, the project has put together a Galley Interface Definition Document ("GIDD"), which contains information on the galley units and footprints that have been catered for. It refers to these as the 'preferred galleys' and 'preferred locations'. If, however, a situation arises where the galley footprints and galley units are not suitable, this is not necessarily disastrous. Due to the structural philosophy chosen for the underfloor structure i.e. fitting the attachment brackets to intercostals, this means that in certain places, the attachment brackets can be physically shifted along the intercostal. Therefore, there is the possibility that other galley footprints can be catered for with only a slight adjustment to the galley attachment bracket installation drawings. This is minor work compared to designing a completely new underfloor structure. Figure 4.47 uses the 3R position to illustrate this range of flexibility.

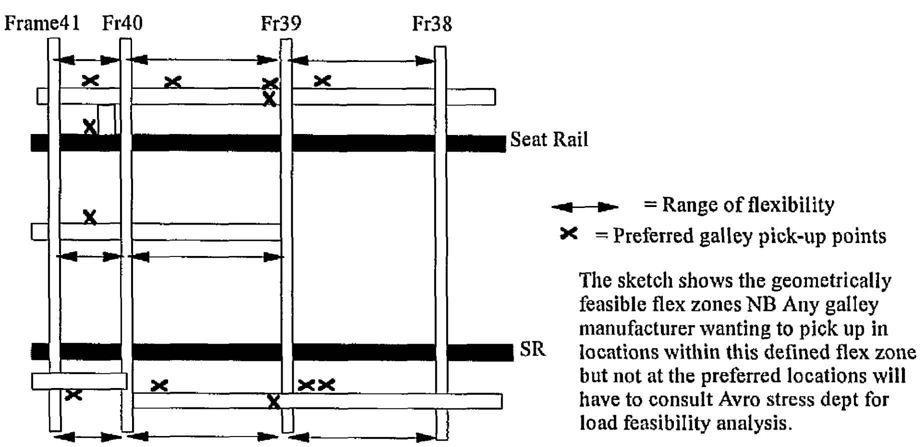


Figure 4.47 Ranges of Flexibility at the 3R Position

This 'deviation' from the preferred locations is obviously something that will not be encouraged. Something that must certainly be avoided at all costs, is the selection of a galley unit with a footprint which falls completely outside of the Four Corners scope.

The Four Corners project effectively disallows Customer Special options with regard to galley equipment on the RJ. All the options that have been catered for have all the necessary drawings, engineering and parts is place so they are all effectively Standard options. However, from a Sales and Marketing point of view the idea of Standard option and Customer Special option galleys will still be used during Sales negotiations. This makes sense from a commercial perspective because any deviation from the original Standard option can still be charged to the customer, even though the selection of any of the options within the preferred list has equal impact on Avro's customisation activity.

With the move of Avro's Sales and Marketing function to the AI(R) joint venture headquarters in Toulouse, France, it is important that the new organisation is fully aware of what the Four Corners project has put in place. The GIDD should help bridge this communication gap.

A recent indication of the effectiveness of the GIDD in sales negotiations is reflected in Avro's two most recent orders from Air Azzurra and CityFlyer. In both cases the airlines have selected galleys that have been catered for in the Four Corners project.

4.5.5 Improvements to Avro/Galley Supplier Interface

The GIDD will also play a vital role in the interface between Avro and its galley suppliers. Until now there has never been a document in place to convey the information needed for a comprehensive galley specification. This has resulted in a situation where both parties are disadvantaged: Avro have been incapable of specifying their weight and space restrictions effectively, resulting in a loss of control and uncertainty, and the suppliers never knew exactly what boundaries they had to work within. Invariably it was Avro who came off worst; the suppliers made decisions that suited them.

The GIDD gives the balance of power back to Avro. Avro is now able to tell the suppliers what is possible on the aircraft instead of the suppliers dictating what suits them. The galley suppliers are used to working with a GIDD from other aircraft manufacturers, and they have welcomed the introduction of this document.

4.5.6 Additional Improvements Included as Part of the Four Corners Project

As the Four Corners project progressed, it became a vehicle for solving some of the other customisation related problems. Two additional problems were investigated, concerning the fitting of the airstairs stowage unit, and the alignment of the cockpit door post.

1. Airstairs stowage unit

The airstairs stowage unit is usually located next to the forward passenger door and used to store the airstairs when they are not in use. The main cause for concern was the length of time it took to install the unit. The unit was supplied as 4 major separate items with approximately 50 additional parts, and took up to 70 man-hours to install on the aircraft. The Four Corners project team co-ordinated the design of a new modular airstairs unit via an external supplier. The new unit is simply offered up to the aircraft as a complete unit and fastened in place; the installation time has been reduced by 5 days.

2. Cockpit door post

The cockpit door post, although only a minor item itself, played a critical role in the alignment of the 1R galley and 1L toilet. It came as a separate item and had to be attached to the side of the 1R galley unit, during Completions. The Four Corners solution to this problem was to design an 'integral' door post. i.e. integral with the 1R galley wall and hence supplied with the galley unit.

4.6 Savings and Benefits

The financial investment and savings of the Four Corners project can be summarised as follows:

Total Investment	=	£ 415,200
Total Savings per year	=	£ 811,290 (assuming 3 new customers and 18 aircraft sold/ year)
Payback	=	6 months i.e. 9 aircraft sets.

For a detailed breakdown of the investment and savings see Appendix 7.

The Four Corners project became much more than simply a physical design change aimed at easing production. It generated benefits within all areas of the business:

1. Design and Engineering

All the drawings and engineering for the complete galley installation package i.e. installing the underfloor support structure, the galley attachment brackets, and the galley unit itself is now in place and ready to be used. This means that from now on, during the customisation activity, there will be no substantial design or engineering work associated with galley installation. This releases resource for use on other customisation design changes.

2. Production

(a) The method of galley unit installation has been made easier by the use of barrel nut type fittings over the old threaded insert type.

(b) The sealing method and trimming of the galleys has been simplified.

(c) Since the variation of the galley design has effectively been eliminated, there is now an opportunity to take advantage of the learning curve. Reductions in assembly time should follow.

(d) The re-sequencing of the underfloor support structure and galley attachment brackets, has removed a substantial work package from the critical Completions phase of the final assembly business.

3. Procurement and Logistics

(a) Through rationalisation and standardisation, the Procurement department now have fewer parts to order and the Logistics function have fewer parts to chase. The number of types of bolts used during galley unit installation has been rationalised from 23 down to 2 and the items that are comprised in the underfloor support structure have been rationalised as far as possible. Throughout the project care was also taken to ensure that the parts used for each option within the design were standardised as much as possible, not only within each position, but also read across from the 3R position to the 2R position.

(b) By classifying the underfloor structure parts as open access "C" class items, the associated procurement and logistics activity is now simpler.

(c) The fact that the variation in underfloor support structure has effectively been eliminated means that Procurement can better use economies of scale when ordering these parts.

(d) As a result of the Galley Interface Definition Document, there will now be a more effective interface between Procurement and the galley suppliers.

4. Sales and Marketing

It has already been stressed that the key to the success of the Four Corners project lies with the Sales and Marketing function. The introduction of the Galley Interface Definition Document will give clear guidelines during sales negotiations as to the customer requirements Avro can easily accommodate.

5. Build to Order initiative

Phase 1 of the BTO initiative (see Figure 4.48, see Appendix 4 for details) is aimed at ensuring that the Completions business process cycle time falls inside the Customer's Acceptable Delivery Lead Time ("ADLT"). The Four Corners improvements contributed to phase 1 in the following ways:

- putting all the necessary drawings and engineering in place for the galley underfloor support structure and having all the parts as 'C' class items (i.e. stocked open access as opposed to ordered when needed), reduced the lead time associated with the engineering and procurement elements of the Completions business process cycle time;

- removing the need to design and engineer underfloor support structure in any future customer orders, has effectively freed up resource for use on other jobs within the customisation activity, therefore reducing even more the lead time associated with the engineering element of the Completions business process;
- re-sequencing the installation of the underfloor structure and galley attachment brackets, removed a significant amount of work content from the physical assembly aspect of the Completions business;
- this removal of work content similarly freed up resource for use in other areas of the Completion's physical assembly process.

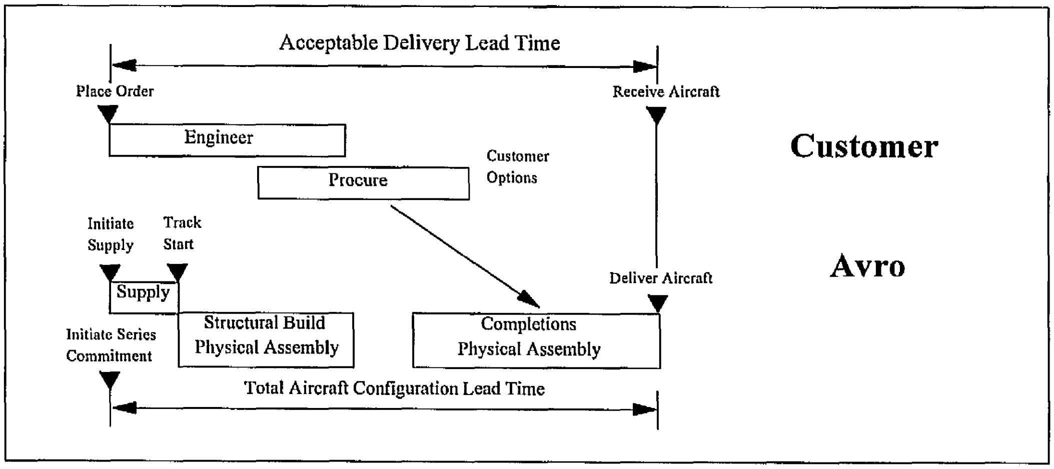


Figure 4.48 Avro's Build to Order Model

Chapter Review

This chapter described the main element of the Eng.D. study's investigation into DFMA. It described how the qualitative DFMA rules of part rationalisation and standardisation, modularisation and simplification were applied to a production easement exercise carried out on one of the most troublesome areas of the RJ's customisation activity, namely, galley installation.

The Four Corners project became much more than simply a physical design change aimed at easing production; it generated benefits within all areas of the company. The principal benefit was for the Design and Engineering functions as it eliminated the need for any future galley design and engineering work. All possible combinations have been catered for and all the drawings and process layouts have been put in place. For Production, the method of galley attachment and sealing has been simplified and the variations in galley design have been minimised. The Procurement and Logistics functions have also benefited from the elimination of variation and the production of the Galley Interface Definition Document means suppliers are now better able to understand Avro's needs and requirements. Sales and Marketing now have a clearer understanding of the impact their negotiations regarding galley equipment can have on the rest of the organisation, and the combinations catered for in the Four Corners project will now be used as a clear guide during sales negotiations.

In summary this aspect of the Eng.D. study has made and will continue to make, a significant contribution to Avro's business position, as it has put in place improvements that will achieve savings in the order of £1million per year.

The Four Corners project was not just a practical element of the Eng.D. study. From this activity, conclusions have been drawn and recommendations made in the following areas (see section 7.1 of Chapter 7):

- general recommendations on how the design process can be improved;
- implications of trying to incorporate design changes late in a product's life cycle;

- recommendations on how the customisation activity should be approached on the next generation regional jet.

The next chapter introduces quantitative DFMA tools and describes the investigations carried out to assess the relevance of these tools within the aerospace environment in general, and particularly at Avro.

Chapter 5 Quantitative DFMA Tools

Summary

Several quantitative DFMA tools are available for application in industry. This chapter describes the investigation into the value of these tools in an aerospace environment.

Firstly, a review of the most popular tools is presented: Boothroyd-Dewhurst, Lucas and Hitachi with a description into the mechanics of each being given. The next section describes several case studies highlighting the effectiveness of these tools within various industries.

This is followed by a description of how these tools were investigated at Avro, and, how their potential application was assessed through demonstrations and a pilot study with a key RJ supplier.

BAe Plc.'s Research and Development Centre at Sowerby, is involved with the development of a DFA expert system based on Boothroyd-Dewhurst and Lucas methodologies. A pilot study into its effectiveness was done in collaboration with the Eng.D. study, and an account of this work is also given.

5.1 Popular Quantitative DFMA Tools

The qualitative rules and guidelines which form the background to DFMA were described in Chapter 1. These informal guidelines have been combined with quantitative databases and used as the basis to create systemised methodologies known as DFMA tools. The most publicised DFMA tools are those developed by Boothroyd-Dewhurst, Lucas, and Hitachi.

The DFA and DFM aspects are in fact separate tools.

The DFA tools follow similar methods:

(a) they analyse the assembly operation in detail in terms of ease of handling, insertion and fixing, thus producing assembly difficulty measures;
(b) they produce a 'design efficiency' rating which can be used as a measure for comparison with the other design ideas or with the original design.
Following the analysis, the aim is to focus on the high cost areas and propose ideas for improvement.

The Boothroyd-Dewhurst and Lucas DFA methods have a third aspect. The DFA analysis begins with a procedure which seeks to simplify the product through part count reduction by highlighting opportunities for part elimination or integration.

The DFM tools enable quick cost estimates to be made so the designer can assess alternative materials and processes for the simplified design solution. All three tools are similar in that they evaluate manually input information regarding preferred process, dimensions, tolerances, surface finish etc., and use this to calculate the cost estimates.

5.1.1 Design for Assembly Tools

5.1.1.1 The Boothroyd-Dewhurst Method

It was around 1980 that the term Design for Assembly was coined to describe Boothroyd-

Dewhurst's methodology and databases. Boothroyd-Dewhurst's DFA grew out of collaborative research by the University of Massachusetts, USA and University of Salford, UK and was first introduced in handbook form in 1980. The DFA software implementation was later introduced in 1982.

The first stage in this method is to establish whether the intended assembly system will be manual, high-speed automated (dedicated), or robotic. This selection is based on an analysis of the expected annual production volume, the payback period, the number of parts in the assembly, and, in the software package, on equipment costs. Clearly the higher the equipment costs relative to labour costs, the less viable automation becomes.

The particular DFA evaluation mechanism chosen then depends on which of the three assembly systems is expected to be used. High-speed automated assembly will be centred on an indexing machine or on a free transfer machine and is only appropriate for very high production volumes. Manual assembly is suitable for low volumes. Robotic assembly holds the middle ground.

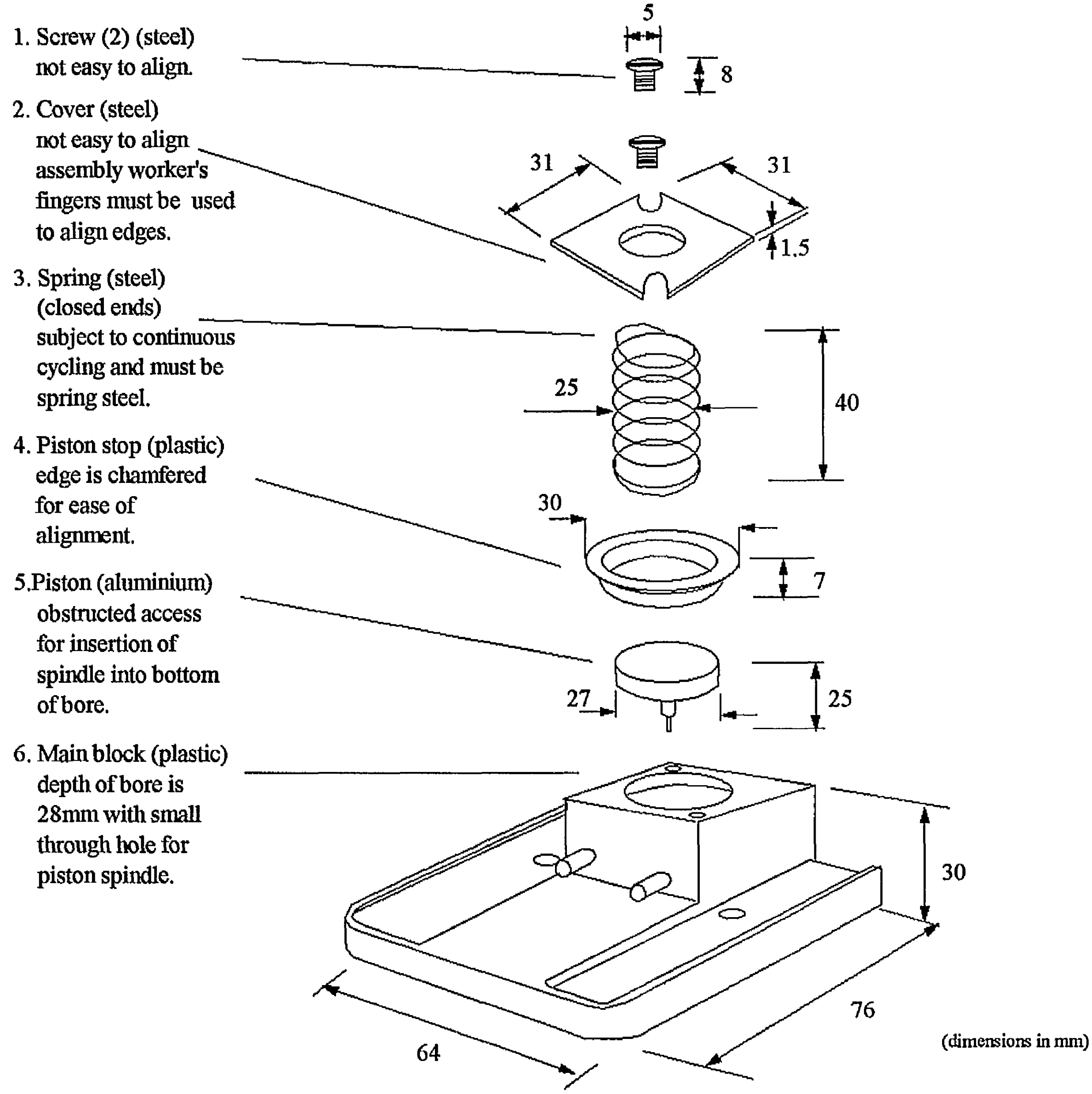
Regardless of whether a design is to be evaluated for manual, high speed automated or robotic assembly, the first means of improving the design for assembly is seen to be the possible reduction in the number of parts of the assembly. The opportunity for this reduction is found by examining each part of the assembly in turn, in order to determine whether that part exists as a separate part for fundamental reasons. If it does not, the aim should be to eliminate the part so as to simplify the assembly and the assembly operations.

Boothroyd suggests that there are only three fundamental reasons for a part to exist:

1. During operation of the product, does the part move relative to all other parts already assembled?
2. Is it necessary for the part to be a different material from or be isolated from all other parts already assembled?
3. Is it necessary for the part to be separate from all other parts already assembled because otherwise necessary assembly or disassembly of other separate parts would be impossible?

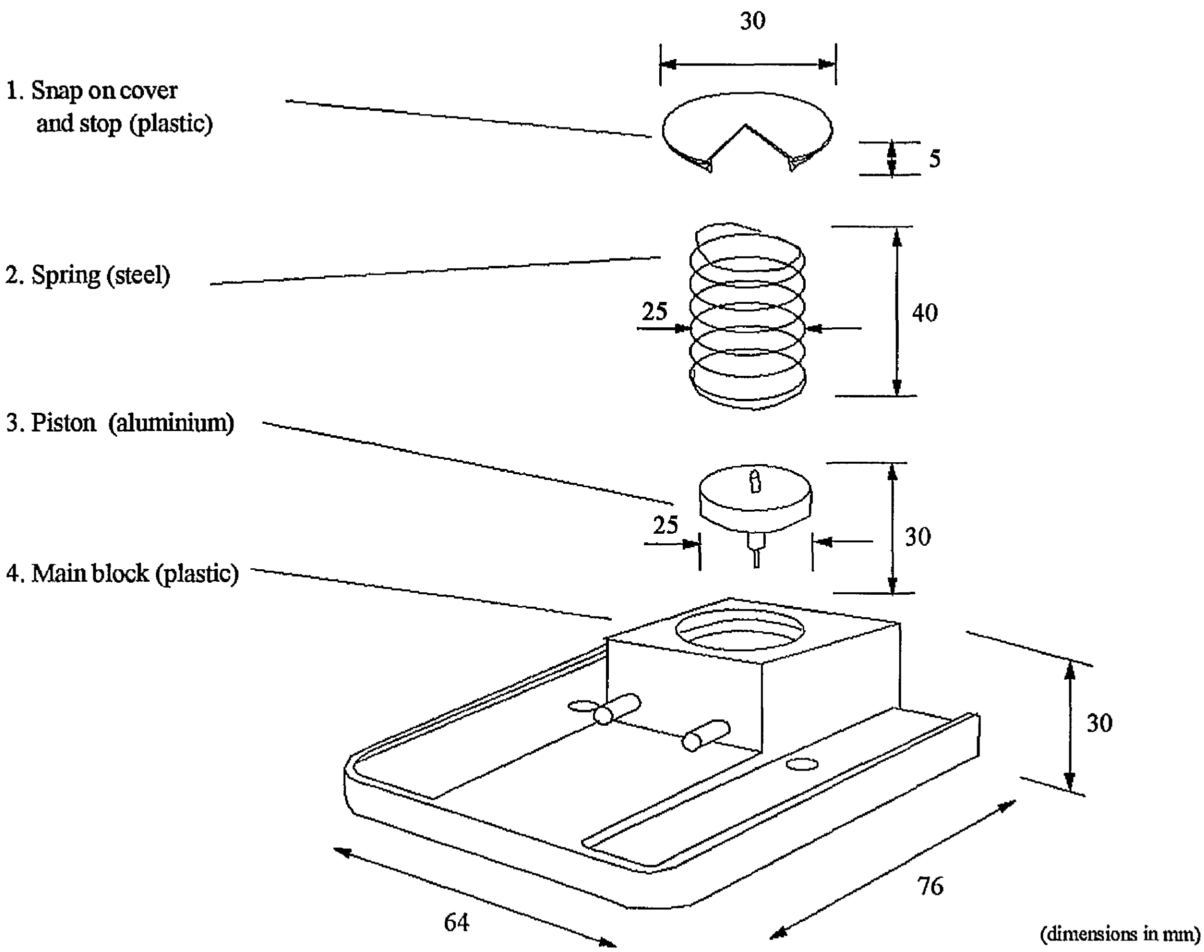
If the existence of a part cannot be justified by at least one of these reasons, it earns a theoretical minimum part value of 0. If the part does exist for a fundamental reason it earns a part value of 1. This information highlights which parts are potential candidates for elimination or combination with another part. This information is also used later in the analysis in establishing the design efficiency of the assembly.

All of Boothroyd-Dewhurst evaluation mechanisms are centred on establishing the cost of handling and inserting component parts, whether this is done manually or by machines. The three DFA evaluation techniques (for manual, high-speed automated and robotic assembly) all depend on the filling in of a worksheet, on which each individual component part of the assembly occupies a row. Figures 5.1 and 5.2 illustrate the Boothroyd-Dewhurst method with an example taken from the Boothroyd-Dewhurst Design for Assembly handbook.



1	2	3	4	5	6	7	8	9	Name of Assembly
Part I.D No.	Number of times the operation is carried out consecutively	Two digit manual handling code	Manual handling time per part	Two digit manual insertion code	Manual insertion time per part	Operation time, seconds (2) x ((4) + (6))	Operation cost,cents 0.4 x (7)	Figure for estimation of theoretical minimum parts	PNEUMATIC PISTON
6	1	30	1.95	00	1.5	3.45	1.38	1	MAIN BLOCK
5	1	10	1.5	10	4.0	5.50	2.20	1	PISTON
4	1	10	1.5	00	1.5	3.00	1.20	1	PISTON STOP
3	1	05	1.84	00	1.5	3.34	1.34	1	SPRING
2	1	23	2.36	08	6.5	8.86	3.54	0	COVER
1	2	11	1.8	39	8.0	16.60	6.64	0	SCREW
						40.75	16.30	4	Design Efficiency = 3 x NM / TM = 0.29
						TM	CM	NM	

Figure 5.1 Example of Boothroyd-Dewhurst Method -- Initial Analysis



1	2	3	4	5	6	7	8	9	Name of Assembly
Part I.D. No.	Number of times the operation is carried out consecutively	Two digit manual handling code	Manual handling time per part	Two digit manual insertion code	Manual insertion time per part	Operation time, seconds (2) x ((4) + (6))	Operation cost, cents 0.4 x (7)	Figure for estimation of theoretical minimum parts	PNEUMATIC PISTON (Re-design)
4	1	30	1.95	00	1.5	3.45	1.38	1	MAIN BLOCK
3	1	10	1.5	00	1.5	3.00	2.20	1	PISTON
2	1	05	1.84	00	1.5	3.34	1.34	1	SPRING
1	1	10	1.5	30	2.0	3.50	1.40	1	COVER AND STOP
						13.29	5.32	4	Design Efficiency = 3 x NM / TM = 0.90
						TM	CM	NM	

Figure 5.2 Example of Boothroyd-Dewhurst Method -- Analysis of the Re-design

Along a row, the handling and inserting tasks are progressively accounted for. For manual assembly the procedure involves identifying a two-digit handling code by answering questions about potential handling difficulties, size, weight and the amount of orientation that is necessary. This code is used to extract a handling time from a chart of synthetic, generalised assembly data built up over years of observation and research by Boothroyd and co-workers. After thus establishing the handling time, the same procedure is applied to the insertion operation. Questions are asked about insertion restrictions concerning access, vision, resistance to insertion, etc. From the two digit insertion code an insertion time is found by referring to a chart of synthetic data. The insertion time includes some allowances for common fastening methods, such as riveting and screwing, when the part being inserted is secured immediately. Additional allowance is made for the situation where the fastening operation is separate from the insertion process. These separate fastening operations would appear in the worksheet as extra insertion times and allow for a greater range of fastening methods, such as welding, soldering, brazing, and the use of adhesives.

The total operation time for that part is then the sum of the handling and insertion times multiplied by the number of occurrences of that part. The operation cost is the time multiplied by the wage rate. The final column represents the theoretical minimum parts, as explained earlier.

The "Design Efficiency" is defined by Boothroyd as the ideal assembly time divided by the estimated assembly time. The ideal assembly time is given by 3NM, where NM represents the total theoretical minimum number of parts and the number 3 expresses the assumption that an ideal component part takes 1.5 seconds to handle and 1.5 seconds to insert, yielding an operation time of 3 seconds. The estimated assembly time is the sum of the operation times for all the component parts.

$$\text{Design Efficiency, EM} = 3 * \text{NM}/\text{TM}$$

Where NM is the theoretical minimum number of parts and TM is the total manual estimated assembly time.

A review of the worksheet will direct the designer's attention to the parts which have relatively high handling and insertion costs. Attention is also drawn to the scope for reducing the number of parts in the assembly by comparing NM with the actual number of parts.

When evaluating a design for manual assembly the assumption is that the equipment costs would be small and would not significantly affect the assembly cost. The opposite is true for assembling with special purpose equipment. A different worksheet is used for automated assembly but the format is similar to that used for manual assembly.

5.1.1.2 The Hitachi Method

The Hitachi Assemblability Evaluation Method or AEM, devised in 1967 is based on the principal of "one motion, one part". For more complicated motions, a point-loss standard is used and the assemblability of the whole product is evaluated by subtracting points lost.

In a 1986 paper by Miyakawa and Ohashi, some details of the AEM were presented. The method endeavours to assess the assemblability of a product design by making use of two indices:

(1) the assemblability evaluation score, E, which is used to assess design quality or the difficulty of assembly operations;
(2) the estimated assembly cost ratio, K, which is used to estimate assembly cost improvements.

The assembly operations relate specifically to the insertion (and fixing) processes. In the Hitachi AEM no direct analysis is available for parts feeding and orientation (handling), it is for this reason that design for automated assembly is not an available option, the argument being that assessment of product design for automated assembly is sensitive to part configuration and is rather difficult to handle precisely at early design stages.

The AEM procedure is illustrated in Figure 5.3.

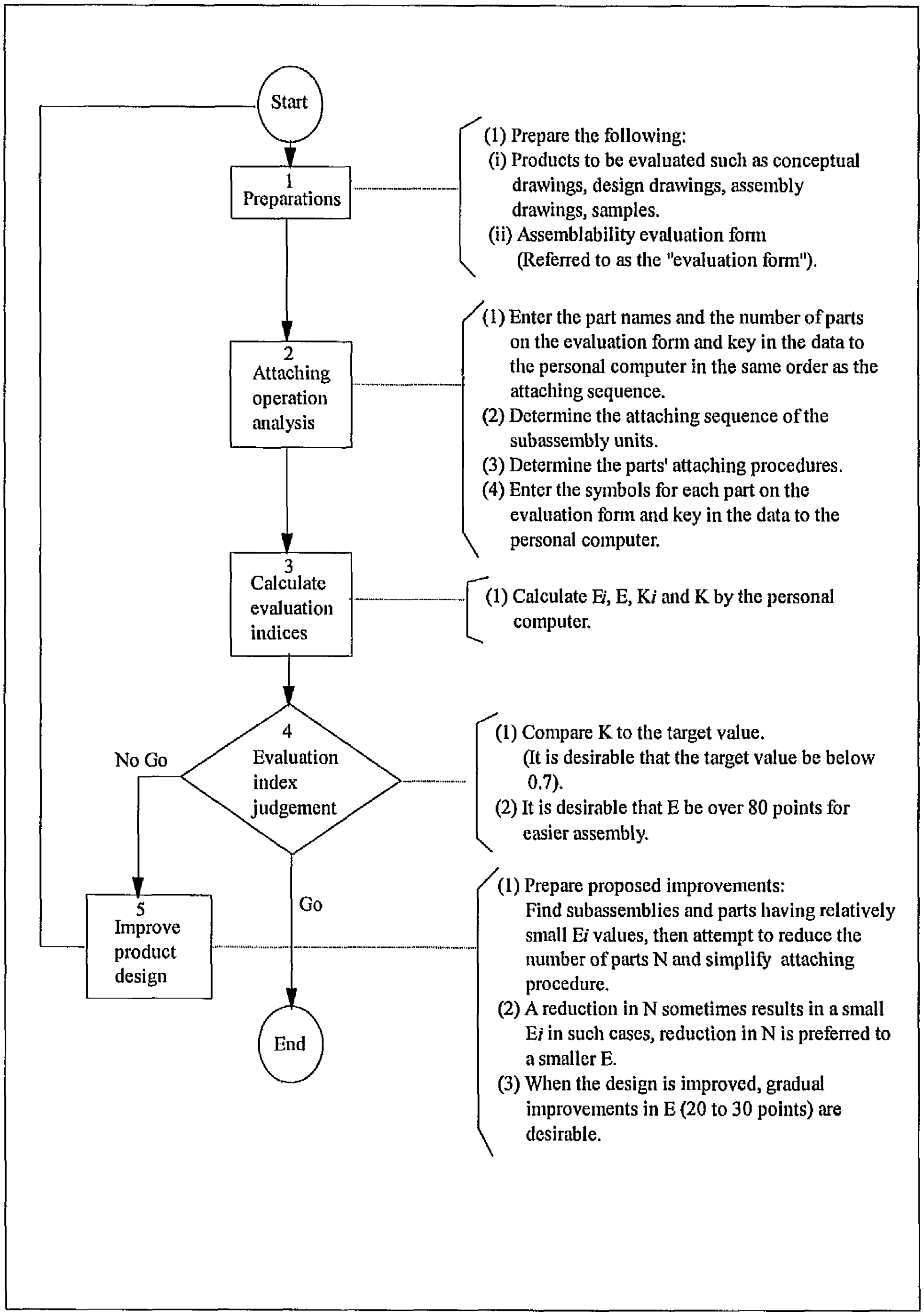


Figure 5.3 Hitachi AEM (Source: NAMRI/SME Technical Paper, 1990)

In Figure 5.3 above, stages 1 and 2 are preparatory to evaluating the indices at stage 3. The procedure consists of first defining motions and operations necessary to insert each part of the product. A simple downward motion is considered to be the fastest and easiest assembly operation for a human or a machine to perform. Penalty points are therefore assigned to every motion or operation that differs from, or is additional to, this simple downward motion. The AEM uses symbols to represent specific motions and processes, collectively termed "operations". There is a set of about 20 symbols, covering such operations as part insertion motions (e.g. straight down, straight horizontal), fixturing (e.g. holding, steadying or securing unstable parts), forming, rotating, and joining.

The evaluation procedure is based on completing a form in the same order as the envisaged assembly sequence. Each row relates to one part. Intersecting columns contain various information relating to that part, such as the part description and symbol(s) that represent specific motions and processes (called "elemental operations") of attaching that part. Each elemental operation is given a penalty score from Hitachi's synthetic assembly data. The basic elemental operation, which is the simple downward motion, has a penalty score of zero. The penalty scores are manipulated to give an assembly value for each part (Ei for part "I"). All the Ei values are then combined with N (the total number of parts) to produce the total assembly evaluation score E. If each of the parts were to be assembled with a simple downward motion only, each Ei would have a value of 100 and the total E would be 100. Thus the score of 100 represents the ideal situation.

The E score may be thought of as assembly design efficiency. Guidance is given that an E score of 80 or more is desirable. The higher the E score the lower the manual assembly costs and the greater the ease of assembly automation. The general advice is that products with an E score greater than 80 can be assembled automatically.

The E score does not, in itself, provide feedback on the advantages to be gained by reducing the number of parts in the assembly. For that, the assembly cost ratio K is used. The cost ratio K can be interpreted as the total assembly operation cost of the new product design divided by the total assembly operation cost of the previous product design. The method for determining assembly costs includes a mechanism for calibrating estimated costs with historical actual costs. This is done by allocating a time (and cost) to the basic elemental operation, the simple downward motion. Calculation of K depends on the earlier calculations for E. The design target suggested is a K value of 0.7 or less. This is a cost saving of 30% or more. This can be achieved by reducing the number of parts in the re-designed assembly and/or making the assembly operations easier. The AEM analysis will help the designer focus on problem areas in the design by making him endeavour to achieve target values of E and K.

In a 1990 paper by Miyakawa et al., a new Assembly Evaluation Method is described where examples of the symbols and penalty scores used are given (see Figure 5.4) together with examples of their application (see Figure 5.5).

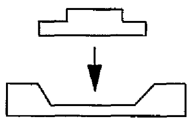
Elemental operation		AEM symbol	Penalty score
	Downward movement		0
	Soldering	S	20

Figure 5.4 Examples of AEM Symbols and Penalty Scores

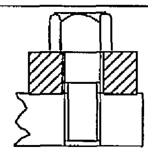
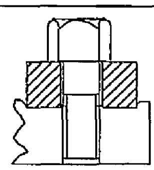
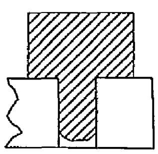
Product structure and assembly operations		Part assemblability evaluation score	Assemblability evaluation score	Assembly cost ratio	Part to be improved
	1. Set chassis	100	73	1	block
	2. Bring down block and hold it to maintain its orientation	50			
	3. Fasten screw	65			
	1. Set chassis	100	88	Approx. 0.8	screw
	2. Bring down block (orientation is maintained by spot-facing)	100			
	3. Fasten screw	65			
	1. Set chassis	100	89	Approx. 0.5	block
	2. Bring down and pressfit block	80			

Figure 5.5 Assemblability Evaluation and Improvement Examples

By 1986 more than 1500 engineers at Hitachi had been trained to use this method and it was claimed that the method was saving tens of millions of dollars annually. Apparently, the Hitachi DFA method is mandatory within the company.

5.1.1.3 The Lucas Method

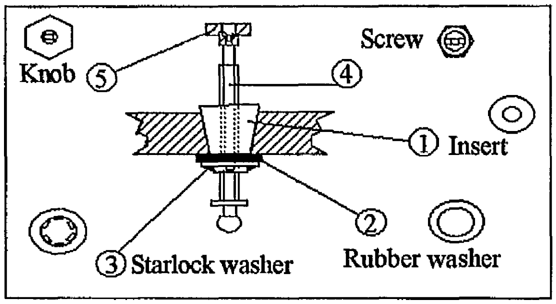
The Lucas DFA method arose out of collaborative work between the Lucas organisation and the University of Hull. The first commercial computer version was launched in October 1989, following a period of successful use of the paper-based version. In 1994 Lucas integrated the DFA method into a suite of Concurrent Engineering tools. They now market the package as the Lucas TeamSET suite. The package includes six proven Concurrent Engineering methodologies:

- Design for Assembly (Lucas DFA);
- Concept Convergence (ConCon);
- Manufacturing Analysis (MA);
- Design to Target Cost (DTC);
- Quality Function Deployment (QFD);
- Failure Modes and Effects Analysis (FMEA).

In the Lucas DFA method the steps are:

- a functional analysis;
- a handling analysis;
- a fitting analysis.

The DFA method is based on an Assembly Sequence Flowchart ("ASF"). Figures 5.6, 5.7 & 5.8 illustrate the Lucas method with an example taken from the Lucas DFMA Practitioners Manual. The method involves assigning and summing penalty factors associated with potential design problems in a way reminiscent of Hitachi but the Lucas method includes an assessment for handling (or feeding) as well as for inserting (or fitting). The penalty factors are manipulated into three assemblability indices: "design efficiency", "feeding ratio", and "fitting ratio". These indices are compared to thresholds or values established for previous designs. The feeding and fitting analyses are preceded by a functional analysis, described below, and all the information is entered on the ASF.



Component Description	Component Number	Functional Analysis	Manufacturing Analysis	Feeding Analysis	Feeding Technology
Insert	1	A	1.09	2.4	MT
Rubber Washer	2	B	0.92	8	M
Starlock Washer	3	B	0.86	1.3	MT
Screw	4	A	3.43	3	LT
Knob	5	B	1.57	1.9	MT

Totals	5	2	7.87	16.6

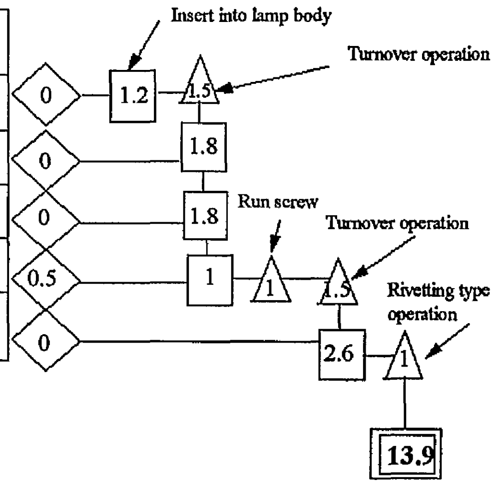
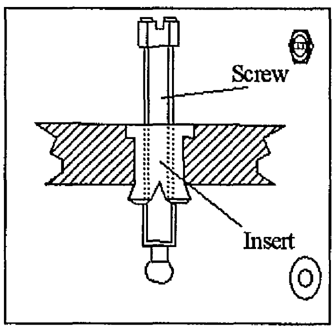


Figure 5.6 Original Headlight Screw



Component Description	Component Number	Functional Analysis	Manufacturing Analysis	Feedng Analysis	Feeding Technology
Insert	1	A	1.03	1.5	MT
Screw	4	A	3.74	3	LT

Totals	2	2	4.77	4.5

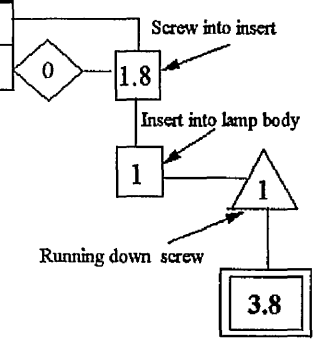


Figure 5.7 Re-Designed Headlight Screw

	Before	After
Total Parts Count	5	2
Design Efficiency	40%	100%
Total Manufacturing Analysis	7.9	4.8
Total Feeding Index	16.6	4.5
Feeding Ratio	8.3	2.3
Total Fitting Index Ratio	13.9	3.8
Fitting Ratio	7	1.9

Figure 5.8 Results Summary

The ASF comprises a component description in the first column, followed by columns containing the component number, a functional analysis and a feeding analysis. The fitting analysis, representing the assembly sequence, is built up elsewhere on the form using various symbols for various assembly operations.

The functional analysis addresses each component in turn and establishes whether it exists for fundamental reasons. Each component is found to be either an essential part – an "A" part (demanded by the design specification) – or a non-essential "B" part (required by that particular design solution). These values are entered on the ASF. The design efficiency is then defined as: essential parts divided by all parts, (A/(A+B)). Essential and non-essential parts are categorised in a way analogous to the Boothroyd-Dewhurst method (i.e. using the 'three criteria').

The objective is to exceed an arbitrary 60% target value by elimination of category B parts through re-design.

The feeding (or handling) analysis consists of answering questions about each component, in order to determine a feeding (or handling) index. The minimum feeding index is 1. The suggested threshold is 1.5, which means that if a component attracts a feeding index greater than 1.5, the designer's attention is drawn to the desirability of improving the component design in respect of feeding it. A very high feeding index is sometimes due to a combination of penalty features. The component may, for example, be abrasive and have a tendency to nest.

After completing the feeding (or handling) analysis, the user will carry out a fitting analysis. This is used to determine values for every possible operation during assembly. These values are entered on the ASF. Fitting indices have a suggested threshold of 1.5, apart from the gripping index, which has a threshold of 0. Any operation or process with value above these thresholds will suggest to the designer that he should seek improvements. Alternatively, the overall results could be assessed by perusing the design efficiency, the feeding ratio and the fitting ratio, where:

Feeding ratio = feeding index total/number of essential components (Threshold 2.5)
Fitting ratio = fitting index total/number of essential components (Threshold 2.5)

These measures of performance can be used to indicate the product state of health with regard to assembling. The feeding ratio threshold of 2.5 happens to be numerically equal to all feeding indices at 1.5 (the threshold) for a design efficiency of 60 per cent (the threshold). Having the fitting ratio threshold at 2.5 implies that the average fitting index should be below 1.5.

5.1.1.4 A Critique of the DFA Tools

Leaney and Wittenberg (1992) make several observations regarding the mechanics of the methods:

- all three DFA evaluation methods described above are supported by computer software packages. The advantage of the computer version is that it aids the evaluation procedure by prompting the user, providing help screens in context, and by conveniently documenting the analysis. The user can quickly assess the effect of a proposed design change by editing a current analysis. However, while a computer version is excellent in "what if" and "ongoing" studies it is generally recommended to use the paper-based method in pilot studies and in early training. Using the paper-based version in early stages of adopting DFA improves the user's understanding of the technique. The Boothroyd software program provides an extensive range of analysis output and report formats for the user. This allows the freedom to present results in a number of ways, which can be useful but requires some discipline by the user in document management;
- the Hitachi method centres on insertion operations for components and does not explicitly deal with automation. The Boothroyd method centres on handling and insertion of components, with detailed consideration being given to automation. The Lucas method adopts aspects of both Hitachi and Boothroyd by dealing with handling and insertion with some consideration of automation and some emphasis on fitting (insertion) processes;
- it is often believed that the Hitachi and the Lucas methods give a better process view of

the assembly sequence and insertion operations as each fitting process is clearly documented (flowcharts). Boothroyd tends to have a more component-oriented view. Although the handling and insertion processes are considered in detail by Boothroyd they are embodied, and lost, in the digit coding which appears on the worksheets. Nevertheless the Boothroyd software does retain all the information posted and this can be presented in other output formats;

- the design efficiency of the Lucas method is based solely on the scope for reducing the number of parts in the product design. The design efficiency of the Boothroyd method reflects the scope for improving the handling and insertion (manual) processes. The Hitachi E score (referred to here as a design efficiency) measures the efficiency of the insertion processes only. To dispose of this limitation the General Electric Company in the USA introduced a modification by adding the Boothroyd criteria for minimum parts count when they adopted the Hitachi AEM in the early 1980s. The modified procedure was referred to as the GE/Hitachi method.

Eversheim and Baumann (91) when referring to the Boothroyd-Dewhurst method state that this conventional method can only be implemented by experienced designers, and the required work input is high. However, the essential advantage lies in the fact that the handling, joining and geometry features can be determined independently of one another. This means that assembly-specific weak points can be located easily.

Molloy et al. (91) suggest that most of the currently available DFA techniques are lacking in the following respects:

- the DFA system does not analyse the design directly, but relies on the designer to correctly reply to questions concerning the design and it's components;
- the actual analysis carried out on the product design does not reflect all manufacturing concerns of the user, thus achieving a low level of integration into the design and manufacturing functions of the company;
- the result of the analysis does not offer design recommendations – performing the DFA analysis provides useful information for the design engineer. It highlights which parts in the assembly are possible candidates for elimination or combination and which parts are

generating the highest assembly times. These techniques lead the design engineer to the areas where there is obvious room for improvement. It is then up to the design engineer to come up with these improvements. The techniques simply highlight the areas for improvement they do not come up with re-design solutions;

- the result is no mechanism for incremental capture of manufacturing rules and decisions.

Kroll et al. (88) state that the Boothroyd-Dewhurst method requires specific information like the expected production volume and rate, the cost of assembly hardware, and symmetry properties of the parts. It involves quite a tedious and time consuming process of completing standard worksheets based on several coding charts and formulas. Its main drawbacks, however, are the very implicit way of pointing the direction to design improvements, and even more fundamental its ability to treat products at a higher level than individual parts. As a result, configuration design can only take place by elimination or integration into parts, whilst the separation into parts and sub-assemblies remain unchanged.

Ulrich et al. (93) put forward the argument that since the DFA methodology encourages the combination and physical integration of all parts that, in theory, do not have to be physically distinct, this tends to lead to geometrically complex parts which typically require tooling with large lead times. They have developed a model that makes explicit the trade-off between lower unit costs and longer product development time.

5.1.2 Design for Manufacture Tools

In order to judge the effects of DFA (i.e. simplification of the product structure and reduction in the number of parts), companion methods for estimating part costs must be available. Many of those who have developed DFA methods have also turned their attention to methods of assessment of part manufacturing costs.

5.1.2.1 Boothroyd-Dewhurst DFM Method

In the Boothroyd-Dewhurst DFMA method, once the product structure has been simplified using the DFA technique, the manufacturing cost is then assessed using the DFM modules. This analysis allows engineers to accurately anticipate costs early in the design process, when only rough geometry is available on the product. DFM changes cost estimating from a 'black art' into a reliable and systematic procedure. Few design engineers have detailed knowledge of all the major shape-forming processes and, consequently they tend to design for the ones with which they are comfortable. The purpose of DFM cost estimating analysis is to enable design teams to weigh alternative designs and various production processes and make the necessary trade-off decisions between parts consolidation and material/manufacturing costs. The DFM series was developed to enable designers to review evolving designs for cost efficiency by providing a means for quickly simulating the use of alternate materials and comparing various shape forming processes.

The DFM modules walk the user through the analysis process step by step. They ask straight forward questions, offer fill-in-the-blank screens and consider issues of materials, process, tooling, volumes, machine costs etc. On the final screen they give total part cost based on all the parameters that have been input. Similarly, if the operator changes any of the values to compare the same part using a different material or process, they re-calculate costs instantly.

The DFM modules create an in-house system of expertise that can help predict the cost impact of many different materials and processes. (Kobe 92). The DFM modules cover: machining, sheet metal work, die casting, injection moulding and powder metal parts as separate software packages.

5.1.2.2 Lucas Manufacturing Analysis Method

Similarly, after the Lucas DFA technique there follows a Manufacturing Analysis (MA) technique. The MA is logically based on material usage and processing considerations. The processing cost is determined using a basic processing cost P_c and a design dependent relative cost R_c. Material costs are calculated on the basis of volume, taking into account the material wasted in achieving the final form.

The Manufacturing Cost Index, Mi, is given by:

$$Mi = Rc \times Pc + Mc$$

Mi =	Rc = Relative Cost	X	Pc = Ideal Process Cost	+	Mc - Material Cost
	Cc = Shape Complexity Cmp = Material Suitability Cs= Minimum Section Ct = Tolerance Requirement Cf = Surface Requirement		Pc = Basic Processing Cost (Ideal Design)		V = Volume of Material Wc = Waste Coefficient Cmt = Cost of Material
	Rc = Cc x Cmp x Cs x Ctf		Pc		Mc = V x Cmt x Wc

- Rc is the basic processing cost which compares the actual design to that of the ideal. Therefore, a simple design ideally suited for a particular process gives Rc=1.
- Pc is the basic processing cost per annum for an ideal design using a particular process.
- Mc is the cost of the total material used to produce the component.

Values for Rc, Pc and Mc are obtained from a series of tables.

5.1.2.3 Hitachi's Machining-Producibility Method

The purpose of Machining-Producibility Evaluation Method (MEM) is to facilitate design improvement relative to processing (cutting (turning) and grinding, sheet metal working, welding, moulding, die casting, and casting, etc.) at the earliest possible stage. This is accomplished by calculating the estimated processing cost index (MEM cost index:K) and evaluating the machining-producibility evaluation score (MEM score:E) based on conceptual or design drawings, samples etc. Based on the evaluation, the design is judged with regard to ease of processing, problem points are found, design improvement guidelines are indicated, and the effect of design changes are quantitatively evaluated. The concepts and basic calculation formulae are intended to parallel AEM. (Arimoto et al 93)

MEM has been effectively used in the Hitachi Group and other companies.

5.1.2.4 A Critique of the DFM Tools

With regard to the DFM tools described above, the following points can be made:

- the Boothroyd Dewhurst DFM database can be tailored to suit specific industries, i.e. cost information on processes peculiar to an industry can be added to the database;
- the tools are primarily concerned with cost estimation as opposed to making detailed recommendations on how a component should be designed to suit a given manufacturing process. The designer would still, therefore, have to have a reasonable level of manufacturing process knowledge, to understand where the costly aspects of the design lie;
- as with the DFA tools, the DFM tools provide measures 'after' the design solution has been created rather than interactively during its creation. The measures are not absolute values they should be used for comparison purposes only (except for in the case of tools whose database can be tailored to suit the processes specific to the company).

5.1.3 Industrial Case Studies

The Boothroyd-Dewhurst DFMA tools are being used by approximately 400 companies worldwide (Constance (92)). There are many published case studies describing the success of this method within industry:

1. Lockheed Martin Electronics & Missiles

Located in Orlando Florida, Lockheed Martin's Electronics & Missiles company develops, manufactures and supports advanced combat systems. They claim to have applied DFMA extensively across many programs. Implementations started with DFMA workshops facilitated by external consultants. As the value of the process was recognised, the company transitioned to internally-facilitated workshops, both in-house and at suppliers. DFMA practices, in lieu of stand-alone workshops, are now integrated into the daily life of new development programs. The company has completed more than 60 evaluations across 17 programs, giving special attention to key suppliers. They estimate a saving of 20 to 30 % in production costs when the DFMA re-designs are implemented. This will translate to millions of dollars of savings to their customers. (Davidoff (95)).

2. Ingersoll Rand

At Ingersoll Rand, DFMA software was introduced in 1989. Examples of its success are:

- on a control and instrument panel assembly the number of parts was reduced by 33%, the number of fasteners used fell by 38%, assembly operations decreased by 33%, and assembly time improved by 28% (Constance 92);
- on an oil cooler and radiator assembly the number of parts was reduced by 64%, the number of fasteners fell by 47%, and assembly time improved by 65%. (Gerhardt 90).

3. Delco Chassis Div. General Motors Corporation

DCD have been using DFMA tools for many years. One of their more recent successes came with the design of the fourth generation 1993 Camaro/Firebird. This re-design involved a major chassis change that included a short-long-arm front suspension and the opportunity to adopt a new wheel bearing. Before DFMA analysis, the wheel brake assembly was to be manufactured on what is called a non-synchronous, palletised-assembly machine. In the assembly process, each bolt would have been driven and the bearing flange rotated by separate, sequential stations. A further complicating matter was that one bolt was longer than the others and required a nut. After DFMA analysis, engineers decided to build the assembly upside down. This permits using four identical bolts and driving them simultaneously. The process eliminates the nut, and the assembly does not move down a line; instead, parts come to the assembly, with few fasteners and little orienting. (Green & Reder 93).

4. Minnesota Mining and Manufacturing Co. (3M)

Minnesota Mining and Manufacturing Co. (3M) in St. Paul Minnesota uses DFMA to move new products to market in half the time it took before it implemented the system in 1989. The Hard Goods Group has used DFMA to make overhead projectors and laser imagers used in medical imaging. (Constance (92)).

5. Storage Tek Corporation

In 1988 Storage Technology Corporation (Louisville, Colo.), manufacturers of tape and disk peripheral computer equipment, implemented a 'quality-of-design' program. After visiting the Ford facility to see the technique in action, about 1400 Storage Tek employees were trained during 1989 and 1990. (Constance (92)). The company has streamlined components from about 90 parts down to 36 parts. Storage Tek is now implementing DFMA on all of its products (approximately 40 in total).

6. Allied Signal

A division of Allied Signal Aerospace Co. reports that it slashed development time on a new product by 70% and cut its part count by 73%. (Dvorak (92)).

7. NCR Corporation

At NCR Corporation's engineering and manufacturing facility in San Diego, DFMA was used on the fourth generation of its 9800 on-line transaction processing and real-time computing system. These products are used by banks in their automated cash machines. The results were: 99% of all assembly labels were removed, the number of operation assembly sheets was reduced by 20%, no assembly errors occurring on the first 10 units, there was a 66% reduction in continuing engineering efforts after product release. (Constance (92)).

8. Motorola Inc.

Motorola Inc.'s Manufacturing Division, Plantation, Florida, intrigued by success stories such as Ford's, decided to test the DFMA waters. It chose the DFMA methodology and software of Boothroyd-Dewhurst, to improve on the design of an older model battery charger for its Radius portable-radio line. Their re-design reduced the assembly time by 94%, decreased the number of parts by 85%, used no fasteners and reduced the material costs by 50%. (Welter (90)).

9. Precor USA Inc.

At Precor USA Inc., a maker of aerobic exercise equipment based in Bothell, Washington, DFMA is being applied to about a dozen products. DFMA has enabled Precor to reduce the number of fastener types by 54% and total fabrication and assembly time by 36% on one product. On another product, the number of fastener types was reduced by 75% and total fabrication and assembly time was cut by 27%. (Constance (92)).

10. Fibrecraft/DESCon Inc.

With DFMA, Fibrecraft/DESCon Inc. in Rochester, Michigan, was able to eliminate about 120 parts and 109 fasteners in the instrument panel for the Oldsmobile line. (Constance (92)).

11. Ford Motor Company

Ford reportedly took $1billion out of the development costs of its Taurus/Sable program using Concurrent Engineering and DFMA.

12. General Motors Corp.

General Motors Corp.'s Cadillac Brougham found benefits with DFMA: ready for assembly parts were reduced by 37% from 3244 to 2083; one door pad on all units replaced four different types, fewer pieces in the door pad also simplified installation; a new hood and fender design eliminated a front-end pad, and consolidated hood and grille into one element; the weight of the instrument panel was cut in half. (Winter (92)).

13. McDonnell Douglas Aerospace

McDonnell Douglas Aerospace are implementing DFMA on an number of their aircraft programs, for example, F-15, F-18E/F, MD-11, and MD-90. Reported successes include: nose landing gear wheel door, part count reduction 73 down to 6, fasteners 400 down to 191; ram air door, part count reduction 2,172 down to 1,383; bulk-head, parts count reduction 62%, assembly/fabrication hours reduced by 53%.

5.2 Recent Developments in the Field of DFMA Tools

5.2.1 Developments to the Hitachi and Boothroyd-Dewhurst Tools

Hitachi are planning to combine their AEM and MEM for an overall evaluation tool.

Recent developments with Boothroyd-Dewhurst:

- a Design for Service (Disassembly) tool has been recently introduced and new databases for the design for assembly of large products have been developed (Boothroyd and Fairfield 91);
- a recently expanded extension of the Boothroyd-Dewhurst method allows the assembly cost of printed circuit boards (PCBs) or of products containing PCBs to be evaluated; this facility is not available in other methods;
- the DFMA tools have been linked to a CAD system (ProEngineer) so that the initial, mundane, analysis work regarding the geometry of the parts can be extracted directly from the CAD database.

5.2.2 Related Research Activities

There are many research programmes currently looking at how DFA analysis can be linked direct to CAD databases and also looking at developing expert systems for DFA and DFM:

Molloy et al. (88)

Molloy et al. (88) are studying the auto-generation of disassembly sequences and the linking of these with computer-aided process planning tools.

Eversheim and Baumann (91)

Eversheim and Baumann (91) explain how the DFMA methodology could be included in a CAD system and describe a computer supported program that makes it possible for the first time to take assembly specific aspects into account systematically during the whole design process.

Kroll et al. (88)

Kroll et al. (88) present a knowledge-based computer system to assist engineers in the process of designing products for easier assembly. The emphasis is on the conceptual design team on how to optimise the product design as a means of overcoming the shortcomings of the Boothroyd-Dewhurst method.

Much research is being conducted into the development of DFM systems to try and overcome the problem of lack of expert manufacturing process knowledge in the design process. Systems have been developed which can evaluate a design in terms of its manufacturability, and in some cases make recommendations for re-design.

Poli et al. (93)

Poli et al. (93) have developed a *Design for Stamping* knowledge based system. It highlights those manufacturing-related features that significantly increase the die (tooling) construction costs so that designers can minimise difficult-to-produce features.

Delbressine and Hijink (91)

Delbressine and Hijink (91) have developed a methodology which takes manufacturing restrictions into account for *milling* operations.

Corbett and Woodward (91)

Corbett and Woodward (91) have developed a CAD-integrated, knowledge based system for the design of die case components.

Abdalla and Knight (94)

Abdalla and Knight (94) have developed a prototype system which links a knowledge based system shell with a solid modelling system and allows the user to create a set of design features. The system captures topological and geometrical information about the model features and estimates the machining cost for these features at each design stage. It then recommends how to improve the design and eliminate potential defects.

Shankar and Jansson (93)

Shankar and Jansson (93) have developed a generalised methodology for evaluating manufacturability. The methodology acts as an aid in identifying the critical parameters which affect manufacturability in any design, i.e. complexity, quality, compatibility, efficiency and coupling. Further, the methodology yields quantitative metrics which can be used to evaluate and compare designs.

Most work related to DFM has been focused on producibility, the analysis part of the design work (i.e. looking to see if the part is designed to suit the chosen manufacturing process, or performing cost estimations). Not much work has been done on the early selection of processes and materials. Torben (96) has developed a tool called the 'Designers Manufacturing Inspirator' which is a multimedia based database, which *inspires* the designer to consider materials and manufacturing process alternatives.

5.3 Trial of Tools at Avro

During the course of the Eng.D. research into DFMA tools, several pilot studies with various partners were carried out. These investigative pilot studies have exposed the benefits and limitations of the DFMA tools. From these studies it was possible to form an opinion on the usefulness of such in the aerospace industry in general, and on whether these tools are suitable to the type of business activity to which Avro is now geared.

The partners involved in these studies were: BAe Sowerby, BAe Filton, Westland Industrial Products Ltd and Lucas.

The following sections will give a brief description of the work done in the pilot studies. The conclusions and recommendations resulting from these investigations will be presented in section 7.2 of Chapter 7.

5.3.1 Boothroyd-Dewhurst DFMA Software Demonstrations

As part of the Eng.D. investigation, several demonstrations of the Boothroyd-Dewhurst

DFMA software were arranged at Avro. Personnel from Design, Engineering, Production and Estimating attended. These demonstrations were the first introduction to DFMA tools at Avro, and they were received with much enthusiasm.

5.3.2 Avro/Westland Pilot Study

The purpose of this study was to trial the Lucas DFA method.

As part of Avro's company wide break-even initiative, BPIP, (introduced in section 3.2.4.1 of Chapter 3), Avro's Procurement department are running a comprehensive cost reduction program called the Cost Management Journey. This program is based on a three tiered approach:

Step 1. Improving the supplier's business/commercial set up;
Step 2. Improving the efficiency of the supplier's production process;
Step 3. Re-design of the actual sub-assembly;

In July 1995 an exercise with Westland Industrial Products Limited was instigated in support of step 3 of this cost reduction program. Westland supply the RJ passenger and service doors, and it was felt that cost reductions should be sought through re-design.

The exercise was concerned with investigating design changes that could be made in order to facilitate both easier manufacture and assembly of the RJ doors. This exercise was not going to be the usual customer/supplier workshop activity, to come up with ideas for design improvements; Westland requested that the exercise be carried out using Lucas's DFA tool.

This was the first time a DFA tool had been piloted within Avro, on a topical activity with a group of engineers and designers. It was, therefore, an excellent opportunity to assess the tool's potential in the aerospace environment. The exercise had full management backing both from Westland and Avro and subsequently had a high profile within the company. See Appendix 9 for a company newspaper report outlining the project, along with a photograph of the team members.

The initial re-design analysis phase lasted two weeks. The team consisted of Design, Estimating, Engineering and Procurement personnel from Avro, and Estimating, and Production personnel from Westland. Prior to the study, none of the team members had used the DFA tool. Therefore, the initial task was to give them familiarisation into its mechanics; this was done using a facilitator from Lucas.

The team was then split into three groups, analysing the door's structure, mechanisms, and central control box. Each team then used the software package to assess their part of the door; 47 design improvement proposals were generated in total.

Of these 47 proposals only 21 were deemed feasible. The others were seen to be unacceptable from either a functionality/reliability, stress/safety or weight point of view. Of these 21 proposals, 12 are currently being progressed through the company's Production Easement Proposal (PEP) system. Table 5.1 summarises the design proposals. Savings amounting to £7,558 per aircraft set were achieved and 107 parts were eliminated.

	Proposals	Description	Cost Saving	Part Count Reduction
1	Alternative material on side edge	Suggestion that a cheaper material be used for the forgings which make the door edge members.	6000	N/A
2	Alternative supplier of seals	An alternative (known) supplier of door seals would lead to cost savings and improvements in the procurement procedure.	320	N/A
3	Add features to side edges	Incorporation of the two hinge stop brackets and blade mounting bracket within the machining process of the side edge members.	168	15
4	Shoot bolt change	Removal of the requirement to hard chrome plate the shoot bolts	176	N/A
5	Pulley bracket change	Re-design the six complicated pulley mounting brackets using simple bent angles, manufactured to accommodate the alignment required during assembly.	271	156-96
6	Delete holes in handle	Omit three holes on locking point of the door handle, this will reduce the machining time on jig boring.	30	N/A
7	Access holes sealing	Use alternative method for sealing the access holes. Use self adhesive blanking discs instead.	80	N/A
8	Control box lever modification	Combine control box lever with track and guide plate	81	7-1
9	Staking of bearings	Use the staking method to secure bearings into position. This will eliminate the requirement of the retaining bush and also Loctite.	86	22
10	Machine pockets in rod	Machine extra pockets into the rod assembly to achieve weight saving.	45	N/A
11	Pulley Support bracket change	Use one piece top hat sections for pulley support brackets.	42	6-2
12	Alternative rose bearing	Use an alternative type of bearing.	259	N/A

Table 5.1 Design Proposals and Savings to Avro

The cost savings indicated above are the obvious cost savings i.e. labour, materials and machining time. The 'hidden' costs associated with part count reduction though difficult to quantify, are nevertheless substantial and should be remembered.

5.3.2.1 Assessment of the Lucas Tool

At the end of the two week study, the consensus of opinion throughout the team was that:

- the functional, handling, and fitting analysis was straight forward enough to follow;
- the flowchart was difficult to prepare because the team members were not completely familiar with the door assembly sequence. It was difficult to derive any significant benefit from preparing the actual flowchart, this process is time consuming and seemingly does little more than offer a pictorial representation of the sequence;
- the magnitude of the handling and fitting time measures i.e. seconds, are of little relevance in the analysis of an assembly of this type, i.e. when the volume and rate at which they are produced are taken into consideration (18 sets of doors produced per year);
- similarly, some of the questions asked during the handling and fitting analysis were of little relevance, for example, does the part get tangled?, is the end to end orientation easy to see?, is there resistance to motion?, does the part have to be screwed etc.?, trying to shave *seconds* of the assembly time seems to be inappropriate here;
- the most valuable aspect of the exercise was using the part count reduction criteria to stimulate ideas for re-design, rather than the detailed analysis of the assembly sequence. The tool stimulated communication of ideas throughout the teams and seemingly removed the customer/supplier barriers;
- a lot of design expert input was needed after the analysis, in order to clarify whether the design change proposals were in fact feasible, from functional and safety points of view. The door mechanisms and control box are functionally complicated, and the designers in the team were not door specialists, therefore they could not make the decisions;
- the design proposals were not just part count reductions they also included, using different materials, eliminating manufacturing treatment processes and simplifying

sealing methods.

The Avro/Westland pilot study made a contribution in three areas:

- it generated several cost saving ideas which are being pursued for the RJ doors. These ideas were varied, they were not all focused on part count reduction;
- it gave an insight into the usefulness of the Lucas DFMA tool;
- it revealed that there was little standardisation between the four door designs; a valuable lesson for the next aircraft development.

5.3.3 Avro/BAe Sowerby Pilot Study

BAe Sowerby Research Centre, Bristol, is the central Research and Development Organisation for British Aerospace Plc. BAe Sowerby have a research interest in DFMA tools and have developed a DFA expert system based on the Boothroyd-Dewhurst and Lucas methodologies.

BAe Sowerby claimed that their system was able to overcome one of the deficiencies of the Boothroyd-Dewhurst and Lucas methods, i.e. the inability to make explicit recommendations for re-design solutions. Instead of just highlighting which parts were potential candidates for elimination, the BAe Sowerby system could actually suggest how these parts may be merged/combined with other parts i.e. it made recommendations on how a practical re-designed solution could be reached by specifying which parts to merge, keep separate and remove.

BAe Sowerby had already carried out several pilot studies with British Aerospace Space Systems Division at Plymouth and with Rover cars. These pilot studies had demonstrated that the expert system could indeed be used to analyse simple electromechanical assemblies, for example, a car pedal box from Rover, and a gyro from British Aerospace, and reach useful re-design solutions for such assemblies. In an attempt to test the system further, a pilot study was done in collaboration with the Eng.D. study.

5.3.3.1 BAe Sowerby's DFA Expert System

The following description outlining BAe Sowerby's DFA expert system is taken from Puzey 96.

The system uses an expert system shell called MOBAL (Model Based Learning) developed by GMD (Bonn, Germany). MOBAL is described as "a system for developing, validating, and maintaining operational models of application domains". In the present case it was employed to develop a domain model for re-design using Lucas DFA parameters.

By using MOBAL's "knowledge acquisition environment", a user can incrementally develop a model of an application domain in terms of logical facts and rules.

The present study was able to make use of a rule scheme for carrying out a DFA analysis using Lucas DFA input facts. The input facts for constructing a model of the DFA domain are like those described in section 5.1.1.3 i.e.:

- how many parts are there in the assembly over all?;
- what part is inserted on to what other part or parts?;
- what are the numeric values of the handling, fitting and non-assembly indices for each part?;
- is the part an essential, A part, or a non-essential, B part?

Rules were provided to manipulate these facts, and assess the relative cost of each part in the assembly. There was an underlying rule in the rule scheme, that all A parts were to be kept in any re-design proposals that were generated when running the domain model. B parts could be candidates for removal or merging with other parts.

The model was developed by adding rules that calculated the maximum handling, fitting and non-assembly indices, using data from all the parts in the assembly. The indices for each part were then divided by these maximum values to assign a relative weighting factor for each of the three assembly parameters.

These three initial weighting factors were then summed to produce a total weight factor associated with each part in the assembly. Facts relating to the assembly sequence were then taken account of in the rules. This produced knowledge regarding 'associate parts'. This new knowledge was then combined with the knowledge about total weight factors for the two parts in a rule which created a 'merge factor' parameter.

Rules for formulating a re-design plan were then simply generated by comparing these merge factors for different pairs of parts in turn to some user-defined threshold. Apart from recommending the merging of associate part pairs, the rule scheme could suggest that pairs of parts be removed, or kept in a re-design scheme, or single parts (where no associate parts had been identified) could be kept, merged with some unspecified other part or parts, or removed.

5.3.3.2 Trial with Sample of RJ Structural Design

The design sample supplied by Avro for use in this study was that of an attendant's seat underfloor support structure (see Figure 5.9).

The expert system recommended that several of the items should be removed and some of the remaining items merged. The re-design solution is not in pictorial form; it is provided by means of a list, describing which parts to keep, to merge and to remove.

Summary of results:
Initial design efficiency – 40.62%
New design efficiency – 100%
Parts Count Reduction – 84.37%

The results of this pilot study were cited in Puzey (96).

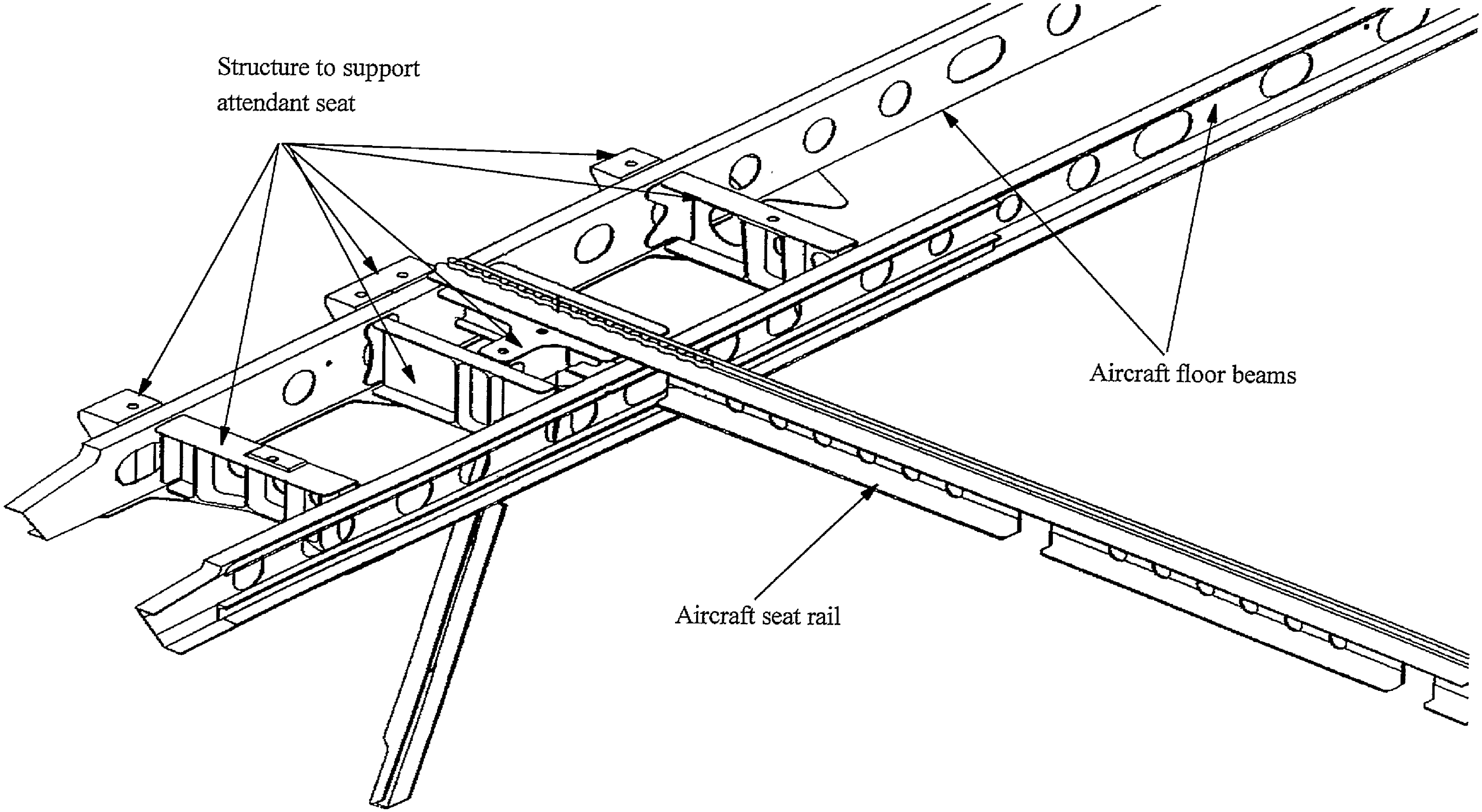


Figure 5.9 Design Sample Used in Sowerby Study - Attendant's Seat Underfloor Support Structure

5.3.3.3 Further Development at BAe Sowerby

The next phase in the research activity into DFMA at BAe Sowerby was to link up the KBS to algorithms that will automatically compute all the DFA parameters from the information in the CAD database. The aim is for a generic system independent of any particular CAD system.

5.3.3.4 Assessment of Avro/BAe Sowerby Pilot Study

The pilot study showed that the sample structure could undergo significant part count reduction, through merging several of the parts. Unfortunately, there are significant implications in merging pieces of aircraft structure. Factors such as crack propagation boundaries and accuracy of tooling play a key role in this example. The Lucas criteria (which is effectively the Boothroyd-Dewhurst criteria) for assessing if a part is essential or non-essential, and ultimately, if it can be merged with another part, does not take into account these peculiarities of aerospace design.

With hindsight the selection of a sample of aircraft structure was not an ideal example to trial this system; an electromechanical sub-assembly would have been more suitable.

However, putting the 'suitability' of the design sample aside, the tool itself is useful in that it can provide suggestions for re-design. However, it is questionable as to whether this facility is really necessary. Is it not sufficient to simply identify the potential candidates for elimination (like the B-D, and Lucas software tools already do) and then leave it up to the creativity of the designer to come up with re-design solutions? By allowing the computer to suggest the re-design solution is it not limiting the scope for improvement?

The most recent work carried out at BAe Sowerby, i.e. linking the KBS system to a CAD system, thus automating the initial handling, fitting, and functional analysis procedure, is in line with other mainstream research activities aimed at improving the DFA tools. This aspect of the DFA analysis will benefit from automation because nothing is lost; there is no creativity associated with the initial analysis.

5.3.4 Avro/BAe Filton Pilot Study

This pilot study centred on the evaluation of a DFM expert system, developed at BAe Filton.

In 1992 BAe Filton began a major research and development project looking into the development of DFM software. It was initially proposed that they would look at all their main manufacturing processes and create an expert system that could be used by designers for cost estimation purposes. Unfortunately, research and development cut-backs have meant that they have so far only been able to produce one module i.e. Pressed Components.

In February 1995 as part of the Eng.D. research, Avro had this system on trial for evaluation. The system is effectively a database of knowledge relating to pressed components. The user inputs information regarding the design of the pressed component they wish to analyse, for example, dimensions, material type etc.. The system assesses this information and provides a cost estimate for the part. It also makes recommendations on how the design of the component could be improved.

The tool was simple to use and it provided quick access to cost estimates, for the design team. The designers at BAe Filton are in fact now using the system.

Chapter Review

This chapter has investigated quantitative DFMA tools. In particular it has:

- explained the mechanics of the popular commercially available tools, namely, Boothroyd-Dewhurst, Lucas and Hitachi;
- presented some industrial case studies where the use of these tools has proved successful;
- described some of the current research activities associated with DFA & DFM;
- described a number of pilot studies and investigations carried out to assess the applicability of these tools within the aerospace environment in general, and particularly at Avro;
- presented the actual savings to Avro resulting from the Avro/Westland pilot study.

The discussion based on the pilot studies and investigations, into whether such tools have a place within aerospace design in general, and then particularly at Avro, is presented in section 7.2 of Chapter 7.

The next chapter describes the research done on the Product Modelling aspect of Concurrent Engineering.

Chapter 6 Research into Feature-Based Design -The "FEAST" Project

Summary

This chapter describes the research done into Product Modelling using features; the second element of Concurrent Engineering selected for investigation as part of this Eng.D. study. This aspect of the Eng.D. study was done as part of a Brite-Euram sponsored project called FEature based ASsembly Techniques ("FEAST").

"The principal objective of the project is to improve the quality of engineering products by eliminating assembly problems at the design stage. The project is planned to research the requirements for 'features' in assemblies, and to develop definitions for the features required to support assemblies of different classes of components (e.g. structure, piping/wiring). A demonstrator and prototype feature-based assembly modeller will be developed to illustrate methods for exploiting features to simplify the assembly process and eliminate errors in assembly. This approach will demonstrate the business and technical feasibility of generating a complete feature-based model of an engineering product, taking account of all classes of component, and supporting the new methodologies for simultaneous engineering". (The project is known by the BRITE-EURAM project number BRE2-CT94-1015).

The purpose of this chapter is to:

- explain the history of Product Modelling;
- explain the advantages of using features in Product Modelling;
- describe the FEAST project in general;
- describe the aspect of the FEAST project which was linked with the Eng.D study.

6.1 The History of Digital Product Modelling

The advent of cheap computer graphics terminals in the early 70s saw widespread introduction of drafting (modelling) systems, to replace the manual drawing boards. Drafting systems were designed to be used by the traditionally trained draftsmen who needed only a short conversion course. These systems often incorporated a 2.5D and 3D capability, enabling 3D geometry and surfaces to be represented, relative to a global origin.

In today's CAD systems three types of model are in common use: Wireframe, Surface and Solid.

6.1.1 Wireframe Models

Wireframe models are the simplest method of modelling and use relatively little computer time and memory. Wireframe models provide accurate information about the location of surface discontinuities on the part. However, they do not give a complete description of the part. They do not distinguish the inside from the outside of part surfaces (see Figure 6.1)

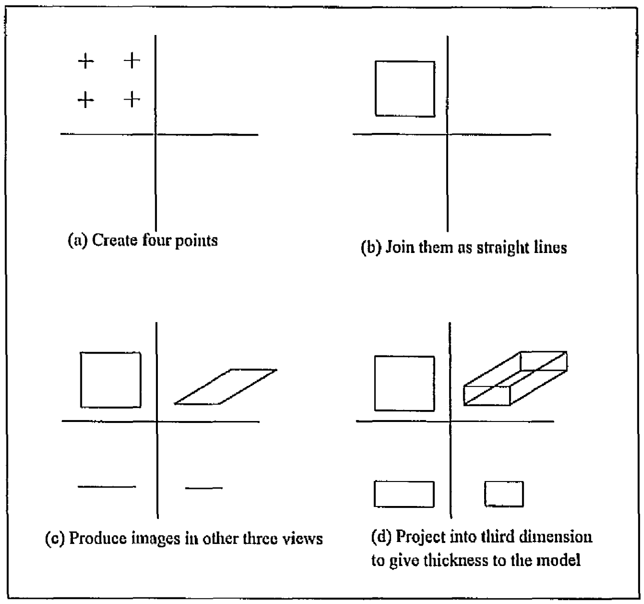


Fig 6.1 Procedure for Creating Wireframe Models

6.1.2 Surface Models

A surface model can be built by defining the surface on the wireframe model. The procedure of constructing a surface model is analogous to stretching a thin piece of material over a framework. As surface models precisely define part geometry such as surfaces and structure boundaries, they can help to produce NC machining instructions automatically. Surface models represent only an envelope of part geometry in computer memory. Since they do not actually represent the solid nature of parts because they contain no information describing what lies within the part interior, they cannot be used as a basis for engineering analysis programs such as finite element analysis for stress predictions. These programs often require such properties as weight, volume and moments of inertia which cannot be derived from a surface model alone.

6.1.3 Solid Models

In more advanced systems, 2D flattened images could be generated from the 3D wireframe images, for dimensioning purposes. However, a true physical representation (computerised mock-up) of the product within the computer could still not be realised. Without a computerised mock-up, the costly process of producing a physical mock-up was still necessary. Also, the introduction of the technology was not integrating all the functional areas of the business, for example, design, manufacturing, assembly etc.; it was only satisfying the unique requirements of the disciplines concerned (i.e. Finite Element Analysis Codes, Finance Systems, Aerodynamic Codes, Configuration Management Systems). The lack of effective data standards caused the product data to be recreated throughout the product life cycle, discouraging data standards and ingraining the sequential approach to the product development process.

In the early eighties, a new technology called solid modelling was introduced that promised to correct some of the limitations of the previous technologies. A solid modelling system may be defined as an application that can create a true 3D physical representation of a real life object. Today, this application of solid modelling technology is more commonly referred to as Digital Pre-Assembly (DPA). These applications allow components to be modelled within an assembly, offering such capabilities as clash detection, moments of inertia and mass property calculation. Also, sections can readily be cut through solid models to reveal internal details. This use of solid modelling is now widespread, as the technology has become more affordable.

Solid modellers are recorded in the computer mathematically as volumes bounded by surfaces rather than as stick-figure structures. To give an example such as a cylinder, a wireframe cylinder is defined in a computer as 2 circles connected by 2 line segments, whereas the solid model of a cylinder is represented as a 3D object that contains a volume. To determine the volume of the wireframe cylinder, the formula for cylinder volume ($\pi r^2 l$) can be used. For other types of volumes, different formulae would have to be programmed into the computer. Obviously it would be difficult to calculate the volume of complex shapes. On the other hand, to calculate the volume of a solid model, it is much easier because the computer can employ a general numerical integration that can be applied to solids of any shape.

Most commercially available solid modelling systems use one of two common approaches to construct solid models:

(a) to use simple geometric shapes such as cubes, spheres and cylinders etc.. These elementary geometric shapes are often called primitives. The idea is to combine a number of these primitives to create complex solid models. The constructive solid geometry (CSG) approach is known as primitive or building block modelling (see Figure 6.2).

Primitives can be combined to construct a solid model by Boolean or logical operations such as union, intersection or difference. e.g. 2 primitives can be added together at some point with a union operation to form a part. A hole in a part can be created by intersecting the part with a 'negative' cylinder.

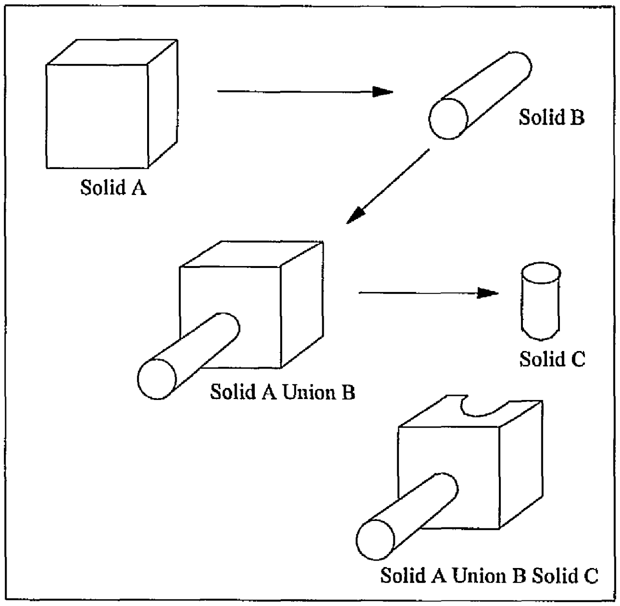


Figure 6.2 Primitive Modelling of Solids

The four main primitives needed to describe most parts are: plane, cylinder, cone and sphere. They are known as natural quadrics.

(b) Boundary or perimeter modelling in which 'elastic' lines are stretched to form the outlines to define the boundary of the part to be modelled (see Figure 6.3).

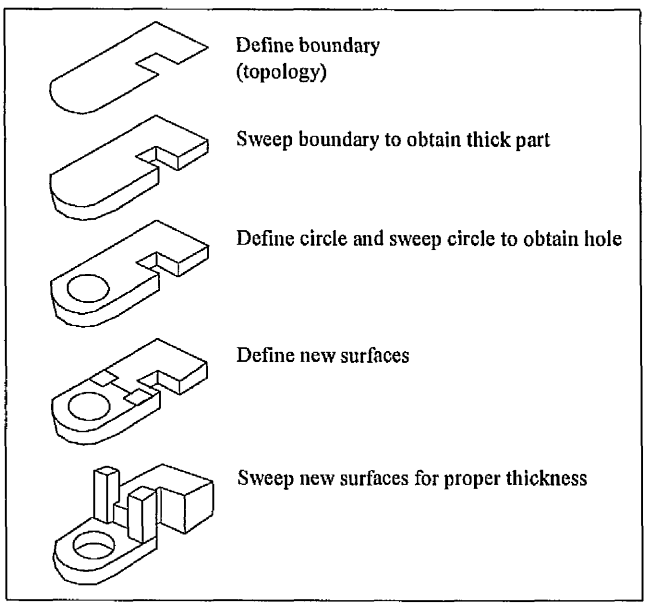


Figure 6.3 Boundary Modelling of Solids

The application of solid modelling during the conceptual design phase proved highly successful. However, throughout the eighties, the full potential of the technology was never realised, as the links to the downstream applications remained weak. In the main, the vendor communities response to the problem was to develop bespoke interfaces, that would download design data to specific applications within the various functional domains (i.e. Manufacturing systems, Drafting systems, Finite Element Analysis etc.). Often, the data exchange standard would be based in IGES (Initial Graphics Exchange Specification), resulting in the loss of solid definition and associativity links with the design data.

In the early nineties, Digital Product Modelling as opposed to solid modelling became more of a reality. Vendors, through either partnership or development of their own code, expanded the use of the 3D solid modelling geometry outside of the concept phase. Through the creation of the common product model, the same solid modelling data was made available for direct use by some of the downstream functions. As the product data was now assessed, rather than exchanged, product data associativity was maintained, and change implications more clearly understood. The concept of the 3D model as the master geometry definition, rather than the 2D drawing, was born.

Although successful, these systems are built on the same "classic" foundations and remain purely geometric systems. This means that design is 'geometry driven', whereas geometry should only be considered as a tool to represent the intended object. As a result, solid modellers are sometimes too constraining; too much time is required to find how to create a consistent geometry. In fact, the geometrical representation of some details such as 'pocket bottom corners' is not really important for the overall business process. Manufacturing people only need to know the depth of the pocket and the fillet radius. Also assemblies are still poorly modelled; concepts such as relative positions, tolerance plays etc. are not supported.

Product Modelling systems have the potential of creating a common product model that can be shared across functional departments. With these applications, the design model, the engineering drawing and the manufacturing model are completely associative. Changing a dimension on a solid model automatically changes the equivalent dimension on the drawing. The creation of a single Master Product Model made available to analysis, simulation, NC and inspection programmers as well as being used in the creation of technical publications and the production of shop floor information gives significant benefits.

Achievement of the above goal will require greater intelligence in the geometry definition. The appropriate data must be extractable from the product model. This requires the use of 'features' in the formulation of the product model.

6.2 Introduction to Product Modelling Using Features

It has already been suggested that the traditional Boolean based (i.e. Constructive Solid Geometry) approach to the definition of engineering components is inadequate (it does not support downstream analysis activities) and constraining (it can take too long to define geometry that may not even be necessary). In order to support downstream activities such as Computer Aided Process Planning (for individual part manufacture), Computer Aided Assembly Process Planning, tolerance stack-up checking, Design for Assembly analysis, etc., it is necessary to hold engineering information in the product model as well as pure geometry. Feature-Based Modelling was introduced to overcome the limitations in geometry creation associated with the original modellers.

The concepts of Feature-Based Design and Feature-Based Manufacturing represent the most promising interface between design and process planning and can be considered as the real first step to concurrent engineering. Most CAD systems can interface to Finite Element Method analysis systems for stress calculations. However, with respect to detailed design support, the traditional CAD systems are still working in the wrong direction. Shape is the input of analysis tools instead of the output. As a consequence time consuming iteration loops of shape modifications and subsequent analysis have to be made (van Houten (92)).

6.2.1 Definition of Features

" A carrier of product information that may aid design or communication between design and manufacturing or between other engineering tasks." (Shah (90)).

"A feature is any geometric or non-geometric attribute of a discrete part whose presence or dimensions are relevant to the product's or part's function, manufacture, engineering analysis, use etc. Typical features: Hole, pin, flat, slot, spline, datum; Typical feature attributes: Diameter, depth, tolerance, orientation, used for (mating, fixing), Mates with (feature ** xx on part yy)." (De Fazio et al. (93)).

"Feature modelling is based on the idea of designing with 'building blocks'. Instead of using analytical shapes like boxes, cylinders, spheres and cones, which are the primitive elements in standard solid modelling packages, the user creates the product model in a better structured way by using higher level primitives which are more relevant to his application. In this way the intent of the designer and the design history can be captured in the product model, which can be very helpful for the downstream tasks.... An engineering feature is defined as : A physical element of a part that has some specific engineering significance." (van Houten (92)).

"To overcome some of the problems of geometric modelling, feature models are currently being widely investigated as an alternative basis of CAD systems. Indeed, features do provide a more natural vocabulary for expressing the design object than plain geometric model; hence, they can capture more of the designer's intent. They also offer a good basis for modelling various kinds of manufacturing information, such as processes, tools, materials and assembly requirements." (Gui and Mantyla (94)).

"Each feature contains some attributes, a necessary set of parameters to define the feature. The selection of each feature explicitly creates or modifies geometry. The knowledge specified in the feature attributes thus contains enough information to create the underlying geometry." (Sodhi and Turner (94)).

"A feature is a higher level grouping of geometrical, topological, and functional primitives into an entity more suitable for use in design, analysis, or manufacture."
(The Automated Manufacturing Research Facilities (AMRF) Process Planning Team at the National Institute of Standards and Technology (NIST)).

"Design is not just a technique to provide a nice representation of an item. In mechanical engineering it is process oriented in general. This includes planning, fixturing, manufacturing, controlling, assembling, etc. ......Automation of these operations requires that appropriate data be available and could be extracted from the product model. This generally requires analysis of the model into features." (Peklenik and Hlebanja (88)).

Drawing with lines, curves and surfaces is just going the opposite way of the human mind which at first recognises structures, shapes, say features, and then if possible analyses the scenery into elements. Indeed when a worker looks at a drawing he at first recognises features to be machined. He sees a gear, a shaft end, a hole to be machined in the appropriate manner and in a certain sequence, then he may see lines (Peters et al. (90)).

Designers naturally think in terms of features, for example, a designer would think of a hole in terms of a diameter and a depth, and not as a negative cylinder. Therefore, it seems logical to try to represent the product model in terms of features.

6.2.2 How to Obtain Features

In the field of feature research there are three ways in which features are handled within the product model; Feature Recognition, Interactive Feature Definition, and Feature-Based Design.

6.2.2.1 Feature Recognition

Feature Recognition is to recognise specific features as a combination of points, contours, surfaces etc.. Basically the elements within the database that make up the geometric model are searched for matching patterns (topology and geometry) and the feature parameters extracted from them.

At present, feature recognition undoubtedly is the most versatile technique for the transformation of product models between application domains (i.e. to other downstream engineering activities e.g. CAPP). As the design history is not recorded in the current generation of CAD systems, and only the final result of the design process is available for the downstream applications, feature recognition has the important advantage that it can provide the proper information to those applications, independent of how the product model was created (van Houten (92)).

In this approach application features are automatically or interactively recognised from a model of the object under consideration. Product models from both conventional solid modellers and feature-based modellers can be subjected to feature recognition (Salomons, van Houten & Kals (93)).

Gadh et al.(91) have developed two approaches to extracting features from a geometric model which are then fed into an object oriented, knowledge based system for a critique of the design.

6.2.2.2 Interactive Feature Definition

In this approach features are defined interactively by the user by selecting and grouping geometric elements of the product model on the screen in such a way that the groups adhere to the definition of a standard feature.

6.2.2.3 Design by Features/Feature-Based Design

In Feature-Based Design the product is represented by features from the outset. Instead of using a top down procedure starting from geometric elements and applying feature recognition programs, one works bottom up, using features stored in a database (Peters et al. (90)). The product model is created by combining pre-defined features stored in the database.

The set of features required for a general Feature-Based Design is virtually infinite.

6.2.3 Types of Features

Ways of improving the design process by using features to store information in the product model have been discussed and three main views on how features can be handled within the product model have been described. The following section describes what are considered to be the two main types of features, namely form features and assembly features (other types of features include: functional features, mating features, physical features, abstract features).

6.2.3.1 Form Features

The first references on the use of features within engineering design, were concerned with the modelling of individual parts to support the automation of manufacturing process planning. Figure 6.4 illustrates an object with its form features.

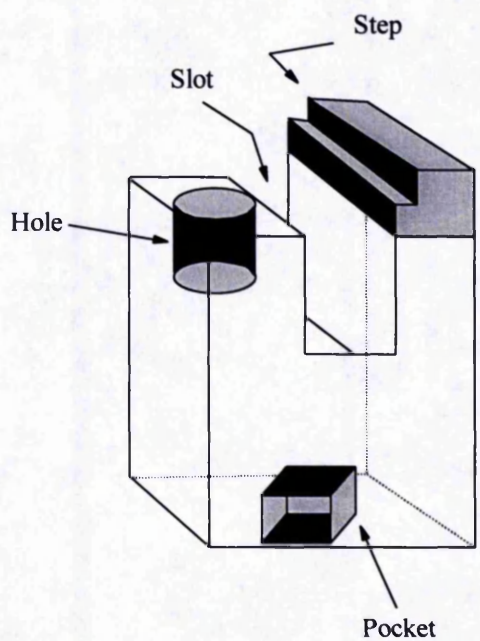


Figure 6.4 A Representation of an Object with its Form Features (Source: Dowlatshahi 94)

Process planning deals with selecting and defining the processes that have to be performed to transform raw material into a given shape. The decisions made in process planning relate to single parts. Process planning includes: selection of machine tools sets, selection of setups, selection of machining operations and their sequence, selection of cutting tools, design of jigs and fixtures etc.

In computer-aided process planning it is necessary to analyse the part under consideration to generate a detailed process plan. In this analysis of the component, (manufacturing or form) features are key to generate the process plan. Form features provide for a natural form of communication; process planners think in terms of holes, pockets etc.. Automation of process planning requires that product data be extractable from the product model automatically. However, CAD product representations in product-modellers usually differ from the type of information required in CAPP (e.g. manufacturing features).

Until now, feature recognition has been the most common approach to extract manufacturing features from CAD product models. In fact, this means inferring a lot of information from the CAD product model at high cost while this information already has been generated during the design process. This information has been lost when the result of the design process was stored in the CAD model. Feature-Based Design could (at least partly) help to overcome this problem (Salomons et al. (93)).

Early feature-based modellers only provided the feature types to generate simple prismatic components rather than complex components common in the aerospace industry. However, feature types for component definition are now becoming more comprehensive, and common definitions have emerged through previous Brite-Euram projects like FEMOD, and ISO/STEP initiatives like the creation of Application Protocol 224:Mechanical Product Definition for process planning using form features.

At present, feature technologies are in their infancy and are not easily tailored to meet the specific business requirements. Many CAD system vendors have incorporated a base set of form feature modelling techniques.

6.2.3.2 Assembly Features

So far the application of the features paradigm to individual components with the aim of automation of process planning for part manufacture has been discussed. Current CAD systems partially support the use of form features for individual components, but do not address the use of the feature definitions to assist in assembly-related tasks. The links between components, such as contact surfaces cannot be fully defined with current solid modellers. These tools can only position components inside an assembly through the use of geometric co-ordinates and simple relationships, and do not use the extra information and relationships inherent in feature definitions. The result is that advanced form feature-based components still have to be interpreted manually when considering assemblies, and the benefits of the feature-based approach can be lost.

The new area of interest in feature research is the application of the feature paradigm to assemblies. An assembly feature is the relationship between two form features which are on different parts.

Shah and Rogers (93) and Libardi et al. (88) provide comprehensive surveys on assembly modelling research.

6.3 The Brite-Euram Project into FEature based ASsembly Techniques – FEAST

6.3.1 Introduction

The purpose of this section is to explain what the FEAST project is aiming to achieve and to describe the aspect of the project which was linked to the Eng.D. study.

The principal objective of the FEAST project is to improve the quality of engineering products by eliminating assembly problems at the design stage. The project is planned to research the requirements for features in assemblies, and to develop definitions for the features required to support assemblies of different classes of aircraft components (e.g. structure, piping/wiring). A demonstrator and prototype feature-based assembly modeller will be developed to illustrate methods for exploiting features to simplify the assembly process and eliminate errors in assembly. This approach will demonstrate the business and technical feasibility of generating a complete feature-based model of an engineering product.

The challenge of FEAST is to improve the definition of features that can be used in the solution of aircraft assembly problems. FEAST is confined to the identification and definition of assembly features and is not be concerned with the actual exploitation of the features for the purpose of life cycle simulation or analysis (i.e. the downstream simulation and analysis activities it is intended to aid), it will, however, briefly show how the assembly modeller can be used to supply information to these analysis activities. The application of features for assembly will provide a further step forward to the ultimate objective of being able to create a digital product model totally designed by features.

Consider the product (aircraft) to be split into three levels (see Figure 6.5).

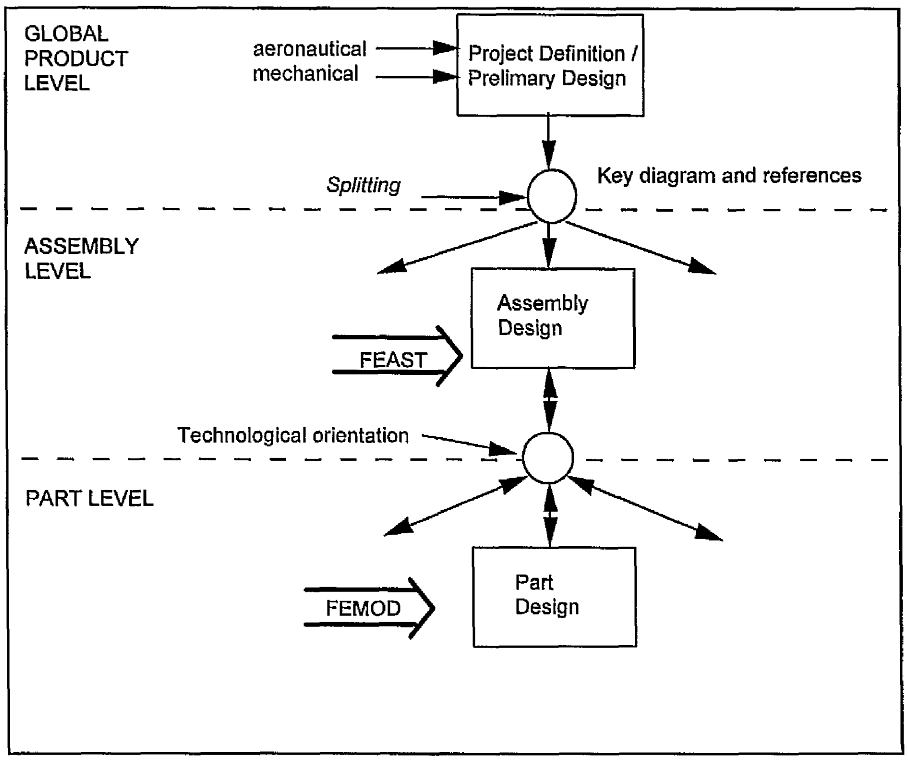


Figure 6.5 The Three Levels of the Product

(Source: FEAST report – *Identification of Feature Requirements*, Sub-Task 2.0 Dec 1995)

The top level consists of activities dealing with the whole aircraft either at a very preliminary stage (e.g. concept design) or on the final assembly line. The mid-level comprises activities dealing with assemblies, both at the design stage and at the production stage. The bottom level corresponds to activities which have a scope limited to a single part (e.g. drafting, detail manufacturing).

The three levels imply a hierarchical decomposition of the aircraft into constituent assemblies, and of each assembly into constituent parts. The first decomposition is performed according to general economic, technical and industrial considerations. In particular, assemblies are assigned to partners or subcontractors on the basis of their financial involvement in the project and their industrial capabilities. The second decomposition matches the physical decomposition of assemblies into parts. The FEAST project addresses the intermediate level. The bottom level was addressed by FEMOD (the Brite-Euram project investigating part (form) features).

The FEAST project is broken into eight sub-tasks, to date tasks 1–4 are complete.

Task 1 – Definition of Business Requirements

Sub-task 1.1 Definition of Industrial Requirements – this activity was an analysis of the functions within aircraft production that could be supported by having a product model which contained assembly features (see FEAST report – *Definition of Industrial Requirements*, Sub-task 1.1, April 1995).

Sub-task 1.2 Survey of Emerging Technologies – this was a study carried out by the University of Valenciennes and the University of Palma which investigated the extent of features usage in currently available CAD systems, and the academic research being carried out into assembly modelling using features (see FEAST report – *Survey of Emerging Technology*, Sub-task 1.2 March 1995).

The academic research is broken down into five sub-parts:

- Part 1 gives an overview of assembly modelling research. It discusses methods developed by Salomons (94), Kim (89), Gui and Mantyla (94), Wolter (91), Popplestone (87), Shah and Tadepalli (92), Sodhi and Turner (94) and others;

- Part 2 describes the uses of the assembly modelling representation i.e. the contribution it can make to the downstream analysis activities;
- Part 3 gives information on the tolerance aspect of assembly modelling;
- Part 4 is concerned with the consistency maintenance (i.e. propagation of change within the product model);
- Part 5 is about ISO/STEP work relevant to the FEAST project.

Task 2 – Identification of Feature Requirements

The objective of this task was to analyse the interaction between components in the same class (e.g. structure/structure), and between components in different classes (e.g. structure/piping) within aircraft assemblies, in order to identify where and how features can be defined and exploited to meet the business requirements identified in Task 1 (see FEAST report – *Identification of Feature Requirements,* Sub-task 2.0 December 1995).

Task 3 – Definition of Features

The objective of this task was to develop assembly features data definitions to meet the requirements of each class of components analysed in Task 2. The specifications were expressed in a formal information model description language (NIAM diagrams and EXPRESS (the STEP product modelling language) were used) to allow computer interpretation. The task provided information on the feature definitions to support the development of a representative demonstrator that will simulate the new working environment. (see FEAST report – *Definition of Feature Requirements,* Sub-task 3.1 March 1996).

Task 4 – Development of Demonstrator

The objective of this task was to develop a demonstrator which will simulate the environment in which assembly features can be defined and exploited. The demonstrator will be used to provide an initial validation of the business feasibility of the concept.

A PC based presentation tool was used to develop a realistic series of scenarios designed to demonstrate the business and technical feasibility of the FEAST concept. The demonstrator will not be functional, it will be used to illustrate the progress of work and to solicit comments from potential users in partner companies.

Task 5 – Specification of Assembly Modeller

The objective of this task is the compilation of a functional specification for a prototype assembly modeller.

The task will take the requirements from Task 2, and the definitions of features from Task 3, as the basis of formulating a modular architecture for an assembly modeller prototype. The modeller will be designed to allow rapid updates to individual functions and the data required to support them, in order to accommodate evolution extensions in response to the results of testing by the partners and their users.

The modeller will be designed to be as independent as possible of any particular commercially available hardware and software environment in order to facilitate portability between partners. Selection of the environment will be deferred to this stage of the project to allow the partners to take advantage of the latest available technology.

Task 6 – Development and Testing of Prototype Modeller

The objectives of this task are to develop a prototype assembly modeller to meet the specification generated in Task 5, to validate the modeller against the specification and the business requirements previously identified and to submit the modeller to extensive testing by expert users in order to validate the functions and data definitions in a realistic environment.

Task 7 – Consolidation of Results

This task is concerned with the documentation of the results of the project. These will include the definitions of the extra features and specifications of the user interactions required to produce them. The project will also document how the various business requirements have been met. A clear statement of business benefits will be produced to assist partners in justifying the further exploitation of the work.

Task 8 – Liaison with STEP

This task provides an active liaison with the STEP project to obtain data and to have the new feature definitions adopted as part of the ISO STEP standard.

6.3.2 Task 2 – Identification of Feature Requirements

The Eng.D. study was primarily involved with Task 2 of the FEAST project. Task 2 was split into three main sub-tasks:

- the *matrix exercise* – had the objective of defining (refining) the concept of an assembly feature between components. Applied to industrial cases, it described this relationship as a link on part features and yielded a classified list of those relationships and their associated part features;
- the *scenario sub-task* – as far as Task 4 was concerned, it was recognised early in Task 2 that the development of a FEAST demonstrator, an outline system specification, would be needed which expressed the partners' initial views on the principles of the exploitation. In preference to a written specification, a "story-board" scenario technique was used to depict how FEAST would work in practice. Three scenarios were produced. After they exposed the embodiment of an assembly feature in the model, the three different sequences of slides showed typical engineering issues being addressed by FEAST in the various fields of tolerancing, tooling and systems.
- the *template sub-task* – the template sub-task was devoted to the creation of a generic template which would be used for the collection of the definitions of assembly features. The template would be used in Task 3 to create a comprehensive catalogue of assembly feature information which could then be formally modelled to allow computer interpretation.

6.3.2.1 The Matrix Exercise

This exercise was the initial approach used in 'Identifying the Feature Requirements'. This exercise served the purpose of aligning the partners thoughts relating to the categorisation of information i.e. relationships, attributes of the relationships and constraints. The following definitions were agreed:

- assembly – a number of parts collected together to form a unit;
- assembly part – a part created as a consequence of linking parts in an assembly, for example, a cleat, a bracket, a joint, a wire connector. Fixing agents are required to attach these parts;
- relationship – a verb describing the connection/association of one object with another in an assembly (e.g. attachment). The description of this yields an assembly feature;
- attributes – named characteristics which quantify or describe a feature;
- constraints – limitations existing on the use, interaction and position of part or assembly features;
- fixing agent – an agent involved in an attachment assembly feature to attach parts together (e.g. rivet, bolt, glue);
- macro-component – a component of an assembly for which a detailed description has yet to be given. It could be a single part or a sub-assembly. A base level/concept part to which detail is to be added;
- part – a component which cannot be reversibly broken down into constituent parts;
- part feature – a feature which is associated to a part to fulfil a function specific to that part (e.g. lightening hole in a floor beam) or the function of that part within an assembly (e.g. a pass-through hole).

The exercise generated a collection of important relationships which existed between parts/sub-assemblies appertaining to the aircraft.

6.3.2.1.1 Approach

The approach used to initiate this activity was as follows:

1. A zone was selected (sub-assembly or partial sub-assembly) of the aircraft for which there was company expert advise at hand.
2. For the chosen zone the parts to be considered from various classes i.e. structure, piping and wiring were selected. For each pair of components the relationship/interaction which

exists between the components was identified.

3. After each identification of the relationship, the part feature which is involved with the relationship e.g. hole, flange, web was specified.

4. For a collection of n parts a square nXn matrix was constructed. The matrix has a double header for the part and part features. The diagonal elements will remain empty as it is not envisaged that a component will have a relation with itself when considering assemblies. The elements of the matrix contain the relationship which exists between one part (or part feature) and another part (or part feature). The general layout of the matrix is shown in Figure 6.6.

Part		Component			
	Part feature	Feature #1	#2	..	#n
Component	Feature #1	* &			
	Feature #2				
	..				
	#n				

Figure 6.6 The Matrix Layout

Where, * = Relationship

and &=

Attributes
List of attributes....

6.3.2.1.2 Components Studied

A variety of different zones of the aircraft were selected by the partners, as follows:

1. A typical fuselage area

The components selected for analysis in this example were: a frame, skin panel, stringer, reinforced cap member, clip A, clip B, shear tie angle.

2. A typical rib assembly in an aircraft wing

The components selected for analysis in this example were: a rib, skins, spars and supports.

3. A typical equipment bay

This example included structural parts (frames, stringers), cables, air conditioning pipes, equipment and cable supports.

4. A typical representative aircraft bay

This example included frames, stringers, pipes, supports, harnesses, clips, a jack and skins.

5. An inboard aft section of a typical commercial aircraft wing

This example contained components such as an inner rear spar, ribs, skins, tie bar, backing plate, bracket, cleats, rib plates, bulkhead plates, seal plates, rib cleats, side stays.

6. A nacelle area of a typical civil aircraft assembly

This included parts such as a web, hinge, moveable panel, pin, fixed skin.

Some of the matrices produced by Alenia who investigated a typical equipment bay, are given below as examples.

Matrix Examples

Figure 6.7 shows a typical aircraft assembly with structural parts, equipment and wiring installations.

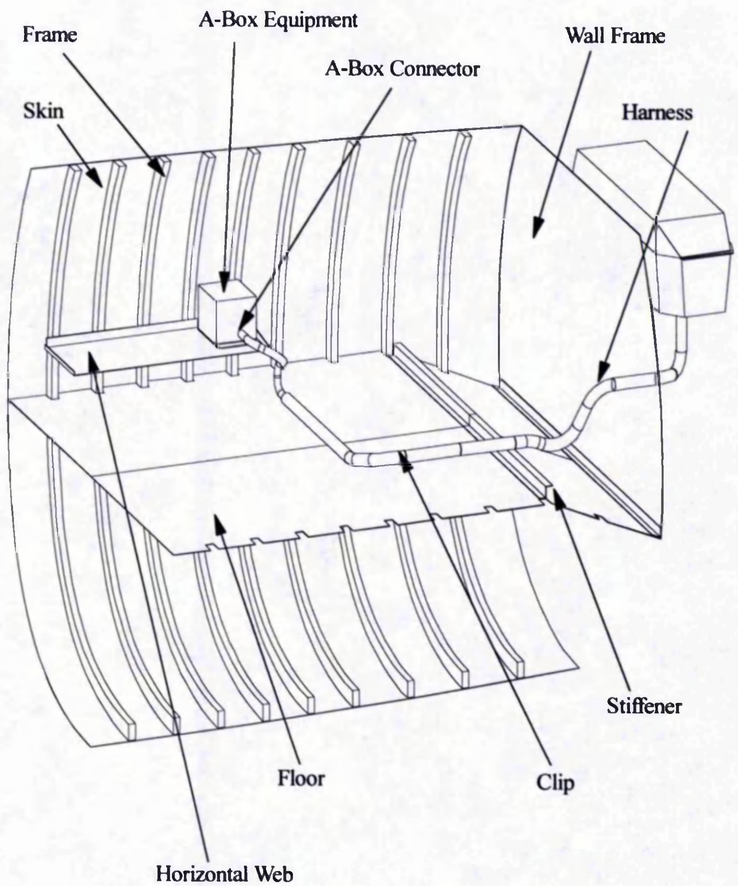


Figure 6.7 Typical Assembly with Structural Parts, Equipment and Wiring Installation

Attention was focused on the relationships between wiring harnesses and structural parts/equipment. The following matrices were developed.

COMPONENTS		**FLOOR**
	FEATURES	**RIVET LINE**
STIFFENER	**RIVET LINE**	ATTACH (JOIN) - *torque*

Table 6.1 Matrix 1

COMPONENTS		**HARNESS**	
	FEATURES	**STOP COLLAR (extremity hole)**	**......**
STIFFENER	**FIXING HOLE**	ELECTRICAL BONDING	
	FIXING HOLE		ATTACH (SUPPORT)

Table 6.2 Matrix 2

COMPONENTS		**A-BOX EQUIPMENT**
	FEATURES	**FIXING HOLES**
HORIZONTAL WEB	**FIXING HOLES**	ATTACH (JOIN) - *torque* ELECTRICAL BONDING

Table 6.3 Matrix 3

COMPONENTS		**A-BOX EQUIPMENT**
	FEATURES	**NOZZLE**
HARNESS	**EXTREMITY**	CONNECT

Table 6.4 Matrix 4

The other matrices produced from this selection of sub-assemblies can be found in the FEAST report for Task 2. The set of matrices provides the FEAST consortium with an essential input, based on real examples. This input fed a 'rationalisation process' which involved identifying and defining the key concepts in aeronautical assemblies.

6.3.2.2 The Scenario Sub-Task

During the early stages of Task 2 it became obvious that a structured way to illustrate the FEAST concepts and ideas was needed. Therefore, it was proposed to create scenarios in order to depict how users (e.g. designers, manufacturing engineers) would work with a feature-based assembly modeller.

These scenarios were seen as an illustrative way to support the discussion process and an aid to reach a consensus on the FEAST modeller specification. They do not constitute a specification of the FEAST modeller itself. These scenarios depict essential concepts that the FEAST modeller will support, and they are limited to these concepts. In other words, all the details are not shown, for example, how the user can interact in detail with the FEAST tool to create a line.

6.3.2.2.1 What is a Scenario?

A scenario is a commented sequence of slides made with MICROSOFT Powerpoint. The slide format has been defined as follows (see Figure 6.8). The top part represents the possible appearance of the FEAST modeller on the computer screen. It is window-based and there are six windows :

- the "Management window" offers general functionality such as "save a session", "retrieve a session" etc. They are fairly common to any CAD systems, and consequently the scenarios do not focus on these aspects;
- the "Graphics window" corresponds to a standard CAD graphical window. Its purpose is to visualise and manipulate the geometry of the assembly model. Usual CAD functions like "zoom", "pan", "create line", are offered. No detail is given as these functions are

also included in any CAD system;

- the "Product structure window" is the term which refers to the view of the feature-based assembly modeller. Its purpose is to show and permit the user to interact with the symbolic structure of the product. Unlike the previous windows, this one is very specific to the FEAST tool. The symbols used in the product structure window are described in detail in the next section;
- the "Dialogue window" contains the menu specific to the FEAST modeller;
- the "Help/messages window" displays the message to the user;
- the "Status window" indicates what the current stage of the session.

The bottom part of the slide format contains three items:

- Actions : to describe what is going on in the current slide;
- Issues : to list the problems and difficulties that are encountered at the current stage;
- Exploitation : to comment on the potential use of the information being processed.

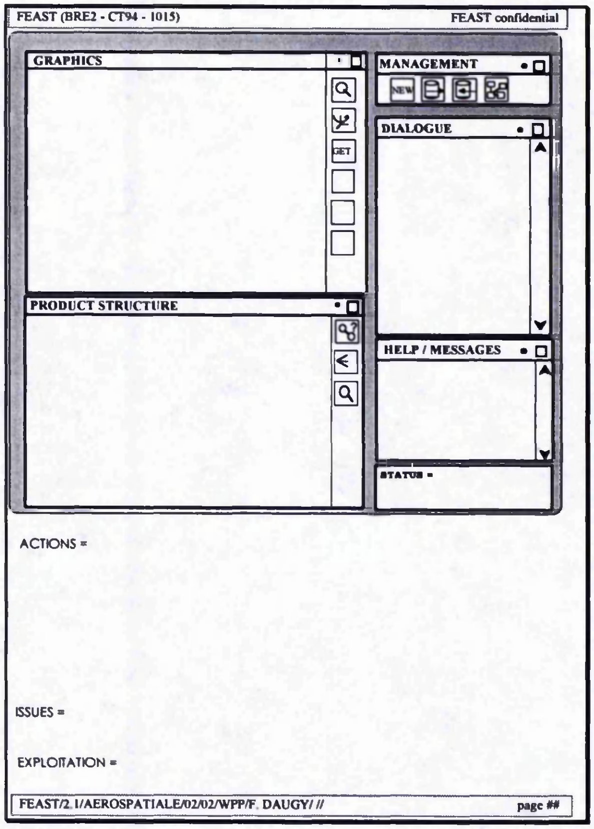


Figure 6.8 The Scenario Slide Format

6.3.2.2.2 Example of a Scenario

By using the slide format described above, the scenario describes the main stages of the design of typical aerospace assemblies.

Three scenarios were created during Task 2:

- the first scenario is essentially based on a skin panel assembly of a commercial aircraft (namely an Airbus A319). Consequently this scenario essentially deals with structures. The second part of the scenario, illustrates how the assembly model can be exploited; it highlights considerations about the assembly process plan, and tolerances. This scenario was created by Dassault Aviation and Aerospatiale;
- the second scenario focuses on systems, and more precisely, on electrical installation. It was created by Alenia;
- the third scenario was created by BAe Airbus and is based on wing production. Its

purpose is to emphasise the manufacturing view on assembly design, and especially the aspects relating to tooling. In this scenario, jigs and tools are seen as being part of the assembly model.

The full scenarios can be found in the FEAST report for Task 2. An example taken from the scenario produced by Alenia, which describes the sub-assembly in Figure 6.9, is given in Figures 6.10 to 6.15 (the Issue and Exploitation items have been omitted, the Action description is given before each figure).

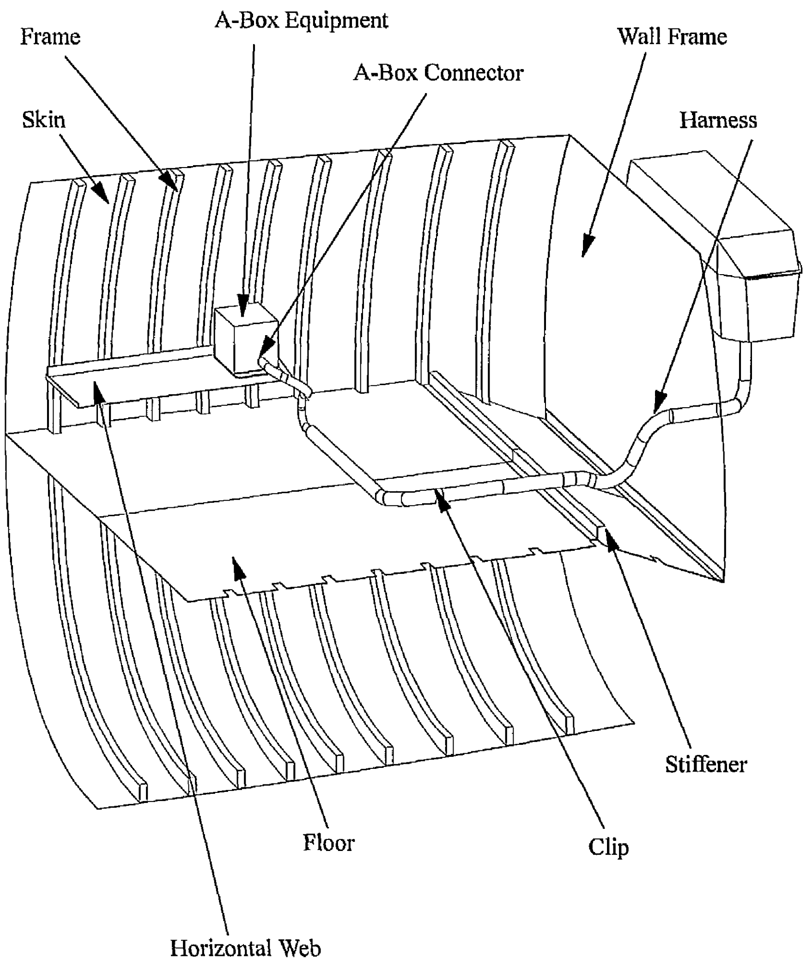


Figure 6.9 Typical Assembly with Structural Parts, Equipment and Wiring Installation

From the sub-assembly depicted above, the following scenario slides investigate the interaction between the harness, the A-Box and the horizontal web.

Slide No.1, Action – the designer chooses to study a zone comprising the harness, the A-Box and the horizontal web.

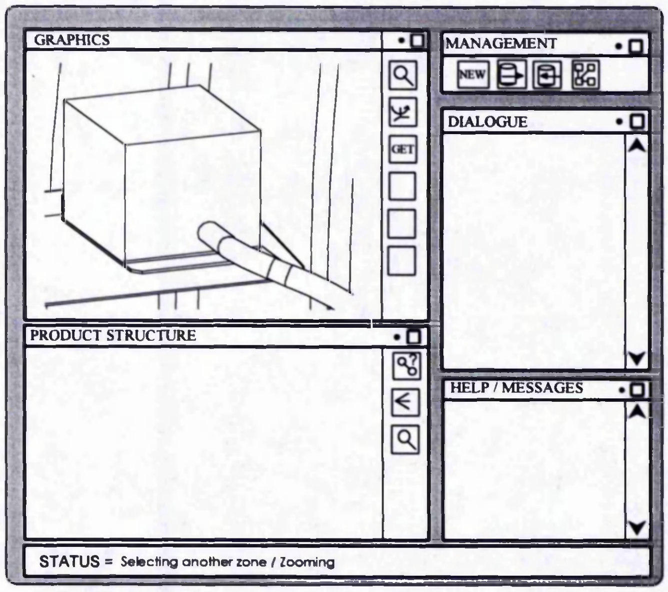


Figure 6.10 Scenario Slide No.1

Slide No.2, Action – once the geometry is imported, the designer formally defines macro-components implied by the conceptual design. Information and objects are attached to the key diagram.

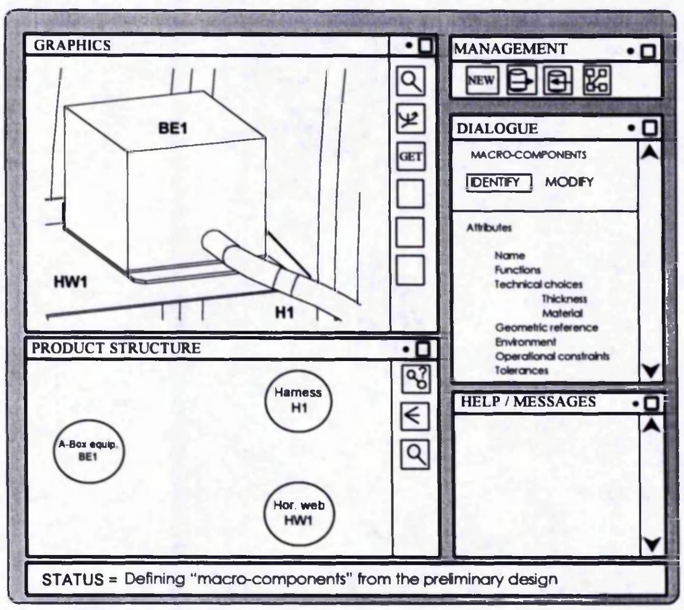


Figure 6.11 Scenario Slide No.2

Slide No.3, Action – in the selected zone the identified relations are:

- a connection between the harness H1 and the A-Box equipment BE1;
- an attachment and an electrical bonding between the A-Box equipment BE1 and the horizontal web HW1.

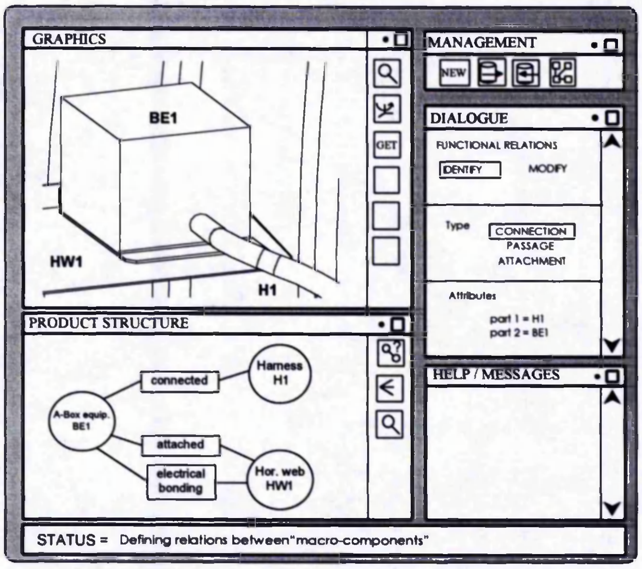


Figure 6.12 Scenario Slide No.3

Slide No.4, Action – an attachment flange (AF3) on the A-Box equipment BE1 is necessary for the attachment with the horizontal web HW1.

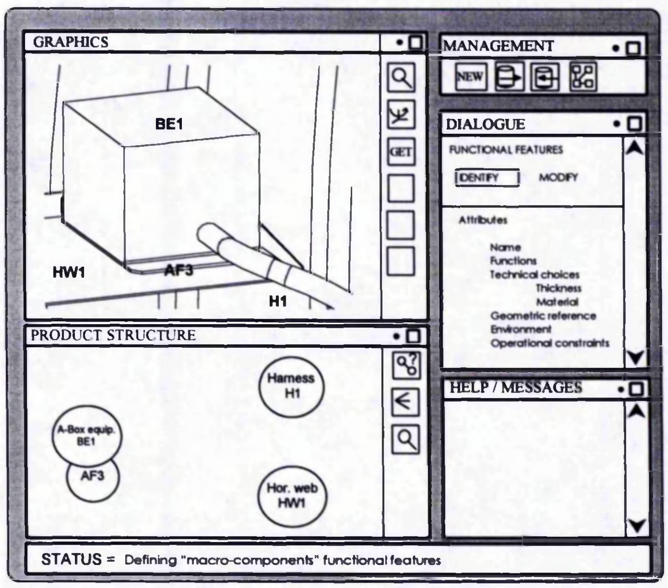


Figure 6.13 Scenario Slide No.4

Slide No.5, Action – the designer decides now to analyse the electrical connection between the harness H1 and the A-Box equipment BE1.

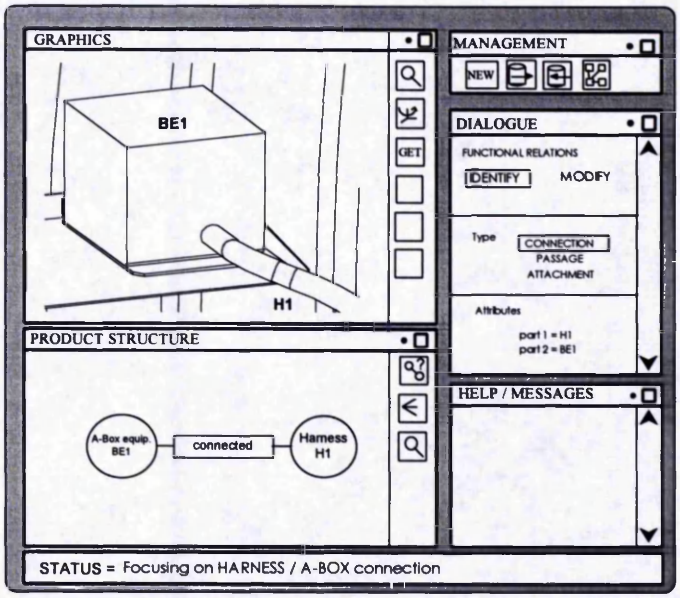


Figure 6.14 Scenario Slide No.5

Slide No.6, Action – The connection between the harness H1 and the A-Box equipment BE1 is realised by means of an A-Box connector AC1 (assembly part). The functional features enabling the connection are:

- the extremity E3 of the harness;
- the nozzle of the A-Box equipment BE1.

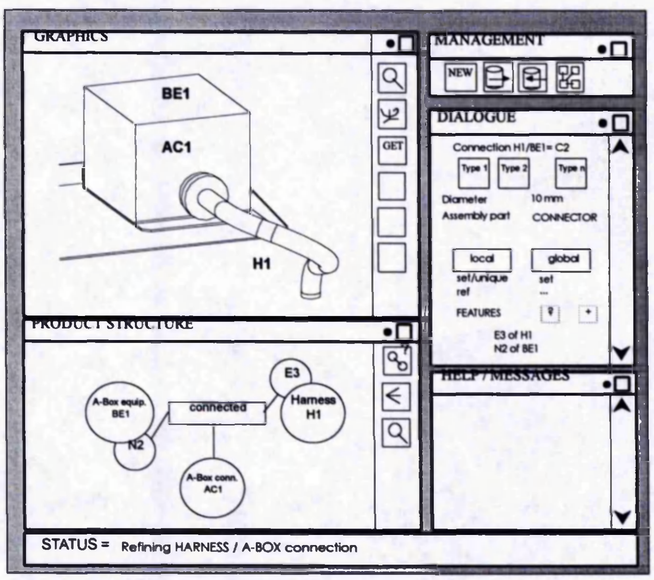


Figure 6.15 Scenario Slide No.6

6.3.2.2.3 Proposed Graphical Representation

The goal is to provide a graphical representation of the product structure that offers the designer a view of the formal aspects of the product structure. The proposed representation should reflect the steps a designer goes through during the assembly design of a product. Two steps in the description process of an assembly design have been identified:

(1) The first step is conceptual: the Macro-Components or Parts are related by a 'Functional Relation'.

(2) The second step can be seen as functional/technological: the 'Means' (that can be Fixing Agents or Assembly Parts) are added or detailed in the geometric representation, and Part Features, acting as Assembly Features, are defined.

The graphical representation of a product structure appears as a sort of hierarchical graph. It consists of some symbols, each representing an entity in the process of product structure design. Figure 6.16 shows the set of graphical symbols used, and their meaning.

Basically, two components (Macro-Components or Parts) are related together by means of a Functional Relation. Macro-Components can be de-composed into sub-components (parts). A Part Feature, part of a Macro-Component or a Part is involved in the relation. A Means is used to fulfil an assembly requirement. Means can be fixing agents and assembly parts. A Fixing Agent is a simple means, while Assembly Parts need to be further detailed, and they may use fixing agents to be linked to other parts. An example of Fixing Agent is "rivet", and an example of Assembly Part is a "cleat". As Assembly Parts are generated parts, they also have Part Features; they have been called Means Features.

A relation where an Assembly Part is involved is decomposed in a sub-graph. That is, the Functional Relation is detailed at a lower level, with sub-relations between Parts and Assembly Parts, related by means of Means. If a Means is an Assembly Part, the relation the part is involved with needs to be further detailed.

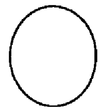
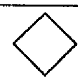
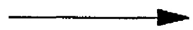
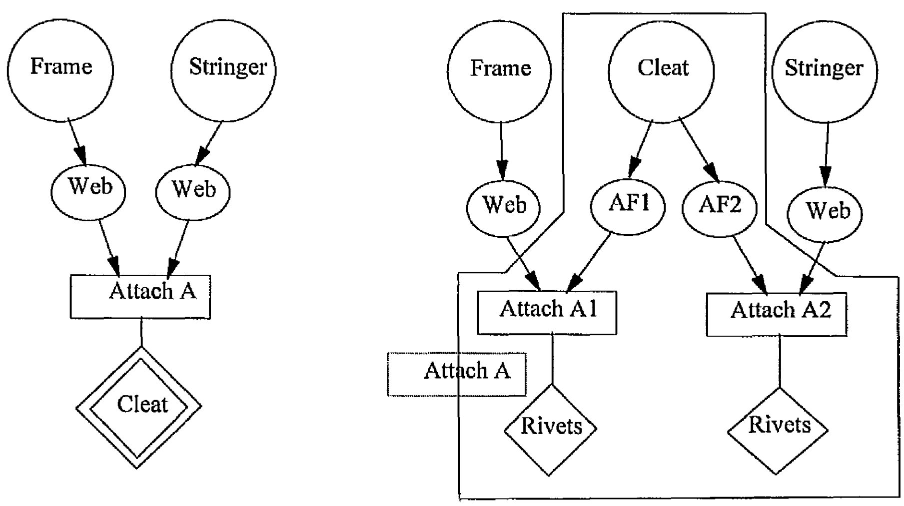
Object	Graphical Symbols
Macro Component/Part	
Part Feature/Means Feature	
Functional Relation	
MEANS Fixing Agent	
Assembly Part	
ARC (connecting parts and relations)	

Figure 6.16 Graphical Symbols Used to Show the Product Structure

The use of these symbols to represent the product structure was shown in the scenario example in the previous section. The figure below shows another example where a stringer is attached to a frame by means of a cleat (bracket). The cleat is an assembly part which has two attachment flanges, AF1 and AF2.



Stage 1 Stage 2

Figure 6.17 Stringer/Frame Product Structure Example

6.3.2.2.4 Inputs and Outputs of FEAST

The FEAST inputs are essentially the information coming from the "global product level" (see Figure 6.5), i.e. the concept design phase:

- external aerodynamic shapes have been defined;
- main structural components have been identified;
- main systems have been approximately routed.

All this information is defined by geometry available in the key diagram, design notes etc. It is assumed by the scenarios that this information is not structured from an IT-point of view, i.e. it is not interpretable by a computer. Therefore, the initial activity described by scenarios consists in importing and structuring this data. In practice, some kind of structured information can probably be directly retrieved from the design Bill of Material database. i.e. instead of manually creating the macro-components, these entities can be imported from the design database.

The objectives to be achieved at the assembly level are also given as inputs, for example, functionality, costs, weight. From this information, a feature-based assembly model is built to represent all the information related to the assembly. This model is then exploited to generate outputs.

These outputs can be divided into three categories :

- outputs sent to the part level activities;
- outputs used by analysis or simulation performed at the assembly level;
- outputs requested by the global product level for overall analysis or simulations, and integration.

The first category corresponds to part specifications which are to be used for single part design as inputs to a FEMOD type feature modeller. The second category contains all the information from the assembly model that can be used as inputs to assembly analysis tools (e.g. tolerance analysis, assembly plan generation, assemblability analysis). Finally, the third category encompasses all the information which must be consolidated at the whole product level. A typical example is the Bill Of Material.

The scenarios are intentionally open and broad. Indeed, they are not limited to the core goal of FEAST which is the creation of an assembly model. The reason is that such an approach would not have shown the potential benefits of modelling assemblies. Modelling assemblies is an extra workload asked of the designer; if the benefits and the potential uses were not shown, the scenario could have been perceived as describing a more complex and costly design approach.

Therefore, the scenarios cover both assembly modelling stages and analysis stages of the assembly level. They not only show how the model is built, but also how the model could be exploited and what kind of analysis or simulation functionality can be expected in the future. The main goal of these analyses is to provide designers with enough information to help them to choose the best design solution.

The FEAST assembly model acts as an enabler for these analysis and simulation activities. By making the information related to assembly accessible both to human and software program, knowledge and reasoning techniques can be applied to the model to generate extra information from the main assembly model. In the long term the demonstrator (developed from the scenarios) will show some of the possible capabilities of the system and the advantage it gives over present methods.

6.3.2.3. The Template Sub-Task

The third part of Task 2 was the development of an Assembly Feature Template (see Figure 6.18). This template was to be used in Task 3 to collect and describe all the identified assembly features from Task 2. The catalogue can be considered as a synopsis table by means of which the user of a potential feature-based assembly modeller should be able to solve any assembly problem. A more detailed explanation of the category definitions of the template can be found in FEAST report – *Definition of Feature*

Requirements, Sub-task 3.1 March 1996.

Figure 6.18 Generic Template

6.3.2.4 Assembly Features Identified During Task 2

Task 2 identified some of the features associated with aircraft assemblies. This section begins to describe the organisation of the assembly features by the functions they fulfil, the attributes which describe them and the constraints which validate their existence. Also included is a list of examples of the assembly features found to be existing within actual aerospace assemblies.

6.3.2.4.1 Assembly Features

An assembly feature expresses a relationship which exists between two or more parts within an assembly. The following relationships/assembly features were identified by the FEAST partners:

Attachment

Attachment is a physical and static link between two components. An attachment may be of a permanent nature as in a typical aircraft structure or may be temporary as in the case of tooling.

Connect

Connect ensures the flow continuity of a circuit. It applies exclusively to flexible cables, rigid tubes/pipes (e.g. hydraulics, air, oxygen) and their connection with equipment.

Pass-Through

The pass-through relationship arises when a hole or cut-out is used for the passage of one component through another (e.g. a stringer through a frame, or a pipe or loom through a structural part). The existence of this relationship may or may not necessitate the creation of the pass-through hole. For example if the hole previously existed for an alternative function such as weight reduction then the passage of a component will not involve modifications to the structure.

6.3.2.4.2 Feature Descriptions

Each of the above relationships will have one or many functions. These functions describe the purpose that the assembly feature fulfils. This may be considered as describing the design intent for the structure as it highlights 'why' the assembly features were created.

The function may also detail what effect the presence of an assembly feature has on the existing data model. For example the creation of an attachment assembly feature will in turn trigger the need for a fixing hole part feature. Representation of assembly features via their function means that modifications or deletions will govern the consequential modification or deletion of other assembly features or part features.

In addition to fulfilling a function there will also be attributes and constraints applied to the relationships. The following are examples of functions, attributes and constraints which may apply to the primary classes of assembly features.

Attach

Attach functions

Permanent

- Creation of attachment of major structure, sub structure, supports, brackets & clips
- Creation of attachment holes
- Creation of attachment flange
- Creation of fixing line
- Creation of supports, brackets, cleats and other 'Assembly Parts'
- Creation of stiffening
- Creation of load path
- Creation of an electrical conductive path
- Creation of aerodynamic steps and gaps

Temporary

- Attachment to jigs
- Attachment to holding fixtures
- Attachment to shape constraining blocks
- Attachment of spacematic templates (traditional techniques)
- Attachment to drilling jigs (traditional techniques)
- Attachment of transportation fixtures
- Association of hole pattern to machine program (modern NC techniques)
- Creation of tooling holes
- Creation of tooling lugs
- Association of tooling function to fastening holes

Attachment attributes

Permanent

- Load Transfer (True/False)
- Load Type (Gravity/inertia and Stress Flow) Shear Load, Tensile Load
- Structural (True/False)
- Interchangeable (True/False)
- Sealed (True/False)
- Seal Type (Fuel Seal, Pressure Cabin Seal, Water Seal)
- Sealant Type (e.g. Thiokol)
- Adjustment Mechanism (solid shim, wet assembly, slotted holes)
- Permanent (True/False) e.g. Major Structural Joint c.f. Removable door
- Geometric Tolerance Type (e.g. parallelism, surface etc..)

- Geometric Tolerance Specification (allowable deviation – to be specified after analysis)
- Manufacturing means (undefined, manual, Fixed Automatic Drill Riveter, Portable Automatic Drill Riveter, Drill Tack Riveter, etc..)
- Fastening means (rivets, bolts, hi-loks, welded, bonded, etc.)
- Torque (If bolts then this specifies the bolt tightness)

Temporary

- Adjustment available (e.g. clamp jaw width etc.)
- Direction of reaction force
- Geometric Tolerance Type (e.g. parallelism, surface etc..)

Attachment constraints

- Respect of existing relations
- Maximum allowable shear load transfer
- Maximum allowable tensile load transfer
- Minimum clearance from hole e.g. stringer
- Minimum clearance from edge e.g. stringer
- Avoidance of collisions/interference
- Material compatibility
- Stress fatigue resistance
- 'Manufacturing Means' specific constraints on fastening hole positioning

Connect

Connect functions

- Connection of hydraulic or electrical systems
- Creation of an electrical conductive path
- Creation of a fluid path
- Creation of a logical connection

Connect attributes

- Fixed connection e.g. Pipe – Pipe, Loom – Equipment Box
- Gimble, Bellows Connection e.g. Flexible pipe – Jack (Degrees of Freedom and so out of scope)

Connection constraints (hydraulic/electric systems)

- Respect of existing relations
- EMC compatibility

- Avoidance of collision
- Connector compatibility

Pass-Through

Passage functions

- Creation of pass through hole
- Enlargement of pass through hole
- Association of passage to existing hole (e.g. to a lightening hole)
- Provides passage for hydraulic piping and electrical looms
- Provides passage for tools, robots or human arms (Assembly/Maintenance)

Passage attributes

- Direction of passage through structure (normal to structure or otherwise)
- Geometric Tolerance Type (e.g. parallelism, surface etc..)
- Geometric Tolerance Specification (allowable deviation)

Passage constraints

- Respect of existing relations
- Minimum clearance to edge of hole
- Avoidance of collisions

Instances of assembly features

During the study many varied aircraft assemblies have been examined. Below is a list of aircraft component definitions and following that are descriptions of example features found within aircraft structures.

Aircraft component definitions

Shearweb – Plate accommodating shear loads
Frame – Structural components providing basic shape to a skin
Stringer – Long, slender stiffener
Pipe – Hollow fluid carrier
Harness – Group of electrical conductors
Clip – Small attachment component
Bracket – Attachment component
Skin – Thin external plate

Spar – Primary beam within an aerodynamic surface, running spanwise

Rib – Separator of two aerodynamic surfaces

Tie Bar – Slender tension member

Cleat – Attachment component

Seal Plate – Component providing or supporting a seal

Hinge – Attachment component

Equipment – Special components fulfilling a non-structural purpose

Floor Panel – Horizontal shear web

Diaphragm – Plate separating two regions

Stiffener – Providing a load carrying path which stabilises the shape of the stiffened component

Lagging – Provides thermal insulation e.g. to a pipe

Examples of permanent/non-permanent attachments

- Web – Stringer
- Web – Support
- Web – Clip
- Web – Jack
- Web – Pump
- Web – Equipment
- Web – Harness
- Web – Pipe
- Web – (Fixed) Skin
- Support – Pipe
- Skin – Stringer
- Skin – Frame
- Skin – Cleat
- Frame – Reinforced cap member
- Frame – Clip
- Frame – Shear tie angle
- Pylon – Fixed hinge
- Stringer – Harness
- Stringer – Pipe
- Stringer – Stringer
- Stringer – clip
- Clip – Shear tie angle
- Bracket – Pipe
- Moveable Panel – Gooseneck Hinge
- Rear spar – Skin panel
- Rear spar – Rib
- Rear Spar – Stay
- Rear spar – Back plate
- Rib – Rib
- Rib – Tie bar

- Skin – Rib
- Wing – Centre fuselage.
- Centre fuselage – Front fuselage
- Centre fuselage – Rear fuselage
- Engine – Pylon
- Pylon – Wing
- Rib – Drill Jig
- Spar – Drill Jig
- Front Spar Assembly – Main Jig
- Rear Spar Assembly – Main Jig
- Skin – Jig
- Stringer – Nesting plate
- Panel – Forming blocks
- Panel – Spacematic templates
- Stringer – Flexible support
- Stringer – Flexible clamp
- Shear web – Flexible end stop
- Shear web – Flexible vacuum ejector
- Flexible fixture – Clamp gripper (robot end effector)
- Stringer – Component gripper (robot end effector)
- Sub-assembly – Assembly gripper (robot end effector)

Examples of connect

- Pipe – Jack
- Pipe – Pump
- Pipe – Pipe
- Harness – Equipment

Examples of passage

- Pipe – Hole
- Harness – Hole
- Tool – Hole
- Machine – Hole
- Assembly Engineer – Hole
- Frame – Stringer
- Maintenance Engineer – Hole

6.3.3 Conclusion

The activities performed during this task have concentrated on examining 'real' examples of assembly structures. As a result the project has a better understanding of assemblies, the primary relationships which occur within an assembly and the constraints and attributes which are associated with these relationships. The relationships identified were formally organised in Task 3 by using the catalogue template developed within Task 2.

The production of several scenarios based on real examples and using the relationships identified, helped the partners to understand the potential use of assembly features. The task also helped to initiate studies on the importance of 'product structure' within the assembly. A methodology of how this structure can be represented both formally and pragmatically in terms of a computer system was developed.

Chapter Review

This chapter has introduced the background to Product Modelling using features. It has described the new area of interest in feature research i.e. the application of the feature paradigm to assemblies. It has outlined the objectives of the FEAST project and focused on the sub-task which was linked to the Eng.D. study.

The next chapter is the main discussion chapter of the thesis and is concerned with the research into DFMA.

Chapter 7 Discussion

Summary

The principal aim of this research project was to investigate and improve DFMA in the aerospace environment. This chapter will discuss the issues raised during the research done on:

- the practical application of qualitative DFMA rules and principles at Avro (Chapter 4);
- the application of established, quantitative DFMA tools, first of all in the general aerospace environment, and then specifically at Avro (Chapter 5);

7.1 The Practical Application of Qualitative DFMA Rules and Principles at Avro

The element of the Eng.D. research activity that primarily focused on the practical application of qualitative DFMA rules and principles at Avro, was the Four Corners project. From the description of DFMA given in Chapter 1, recall that DFMA is a philosophy or check that must be applied to all design changes. In this case, the Four Corners project is a *Production Easement* that has had DFMA principles applied to it.

From the Four Corners project conclusions and recommendations have been be drawn on three areas:

- recommendations on how the design process can be improved;
- implications of trying to incorporate design changes late in a product's life cycle;
- recommendations on how the customisation activity should be approached on the next generation regional jet.

7.1.1 Recommendations on How the Design Process Can be Improved

The following recommendations apply to both the new product development design process and the existing product design change process.

1. Give designers more responsibility

Most designers are capable of carrying out simple stress calculations. Why is it necessary to seek Stress department approval for every single design change? This is time consuming, and it holds up the design process. A scheme similar to the Approved Operator Scheme (i.e. operators on the shop floor approving their own work instead of having to wait for an inspector) could be introduced into the design process. With the Approved Operator Scheme, work packages are graded, some things still need an Inspector's approval, other less critical work does not. Surely this can be applied to the stressing aspect of design.

2. Encourage creativity

Since Avro now has limited design resource, there is rarely enough time to produce design alternatives. Designers have to stick to traditional methods and philosophies in order to meet the design delivery targets. This is leading to sub-optimal design solutions. Sufficient resource should be allocated to allow several design solutions to be created and evaluated in the time available.

3. Reduce the clerical aspect of drafting work

Designers should spend more time optimising the design solution and less time chasing up paperwork. Design estimates are done for drawing the job not carrying out all the cumbersome and sometimes lengthy investigation of establishing the mod states in preparation for the job. Designers are also having to do clerical jobs once the design is complete, for example, writing ESOPS (electronic parts list) and DDIs (documentation that enables the drawing to be issued onto the drawing system), issuing drawings etc..

Designers sometimes experience difficulty in trying to establish the Mod standard of the aircraft (see scenario 2 in section 4.3 of Chapter 4 for an example). The Mod standard has to be established so that the designer knows what existing structure or equipment is likely to impact on the design changes he is trying to incorporate. This type of preparatory information should be prepared in advance by clerical staff and presented to the designer.

4. Have traceability within the drawing system

Avro's current drawing system is inadequate in the area of traceability. There is no coding and classification capability in place, that will allow parts of identical or similar types to be traced. This leads to the proliferation of part numbers and duplication of effort within the design organisation. The only form of traceability is in the memory of the designer. If he is able to recall a similar part that he may have created before, then this can be manually traced, otherwise a new part has to be created.

5. Improve the teamworking capability

The Four Corners project was a particularly good vehicle for testing the effectiveness of teamwork within Avro. The team had representation from all the necessary disciplines:

Design, Stress, Engineering, Operations, Procurement, Sales and Marketing, and external suppliers; however, the only full time team members were those from the Design and Engineering functions.

The team members were not co-located and progress communication was done principally through weekly team meetings. Consultation between the disciplines within the team was done informally as and when each member felt he needed advice or a decision.

Although the team had a good balance of the necessary 'type' of resource, the communication within the team was not ideal. The following points highlight some of the problems:

(a) Changes in the scope of the project

The scope of the Four Corners project changed several times due to political sales issues which were not within the control of the team. Although this was sometimes frustrating, it was nevertheless inevitable with design changes of this type i.e. those directly linked to customer requirements. Unfortunately, re-scoping the project as a result of these changes did cause some confusion and conflict within the team.

(b) Understanding and applying the agreed design philosophy

It is important that the design philosophy agreed at the start of a design project is communicated to the team and then more importantly, adhered to throughout the duration of the project. Trying to ensure this happens is not always easy; it is easy to inadvertently revert back to old habits if the new philosophy is not continually emphasised. At certain stages in the Four Corners project the team lost sight of the original agreed design and build philosophy.

(c) Commitment and communication between the functions within the team

Setting up a multi-functional team does not guarantee good communication. Commitment from the individual functions is one of the keys to successful communication.

In the Four Corners project an example of poor communication between the team and the

Stress department led to late changes to the design of the 3R modular underfloor support structure. These changes resulted from the re-stressing of structure that the Stress department originally thought was for one purpose when in fact it was for another. Unfortunately, BAe Chadderton who are responsible for supplying the structure as part of the rear fuselage assembly had already been instructed to install the original design and had subsequently manufactured several kits of the original parts. This late design change, thus, led to rework, scrap, and slippage of the introduction of the complete 3R modular support structure.

Another example involved the Production function. At the start of the project the Production function played a vital role in scoping the design changes. However, as the project progressed the commitment from Production became less and less; this led to problems towards the end of the project. Although the management in Production were briefed in detail on several occasions, on the design and build sequence changes about to be introduced, they did not do the necessary preparatory work to assess the magnitude of these changes. Had this matter been given the attention it warranted the introduction of the Four Corners improvements would have been a lot smoother.

Getting the Production and Stress functions to commit full-time resource to design improvement teams is extremely difficult. Resource is becoming scarce in all areas of the business, and obtaining full-time personnel in the early stages of a design project is becoming increasingly difficult.

(d) Communication with external suppliers

The Four Corners team also experienced communication difficulties regarding the galley design modifications and required target dates with one of the galley suppliers.

In summary, the communication problems discussed above could be improved or perhaps completely eliminated if teams have:

- full-time resource – the "consult, if and when needed" philosophy does not work in projects such as Four Corners. Full time commitment is needed from all functions, even suppliers. Without it proper communication of the relevant information is impossible.

- co-location – this is the only way team members can keep up to speed with everything that is going on within the project. The team must not rely on weekly progress meetings; too much happens in between times.

6. Develop manufacturing process knowledge expertise

As Avro does not have a detail manufacturing capability, there is a deficiency in the design organisation of access to manufacturing process expertise i.e. knowing which processes are best suited to given applications, and being able to make recommendations as to how a part should be designed to suit the chosen manufacturing process. Even in companies that have a detail manufacturing capability there is still no guarantee that the capability is "state of the art" and that manufacturing knowledge gets fed into the design organisation.

There is a need for some reliable and consistent way of providing designers with information on new manufacturing processes and assembly techniques. There must also be relevant expertise available in the design organisation to support the creation of efficient designs that suit the chosen manufacturing process. This may come from: educating designers, having dedicated manufacturing experts, or utilising DFM expert systems.

7. Disseminate manufacturing and assembly cost information

Several design concepts cannot be evaluated or trade-offs be carried out without sufficient manufacturing and assembly cost data. Designers and engineers have limited knowledge of costs therefore a Design for Manufacture tool similar to those described in chapter 5 would be particularly useful.

Access to the Procurement department's cost database is another option. A system could be set up where parts of similar designs can be traced for cost purposes. This links into the coding and classification system for part type traceability discussed in point number 1.

8. Work to manufacturing and assembly cost targets

It is no use having access to cost data if nobody works to cost targets. All design work should be carried out to stringent cost targets. Design work packages are given overall cost targets but they are not broken down to the detailed manufacturing and assembly level.

9. Be aware of the decision 'Design <u>for</u> Manufacture or Manufacture <u>for</u> Design?'

In section 1.2 of Chapter 1, the principle of DFM was explained. The point was made that in companies that perform in-house component manufacturing, ideally importance should be placed on designing components to suit the equipment and machinery that is available.

However, the question of "When should Design dictate to Manufacture and when should Manufacture dictate to Design?" should be explored.

When the functionality and performance of a product are dictated by the shape or contour of its major constituent components, as in the case of aircraft manufacture (nose section, wings, centre fuselage, engine nacelles etc.), then *manufacture <u>for</u> design* should be the edict. That is to say the design and ultimately the performance of the final product should not be compromised by the limitations of the currently available manufacturing and assembly processes. New manufacturing and assembly technologies should be looked for, that will allow the desired design to be achieved. For example consider the case of an optimum aerodynamic design of the aircraft nose section, the full advantages given by the aerodynamic development efforts must be retained by finding a manufacturing process that will produce the desired skin profiles. This is Manufacture <u>for</u> Design.

When the functionality and performance of a component is not critically reliant upon its external shape or form, then efforts should be made to tailor the design to suit existing manufacturing processes and the emphasis should be on reduced part count and standardisation. At sub-assembly level, designers must seek to ensure that parts designed conform to the capabilities of currently available manufacturing process. This is Design <u>for</u> Manufacture.

Surrounding this debate is the issue of cost; ultimately this will dictate the final solution.

10. Have better access to competitor product information

It is important that designers and production personnel are aware of competitor practices and developments. However, since purchasing competitor products and performing 'tear down' analysis (i.e. stripping it down to find out how it is made) is somewhat impractical in the aircraft industry, perhaps visits to maintenance facilities and aerostructures manufacturers on a regular basis should be instigated. Existing information on competitor products should be centralised and more readily available, so that it can be utilised by all design teams. In the heart of the design and production organisation, it is easy to forget that there is competition out there!

11. Develop a better understanding of the new trade-off model based on today's business priorities

The peculiarities of the aerospace industry were discussed in Chapter 2 with the aim of highlighting the factors that influence the trade-off decisions in aerospace design. There is a fine line between accepting these limitations and hiding behind them, i.e. not pushing forward the boundaries of development and innovation.

In section 2.2.2 of Chapter 2, the traditional approach to aerospace design was described. The following discussion attempts to highlight the complexity of the trade-off decisions faced in today's design environment and the need to develop a structured model to help clarify all possible implications. In order to develop this model, the information described above i.e. manufacturing and assembly, cost and cycle time data, along with information on new manufacturing processes and assembly techniques, must be made available to the design teams.

Trade-Off Model

Safety, weight, drag, and systems integration i.e. all the functionality, performance, and reliability aspects of product realisation can no longer be considered in isolation from the cost aspects i.e. manufacture, assembly and maintenance.

Obviously, safety is still the key design priority, yet even the important aspect of safety can be managed in a cost effective way.

If manufacture, assembly, operation and maintenance are referred to as the *stages,* weight, stress, production volume, drag, cost, flexibility, CAA regulations etc. as the *constraints*, and part count reduction, assembly automation, standard parts, self-jigging components etc. as the *design aims,* then a new trade-off model can be set up. The following examples illustrate the complexity of the model.

***Example 1*.**

Aim – part count reduction

Effect of constraints:

(a)Weight and stress

There is a possible decrease in weight, simply due to the elimination of a physical part, but, it depends on how the part is eliminated. There could be three options:

1.A completely new design – it is possible to predict how the weight will be affected with this option.

2. Simple integration (union instead of attachment) – the weight is unlikely to reduce much if the same manufacturing process is used. However, if a completely new process is chosen to achieve the integration, there could be a considerable increase in weight. This is because in order to meet stress requirements i.e. resistance to crack propagation, the component walls may have to become thicker. This would be the case if several fabricated parts, for example, are replaced by a complex casting or a machined item.

3. Discarding the part altogether – this option obviously contributes to weight saving, but its occurrence is rare.

(b) Cost

1. There will be a reduction in associated 'hidden' costs, i.e. producing a purchase order, inspection, delivery, producing a drawing, etc..

2. There could possibly be an increase in manufacturing process cost. The effect on cost is similar to the effect on weight; it depends how the part integration is achieved.

3. The maintenance cost could increase since the entire unit would have to be replaced as opposed to a small part of it. Therefore, the decision to reduce part count must take into account maintenance requirements. It is commonly assumed that if a component is easy to assemble then it must also be easy to maintain; this is not always the case.

Example 2.

Aim – assembly automation

Effect of constraints:

(a) Cost

Assembly automation increases the cost of assembly tooling and part manufacturing tooling. Interchangeability (tight tolerance design) is vital when adopting assembly automation: 'fettling to fit' will not do.

(b) Flexibility

Assembly automation decreases the assembly cycle time and therefore increases the flexibility of the production process.

The trade-off here is the cost of tooling investment versus the increase in flexibility. Some issues to consider are:

1. Is it cheaper to increase labour even if it proves necessary to forfeit the reduced cycle time?

2. Is volume the parameter which should be used to try to justify automation or does flexibility carry more weight?

3. How do you measure the cost of not having flexibility?

These examples illustrate how complex today's trade-off evaluations can be. A *design aim* that may be beneficial to one *stage*, may be detrimental to another, as a result of the *constraints* associated with today's business. To arrive at an optimum solution, the design team must investigate these implications thoroughly. They must have access to data that will allow them to quantify their assessments and they must work to production cost and cycle time targets. Traditionally design targets have originated from the design environment itself for example, weight, aerodynamic tolerance, stress, etc. These targets are associated with product functionality and performance as opposed to production feasibility. If any kind of valid trade-off evaluation is to be achieved, a comprehensive set of data relating to both product performance and production feasibility must be readily available to the design team, during the early stages of the design process.

7.1.2 Implications of Trying to Incorporate Design Changes Late in a Product's Life Cycle

Although the RJ/146 was designed some 25 years ago, and can therefore be classed as a mature product, it is still subject to many design changes. When the sources of these design changes are investigated (see Appendix 1), it becomes clear that some of them are inevitable and others could have been avoided, had attention been paid to manufacture, assembly and maintenance issues at the original design stage.

Introducing design changes late in a product's life cycle, for whatever reason, brings with it a host of implications which need careful consideration. The purpose of this section is to draw on experiences gained primarily from the Four Corners project and present a hypothesis on whether 're-design' is effective within the aerospace environment. The following points help develop the discussion:

1. Impact of re-certification

The question of re-certification is a prime factor in deciding if a re-design proposal is feasible. Substantial modification to any structure or equipment on the aircraft could also involve costly re-certification. In the Four Corners project it would have been far easier to design one underfloor support structure and have the galley suppliers modify all their galleys to suit. Unfortunately, moving the galley attachment points any great distance would have involved re-certification of the galley unit. The cost and time associated with this activity made galley modification absolutely impractical. The Four Corners project had to work within the restriction of minimum modification to the galley unit itself.

2. In-sequence design issues

The term "in-sequence" means to ensure a re-design is amended so that it is in line with the build sequence of the aircraft, i.e. find the best place for it in the build sequence (push it as far back as possible) and then do all the necessary alterations to the actual re-design work package and to the surrounding area on the basic aircraft so that the design is as efficient as it can be.

This exercise may involve remove lightening holes from the basic structure, re-positioning bug eyes (electrical wiring clips) in the original wiring etc. If for example, a re-design involved a bracket that had to be an odd shape otherwise it would have collided with an existing wiring connection, the in-sequence design would involve moving the wiring connection out of the way and then designing a more simple bracket.

There is rarely the inclination or resource to transfer a product improvement re-design (or "retro" design), such as Four Corners, into a proper in-sequence design. Therefore, although a design change might be justified late on in the product's life cycle, the design solution is unlikely to be the most efficient because it will be done 'around' existing structure and systems. It is very rare that a retro design is turned into an in-sequence design.

3. Justifying the investment

The later the decision to make a design change, the harder it is to justify the investment. In trying to prepare the financial justification for investment in a re-design proposal, it is also difficult to clearly understand all the implications and accurately establish the cost savings.

4. The scope of the re-design activity should be clearly defined at the start and supported to completion

In point number 2 the issue of incompleteness regarding turning retro-drawings into in-sequence drawings was discussed. The issue over the lack of money and resource can also affect the actual scope of a design change. As the Four Corners project progressed, it experienced this kind of cut-back.

The Four Corners project soon became a very high profile improvement project within the company. The savings and benefits anticipated as a result of project were well documented and supported by senior management. However, even with this backing, lack of sufficient manpower resource for the project caused many problems and the scope of the design improvements had to be scaled down. Although significant improvements were made, they could have gone even further, for example, the 1R position could have been re-designed and brought to the same standard as the 2R and 3R positions. This lack of commitment has led to two standards of galley attachment on the aircraft.

5. Ambiguities over the original intended purpose of a component in a design

In attempting to perform re-design, cases can arise where much time and effort is wasted into trying to establish why certain parts were designed in such a way in the first place. For example, was it solely to do with the functionality of the design, or was it for stress reasons, or aesthetic reasons.

Designers do not have to document the purpose of a particular component in a design. This then has implications when design improvements such as part count reduction, are being sought. If no one can understand why a component exists, then the part cannot be confidently modified or eliminated. The only solution would be to develop a completely new design for the entire system.

An example of this occurred in the Avro/Westland pilot study (see section 5.3.2 of Chapter 5) which tried to improve the design of the RJ doors. A turnbuckle (whose general purpose is to regulate the tension in a control cable) was in a position that appeared to make its purpose redundant within the overall design of the mechanism. Even the design specialist could not offer an explanation.

6. Interrupting a customer order

Trying to make design decisions around a 'living' product (i.e. one that is being marketed and sold) is extremely difficult since it can have a disruptive effect on customer orders. In the aircraft industry customers have a lot of influence on what the aircraft producer can and cannot do. Any proposed changes that may affect the airline's fleet commonality can become major issues.

The debate centres around whether airlines should be allowed to effectively restrict the producer in its capability to make savings.

An example of such conflict with regard to the Four Corners improvements, occurred in a recent RJ order. Soon after the order was placed a substantial stake in the airline was bought by an airline that currently had orders with Avro for one of its other subsidiary airlines. The consequence of this was that the parent airline wanted to have fleet commonality across its subsidiary fleet i.e. it wanted exactly the same equipment on its new orders as it was having on its existing orders. The main reasons it gave for this were related to the maintenance of the fleet. It wanted to maintain the aircraft from both airlines at a central operation and complained that it would be unable to do so if the galleys were not of a similar standard.

In order to meet this customer request Avro would have had to delay the full introduction of the improvements generated through the Four Corners project; the customer was effectively restricting Avro in its capability to make savings. However, the Four Corners improvements had been written into the order contract which had been signed. This led to a situation where the airline attempted to buy its way out of the clause in the contract. Fortunately, the airline did not pursue the request and the Four Corners improvements went ahead.

The issues arising from this situation can be summarised as follows:

- allowing the airline to pull out of the agreement would have been disastrous for Avro. It would have led to unnecessary rework, scrap and reverting back to old build logic. It would have significantly damaged the credibility of the project and affected the morale of those who had worked hard to put the improvements in place;
- the airline did not seem to be concerned about the effects that pulling out of the Four Corners improvements would have on Avro. Reverting back to the pre-Four Corners standard of aircraft would have cost the airline almost £0.5million in compensation costs to Avro (this figure is effectively the 'loss of savings' that Avro would have otherwise been able to generate. It does not include compensation for the disruption to operations which would have occurred as a result of no longer being able to count on a consistent underfloor structure and galley attachment method from one aircraft set to the next. In other words production would have lost the opportunity to 'learn'. This aspect is intangible and therefore difficult to quantify. However, it was nevertheless one of the main advantages envisaged as a result of introducing the Four Corners project in the

first place);

- are the right people involved and consulted during sales negotiations? For example, do the people involved really understand all the important aspects of the airlines maintenance activity?;
- why were Avro's other customers not concerned about having two standards of galleys on their aircraft?;
- a school of thought regarding this case was that it does not matter what the customers want to do as long as they pay for it. But surely, Avro should not be in the business of making money out of going down engineering cul-de-sacs!

7.1.2.1 Is Re-Design Effective Within the Aerospace Environment?

The points discussed in the previous section can be summarised as follows:

- re-certification costs mean the re-design proposals always have to be conservative. The later in the product's life cycle the design proposal comes, the more conservative and 'safe' it has to be. Safe design changes rarely lead to significant savings;
- re-design is never completed to the in-sequence state, therefore the design solution is not the most efficient;
- savings can never be accurately quantified;
- the issues within the day to day business of building and delivering the aircraft are considered much more important than any re-design exercises which are taking place, even though they may be aimed at reducing production costs and cycle times. For this reason resource commitment to the re-design activity is poor;
- investigations into re-design can be further complicated by lack of knowledge regarding the original design intent;
- a political minefield is likely to be encountered with the customers.

In conclusion, for a product that has a long life cycle re-design is inevitable for two reasons:

- the usage or role of the product may change;

- performance improvements will have to be sought in order to remain competitive with the new products in the marketplace that have exploited technological advances.

For these reasons aircraft producers have no choice but to re-design certain aspects of the aircraft at certain stages in its life. The points discussed reveal that although re-design may be justified financially, the resultant design solution far from efficient.

7.1.3 Recommendations on How the Customisation Activity Should be Approached on the Next Generation Regional Jet

As the Four Corners project was essentially about the aircraft's customisation activity, conclusions and recommendations can be made specifically on the area of customisation for the next generation regional jet.

7.1.3.1 The "Vanilla" Aircraft Concept

The debate must be explored, which questions whether, in the current climate, airlines are desperate enough to accept "vanilla" aircraft if it means substantial savings in ownership costs. In America, some years ago, the vanilla plane concept arose. This concept was to build all aircraft to the same standard and have no customer options. As customisation is a major contributor to ownership costs, its elimination would result in significant savings.

Unfortunately the "vanilla" plane concept died. United, for example, reacted to the idea by saying: "No way. The customer has to know he's on a United airplane." But airlines might be desperate enough to listen now. U.S. Air's Financial Planner asks: "If there were no customer options, how much cheaper would a 757 be?" Then he answers: "If the reduction were substantial, I would not want the options. It would be in everyone's best interests. And from the conversations I've had with other airlines, a substantial portion of the industry would prefer cheaper airplanes."

Manufacturers can only do so much. Boeing ballyhooed 777 development that brought customers and suppliers onto the design team to learn valuable lessons on what things cost.

But according to a materiel staffer, the design team argued endlessly about inanities such as the shade of white for the cabin, when all the passengers do is "get on the plane, read or work, eat or go to sleep".

Whilst there is still over capacity in the aerospace industry, at the end of the day airlines still have the upper hand when it comes to negotiating aircraft orders. A U.S. airline rep says with regard to Boeing: "The word is Boeing will always bail you out." A company manager confirms this. "We'll never get to the point of take-it-or-leave-it options. Some airlines like squirt soap, some like bar soap, some want the soap on the right, some on the left. We want to give them the chance to differentiate their product but we want to do it as simply as possible. Increasingly, they'll understand it adds to overall cost but we have to be flexible enough to satisfy their needs without driving ourselves crazy." (Feldman (94))

7.1.3.2 Customised Aircraft

Assuming that for the next generation regional aircraft, the vanilla concept will not be practical and customisation is still a major feature, there is a need to make everybody in the company understand that customisation is the critical aspect of the aircraft production process, and has significant bearing on the company's ability to deliver aircraft on time. Not only does customisation win orders but it is the key to how much profit (or loss) is made. Customisation should not be viewed as an awkward inconvenience at the end of the aircraft final assembly activity.

The following sections will discuss proposals relating to customisation. The marketing process, the physical design of the aircraft, and some aspects of the final assembly activity will be covered.

7.1.3.2.1 Marketing Process

The discussion regarding the marketing process centres around the need to have a clearer understanding of intended product usage at the aircraft development stage. Is this possible?

Section 7.1.2.1 stated that due to the long life cycle associated with aircraft, design changes are inevitable for two reasons: the usage or role of the aircraft may change, and performance improvements will have to be sought.

Many problems in aircraft design result from the usage or purpose of the aircraft changing as the life cycle progresses, for example, the RJ/146 was originally designed with one galley, because at that time this was the level of service passengers expected; the RJ/146 was not originally designed with stretch versions in mind, therefore, the aircraft ended up with two completely different centre fuselages and one hybrid.

It may be acceptable to modify a product to take advantage of new technologies or for performance enhancement, but the examples described above are not changes that are made for these reasons. They are simply done because the role of the product changed during the course of its life cycle.

In section 4.3 of Chapter 4, the problems associated with trying to carry out customisation design changes during the life of the product were described. The only way to completely eliminate re-design on the next regional jet is to prepare all potential customisation design requests at the concept design stage. This is not to say that the aircraft will be customised to the hilt; the customisation packages will be treated as options. It simply means that the drawings and engineering will be in place ready for selection.

The key to successful "concept design stage customisation" is being able to produce a design which is adaptable for a purpose which is not yet defined. There are two issues associated with this. First, is it possible to predict all future customer requirements?, and second, will this up front customisation concept ever overcome the commercial constraints placed on new product development? (i.e. will the additional up front investment be made available?).

If it is deemed impossible to predict all the potential customer requirements of a product which has a twenty year life cycle, a compromise will have to be reached. The customisation design organisation should have a "Marketing Feasibility Group"; a team of designers dedicated to customisation development and marketing feasibility studies. The group will look into the feasibility of including up and coming equipment and services on the aircraft, for example, telecommunications, in-flight entertainment concepts etc. Instead of waiting for customers to demand something new in the middle of negotiations, which will lead to frenzied feasibility studies, the design organisation needs to be able to pre-empt the next customer trend. If, for example, an airline requests telephones, it would be beneficial to have done some preparatory work in advance to assess possible locations, and ideal wiring runs.

The aircraft producer should be one step ahead with their knowledge. If these things are looked at in advance and without the pressure of timescales, much more efficient designs would be produced. Instead of waiting for customers to say what they want, aircraft producers should go to the airlines and tell them what they need.

One way to ensure that the group investigates the 'right' ideas would be to look at the equipment and services being offered on long-haul aircraft. This should be read across to the regional market. Remember, customers want a seamless service, so the large aircraft sector can be used as an indicator of what future regional aircraft should have.

In summary:

- the ideal situation would be to have a clearer understanding of the customisation requirements for the entire life of the aircraft, and to prepare everything at the development stage;
- the compromise situation would be to build in flexibility at the development stage and then to be at least one step ahead of the customer request by having a Marketing Feasibility Group.

The idea of having a Marketing Feasibility Group, responsible for pre-empting customer requests goes part way to alleviate the time pressures which often compound the customisation problems within a "customise as you go" philosophy. The more radical way of approaching customisation would be to do it all at the concept design stage.

7.1.3.2.2 Physical Design

The new customisation philosophy for galley installation on the RJ has been driven by the typical constraints, which inevitably exist when dealing with a product which is this far into its life cycle. Any changes which would have involved major structural modification would have led to unrealistic investment in tooling, re-certification and design effort. Therefore, since the project had to be approached with these boundaries in mind, the most effective design in terms of flexibility, standardisation and simplicity, but with minimum increase in non-recurring cost and weight was sought.

Four Corners was the best solution for the RJ, with the resources that were available and within the time constraints that were imposed. The customisation philosophy of the next generation regional jet should be markedly different. Improvements should include:

1. Designation of customisation zones at the start of the aircraft development

Areas should be identified and designated as "customisation zones" at the start of aircraft development. The customisation zone would be a volume rather than an area; it would include the floor, side wall, and roof. Some features of these zones would be:

- floor beams that have no lightning holes;
- no electrical systems runs, piping, and peripheral structure allowed in the floor, side wall or roof area.

2. More efficient equipment support philosophy

A more efficient support philosophy for installing customisation equipment on the aircraft should be adopted. For example, a structural floor panel, or further utilisation of the seat rails by attaching equipment directly to them. Both of these concepts would have significant implications on how the main aircraft structure was designed. They would significantly improve the method of equipment installation and lead to substantial assembly cost savings.

3. Standardisation of parts

The aim would be for complete standardisation of parts within and across each customisation zone. This would also extend to other areas; standardisation should be sought throughout the aircraft.

4. More efficient sealing philosophy

A better understanding of the causes of corrosion must be gained, so that a more efficient sealing philosophy can be developed. No research has been done on the effectiveness of the RJ's sealing philosophy.

5. More efficient vestibule trimming philosophy

Three aspects of the trim design philosophy need consideration:

- simplification – in order to reduce assembly time;
- aesthetics – there should be an interior design specialist responsible for co-ordinating all decisions associated with trim, otherwise the trim becomes a mixture of endless shades and textures, none of which match;
- robustness – it is vital that the trim can withstand the wear and tear of the aircraft in service.

7. Design customisation equipment that requires no trimming

To reduce assembly time and the risk of damage during installation, equipment should be designed without the need for trimming, so that it can be installed first time.

8. Tooling philosophy

Need to develop flexible/multi-purpose tooling within the customisation zone.
Variation in structural build also needs to be tightened up.

9. Understand the impact on customisation zones of having more than one series of aircraft

If an aircraft is to be developed as a series, then the customisation design should reflect this. The implications of varying lengths, frame positions, peripheral equipment in different locations, etc. should be thoroughly investigated.

The points discussed above highlight that “Design for Customisation” and “Design for Series” should be considered as an important element of the Design for X model, during the development phase.

7.1.3.2.3 Final Assembly Customisation Activity

1. Assembly logistics

Avro’s current philosophy regarding inventory is to operate a just-in-time system for high cost items and to have a stocked, open access parts facility for common low value items.

The new galley underfloor support structure kit of parts approach, devised in the Four Corners project, lends itself to the open access parts philosophy. By having four similar designs the Four Corners project has effectively ‘minimised variation, but still maintained choice’. The structural components used in the design are not considered to be high cost items and as such, having stocks available will not severely impact interest payments on held inventory. Holding such items as readily available stock eliminates the concerns regarding shortages and late deliveries which are particularly critical during the customisation stage of the final assembly process. Also, economies of scale can now be used when ordering the parts.

The design of the next generation regional jet should look for opportunities to standardise low value parts used in customisation, so that the advantages of an open access logistics system can be maximised.

2. Assembly planning/build sequence

The entire customisation activity would be much easier if the customisation work packages were integrated as far upstream in the aircraft build sequence as possible; even back to the major unit suppliers.

The benefits would be:

- minimum disruption in the later, critical stages of the final assembly activity;
- creation of more efficient (in-sequence) designs because there would be less chance of collision with the original structure i.e. the area would be 'clean';
- reduction in assembly installation time because the designs would be simpler and there would be better access.

Although it is clear that there are significant benefits to be gained by integrating customisation work further upstream in the build sequence, the practicality of doing so hinges on the unpredictable nature of customisation itself i.e. not being able to anticipate or foresee customer requirements in advance, ever decreasing delivery lead-times, and last minute changes to customer requirements.

Predicting all customisation requirements at the concept design stage or at least just having flexibility through customisation zones as discussed earlier, will also ensure a more efficient customisation build sequence integration.

7.1.4 Conclusion

The major restructuring that has gone on at Avro leading to the effective dissemination of the design organisation and the elimination of new product development, has meant that it is highly unlikely that many of the recommendations described in the sections above, will be implemented at Avro. The place where they will be valid is in the design process for the next regional jet, which will take place at the joint venture company (AI(R)), headquarters, based in Toulouse.

7.2 The Application of Quantitative DFMA Tools

This section discusses the applicability of quantitative DFMA tools, first of all in the general aerospace environment, and then specifically within Avro. The arguments are based on the results of the pilot studies described in Chapter 5.

To recap, the DFMA tools investigated, seek to simplify product structures through part count reduction, and then provide manufacturing and assembly cost measures that can be used for comparison purposes. These measures guide the designer to the critical areas that need consideration in the re-design solution. The tools do not provide actual re-design suggestions.

7.2.1 Do Quantitative DFMA Tools Have a Place in Aerospace Design?

1. Raises design for assembly awareness

The DFA tools make design teams think about the assembly process in a systematic and disciplined way.

2. In the aerospace application the part count reduction philosophy is more important than the detailed analysis of the assembly sequence

The philosophy of part count reduction is valid and is probably the most applicable aspect of the tools in aerospace design. The detailed analysis of handling and insertion times down to the last second, seems inappropriate when one considers the scale of the aircraft production activity (at Avro it takes 15 weeks to assemble an aircraft and 18 aircraft are produced per year).

Investigations have revealed that some companies, for example BAe Lostock and JCB (manufacturer of earth excavating equipment) after acquiring this type of DFA software, adopted the philosophy of seeking part count reduction, but soon stopped using the detailed assembly sequence analysis facility.

The Avro/Westland pilot study demonstrated that this is likely to happen. By the second week of the study, the assembly sequence analysis aspect of the exercise was abandoned and the search for part count reduction and standardisation opportunities took priority. The design teams just wanted to devise new re-design solutions by focusing on the part count reduction criteria, and sharing ideas between themselves, rather than using the assembly data to direct them to specific areas of high assembly cost.

Welter(90) suggests that these tools "enable communication between the people involved......professionals who might otherwise tend to see designs only from their own perspectives – functionality versus manufacturability, for instance – are freed from their conventional thinking and creativity just flows."

Unfortunately, some of the ideas that came forth in the Avro/Westland pilot study were too radical to implement on the RJ doors because the financial investment could not be justified at this late stage in the aircraft's life cycle.

3. DFMA tools must be further tailored to suit the aerospace application

DFA tools

Application of the DFA methodologies in their current form is not altogether suitable for the aerospace application. The pilot study conducted with BAe Sowerby, showed that the sample structure could undergo significant part count reduction, through merging several of the parts. Unfortunately, there are significant implications in merging pieces of aircraft structure. Factors such as crack propagation boundaries and accuracy of tooling play a key role in this example. The three criteria used by both Boothroyd-Dewhurst and Lucas, for assessing if a part is essential or non-essential, and ultimately, if it should be combined with another part, does not take into account the peculiarities of aerospace design.

The Avro/Westland pilot study has reinforced the view that in order for these types of tools to be used in the aerospace industry effectively, the peculiarities of the industry must be understood and somehow woven into the mechanisms on which these methodologies are based.

Additions to the criteria could include:

- does the part have to be separate for stress reasons?
- does the part have to be separate because tolerances cannot be guaranteed (this criterion is particularly relevant when using the tools for re-design of a mature product).

DFM tools

DFM tools should ideally be tailored to suit particular industries. For example, wage rates, machine running rates, specific process data (sealing, special treatments etc.) etc. should be added to the database.

When material and manufacturing processes are being selected for the re-design solution in aerospace design, weight must be a key factor. This peculiarity of aerospace design should have significant influence on the final decision.

4. There is evidence that DFMA tools are being used in aerospace applications

It is often suggested in the literature on DFMA tools that they were initially developed with relatively small, simple bench assemblies in mind and the majority of the case studies reflect this. Most case studies refer to mechanism-based assemblies of a size that could be conveniently assembled on a desk top. Typically, they would be tape recorders, video recorders or car assemblies like alternators, water pumps or pedal boxes. However, the McDonnell Douglas case study (see section 5.1.3 of Chapter 5) has demonstrated that the tools are useful in the aerospace environment. Unfortunately, it has been difficult to establish exactly how the tools are being used in the company.

5. Not absolute measures

DFMA analysis tools do not give 'absolute' cost measures therefore they cannot be used to compare against real budget targets. They can only be used for comparison purposes to see if one design proposal is better than another.

6. Relevant design expertise is vital in the re-design team

Due to the safety critical nature of aircraft design, it is not always possible to go with a re-design solution, simply because it has a better 'design efficiency', part count and assembly time. Also, due to the complexity of some of the sub-assemblies on an aircraft there may be functional reasons that are not immediately obvious, which may also restrict the re-design solution. Thoroughly understanding the functionality of a sub-assembly or component is more difficult in aerospace design because of the overall complexity of the product. Examples of this arose during the re-design exercise of the RJ doors in the Avro/Westland pilot study.

The way to overcome these difficulties is to ensure that design teams have the relevant functional specialist in the particular area under analysis, and also to have a stressman, because few things can be changed without Stress department approval. Ensuring these skills are included in the team, will mean decisions can be taken immediately, on the feasibility of the new design proposal, without having to go through further, unnecessary explanation of the idea.

In summary:

- the detailed analysis into part handling, insertion and fixing is of little relevance in the aerospace environment. The most applicable aspect of the DFA tools is the simplification of the product by carrying out the structured analysis to look for opportunities for part count reduction either by elimination or combination with another part. However, some modification to the 'three criteria' on which this methodology is based will have to be done;
- the DFM cost estimating tools are of relevance. The ability to estimate costs early in the design process will benefit the aerospace industry as it does other industries. Note, this is in terms of being able to compare design solutions rather than compare against budget 'must cost' target values. In order to obtain 'absolute' cost values some tailoring of the cost database will have to be done to suit the aerospace application, i.e. processes specific to the aerospace industry will have to be included;
- the design team should include a design expert in the particular area under analysis and also a stressman.

7.2.2 Do Quantitative DFMA Tools Have a Place at Avro?

Since the design environment at Avro is now focused on support for the current product and not new product development there isn't sufficient design work to justify an extensive introduction of DFMA software and training. It is important to be clear that it is the quantitative DFMA tools that are being referred to here, the qualitative DFMA rules and guidelines for example, part count reduction, standardisation etc. are always relevant and worth striving to incorporate.

The RJ is nearing the end of its life cycle with an estimated 6 years of production life left. There is no time to recoup the type of investment involved in any substantial re-design of the aircraft. However, there are still opportunities for cost reduction, particularly on vendor equipment. Cost reduction workshops, similar to the Avro/Westland pilot study, but focusing more on the part count reduction aspect of the DFMA tools, may still prove to be worthwhile.

Avro will not be implementing the technique wholesale i.e. buying the software packages, training the designers to use it, and making sure the DFMA method is integrated into the design process as a set procedure . However, with the existing design work which is carried out daily, and with the production improvement work packages that will be done over the remaining life of the product, there is still design work that could benefit from the part count reduction aspect of the DFA tools and the estimating facility provided by the DFM tools.

Chapter Review

This chapter has discussed the issues raised during the research into DFMA. In summary:

- from the Four Corners project, recommendations on how the design process can be improved, implications of trying to re-design a mature product, and proposals on how the customisation activity should be approached on the next generation regional jet were presented;
- from the investigation into quantitative DFMA tools, their applicability in the aerospace environment in general and specifically at Avro was discussed.

The next chapter will outline some ideas for future work following on from this Eng.D. research.

Chapter 8 Future Work

The overall recommendation for future work is to carry the learning from the DFMA research into the development of the next generation regional jet. Some specific recommendations for further research would be:

- the development of a coding and classification facility for the new drawing system. This could be used to:

  (a) trace similar parts so that they can be used in multiple designs; this will stop the proliferation of part numbers;

  (b) access the Procurement department's cost database. The design team could then perform quick cost estimates;

- to investigate the development of a new or the incorporation of some of the established, DFM expert systems, into the new design process to ensure design teams have access to up to date manufacturing and assembly process knowledge;
- section 7.1.1 introduced the idea of having an 'Approved Designer' scheme i.e. allowing the designers to stress certain aspects of the design, instead of having to rely on the Stress department. An area of further research would be to investigate the feasibility of this suggestion. The research would include:

  (a) grading and classifying the types of design changes;

  (b) devising a training program;

- section 7.1.3.1 discussed the "vanilla" aircraft concept i.e. having no customer options. Further investigation of this idea applied to regional jets would be useful. The research would involve:

  (a) estimating the production cost savings that could be achieved and consequently the potential reduction in direct operating cost for the airlines;

  (b) an assessment of the level of customisation the aircraft would have to have; 'no customer options' does not mean 'bargain basic' aircraft;

  (c) an assessment into the market feasibility of such a concept.

Chapter 9 Conclusions

9.1 General Conclusion

This thesis contributes to expanding the boundaries of knowledge in the field of Concurrent Engineering by focusing primarily on Design for Manufacture and Assembly in an Aerospace Environment and secondly on Feature-Based Design.

9.2 Specific Conclusions

The specific conclusions can be grouped as strategic and operational.

Strategic

This thesis has:

- described how the aerospace industry market place has changed over the past decade, and the impact this has had on aircraft manufacturers;
- explained how the aerospace design process operates with respect to trade-off decisions by gaining an appreciation of peculiarities associated with the nature of the product i.e. the aircraft;
- explained how the combination of changes in the marketplace, and the priorities of traditional aerospace design, is affecting the current business position of Avro International Aerospace;
- put forward recommendations that will enhance the development of the next generation regional aircraft. These recommendations centred around two themes: firstly, general changes to the overall design process and secondly, changes to the way aircraft customisation is approached from both a marketing and physical design point of view.

Operational

This thesis has:

- contributed towards improving Avro's current business position by improving the company's customisation activity by applying qualitative DFMA principles and guidelines to a production easement exercise on galley installation; one of the most troublesome areas within customisation. Improvements have been made that could potentially save the company approximately £1million per year;
- investigated quantitative DFMA tools and assessed their relevance in an aerospace design environment in general and also specifically at Avro;
- progressed the research into Feature-Based Design by contributing to the Brite-Euram sponsored FEAST project. This project investigated the identification and exploitation of assembly features in product modelling, for use in the development of future Computer Aided Design systems. The Eng.D contribution was specifically concerned with the identification of assembly features in aircraft assemblies.

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Appendix 1 – Sources of Current Design Activity at Avro

The aircraft design activity is not simply confined to new product development. When the overall design of a new project is 'frozen' and production begins, this does not signal the end of the design work. During the production life of an aircraft there are various sources which generate further design work:

1. CAA regulatory/safety requirements

If the CAA specify a new regulation, aircraft manufacturers have no choice but to comply and the necessary design changes must be carried out. In some cases, the design changes may have to be conveyed to existing customers and the aircraft retro-fitted with the new modification.

2. Customisation

The production philosophy on the RJ is to build a basic stock aircraft which is customised in a separate activity towards the end of the build sequence. In theory, the operator could request modifications to any of the systems and equipment in the aircraft. However, the majority of the customisation work can be attributed to changes in interior decor, seating and passenger servicing equipment such as galleys, toilets, attendants' seats and stowage units. The basic stock build specification of the RJ is for a complete and operational aircraft less the passenger seats. Any operator can purchase an RJ and introduce it into revenue generating service simply by adding seats, but in reality operators rarely select the basic options and the further their requirements are from the basic build, the greater the amount of additional design work.

3. Production easements

Design work can also be generated as a result of trying to improve the producibility of the aircraft. This could either be an attempt to ease final assembly or detail part manufacture.

4. Maintenance easements

At a time where the aircraft's direct operating cost is a key element in capturing market share, feedback from the operators on the aircraft's maintainability is vital. Changes aimed at improving maintenance are a further source of design work.

5. Weight reduction

The weight of the aircraft impacts its performance another design activity aimed at improving the direct operating cost is seeking weight reduction opportunities.

6. Mistake rectification

Another source of design work is in reply to Concessions and Works Query Notes ("WQNs").

Concessions are granted when minor mistakes (i.e. not serious enough to affect the integrity of the aircraft structure or system) are made by the operator during final assembly, for example, a hole drilled in the wrong place. The concession permits a deviation from the official drawing.

WQNs are submitted to design when there is an ambiguity on the drawing which needs clarification or a design mistake which needs modification.

Appendix 2 – Overview of Avro's Design/Engineering Process

The purpose of this appendix is to give the reader an understanding of the mechanics of the design and engineering process at Avro. It will not describe the overall design process with regard to new aircraft development, i.e. it is not concerned with the decisions, trade-offs, specialist functions requirements etc., it will only deal with the day to day processing that is involved with supporting an existing product.

The framework for the design and engineering process is called the 'Mod system' (Mod refers to 'modification'). The Mod system has only two main functions: to define the aircraft build standard and to control alterations.

1. To define the aircraft build standard

Avro and the customer agree to a customer specification. The customer specification is translated, by the Modification Control Committee, ("MCC"), into the Aircraft Master Definition ("AMD"). The AMD is simply a list of the modifications (or building blocks) necessary to build the customer's aircraft. The AMD fits into the drawing system and is allocated a typical drawing number. Individual aircraft within the customer order are allocated sub-groups of the drawing number.

Within the AMD modifications are grouped numerically as follows:

00020A to 29999Z series – Basic Airframe

30,000 series – Basic Features

55,000 series – Changes to Basic Features

40,000 series – Standard Options

45,000 series – Changes to Standard Options

50,000 series – Customer Options

55,000 series – Changes to Customer Options

60,000 series – Customer Special Requirements

65,000 series – Changes to Customer Special Requirements

70,000 series – Vendor Cover Mods

Avro mods approving mods raised by manufacturers of proprietary equipment.

90,000 Series – Ground Support Equipment

00000A to 00019z and F0000 to F9999

Flight Development Mods, Test Specimens, Test Rigs and Mock-ups.

2. To control alterations

After a certificate of airworthiness has been granted for a new aircraft design, all subsequent modifications to this design must be brought to the notice of the Civil Airworthiness Authority and approval obtained before they are fully released for embodiment.

The requirement for proposed changes can come from a number of different sources (see Appendix 1). If the design authority considers the request is reasonable, a formal 'Modification Proposal' is raised by the relevant design and engineering representatives.

The ultimate decision to proceed with the Mod lies with the Configuration Control Board ("CCB"). The CCB has a chairman and the following representatives: Engineering Change Management, Design, Procurement, Customer Support, and Production Support.

The Mod Control department maintain registers from which all modifications are allocated. A typical new modification might be allocated a serial number thus: HCM45123A (HC is the project code for the 146/RJ aircraft).

For every new component that is designed, a drawing, an Electronic Schedule of Parts ("ESOP") and a Design Department Instruction ("DDI") is created. The ESOP is the list of parts called up by the drawing (obviously if the drawing is of a single component i.e. a 'detail' drawing then there will only be one part on the ESOP, but if the drawing is a higher level i.e. a General Arrangement drawing ("GA") then there will obviously be more than one part listed on the ESOP). The DDI is effectively the controlling document for the issue of drawings. The DDI is signed by the designer responsible for checking the drawing and is used to release the drawing into official circulation. There are several types of DDI, for example, to issue a new drawing, to stop/remove an old drawing.

The Manufacturing Engineering Department use all the drawings applicable to a given Mod, to prepare the manufacturing Conditions of Supply (the instruction needed in order to manufacture the part correctly) and the assembly Process Layouts (the method of assembly for use on the shop floor at Avro). Each Process Layout is allocated an Assembly Stage and Operation number ("ASO" number). The Operation is loaded onto the system used by the shop floor to control the production process, known as FAME (Final Assembly Manufacturing and Expediting System) and the parts are ordered accordingly.

Appendix 3 – Avro Production Activity

The production facility at Avro is dedicated to RJ nose assembly, wing equipping and final assembly. No detail manufacture takes place on site. All sub-assemblies (apart from the nose) are supplied either by other BAe sites or external vendors. Figure A3.1 shows the supplier breakdown for the main RJ sub-assemblies.

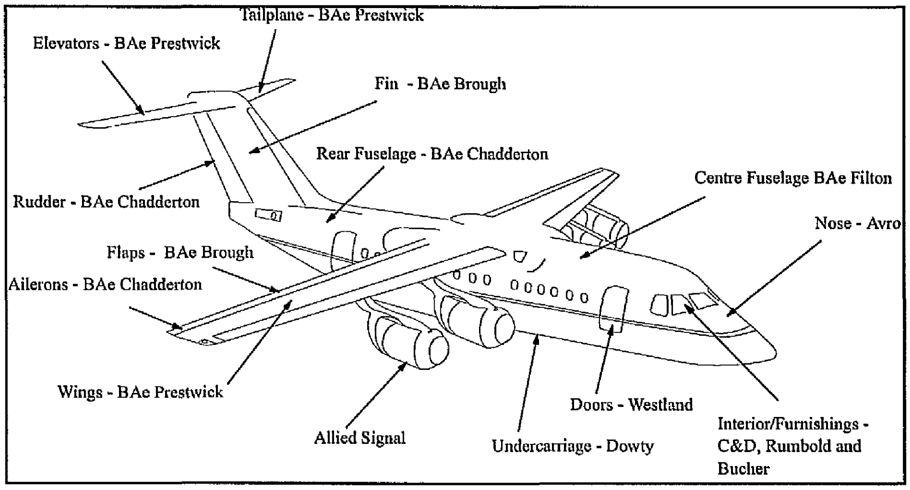


Figure A3.1 RJ Sub-Assembly Suppliers

During the course of the Eng.D. project the RJ's production process has undergone significant changes. At the start of the project Avro's production activity was grouped into four distinct areas:

1. Wing Equipping

In a separate area, away from the final assembly track, the wings were equipped with pylons, ailerons, flaps, spoilers, lights etc.

2. Nose Assembly

In another area separate to the final assembly track, the nose sub-assembly was built.

3. Independent Assembly Stations ("IAS")

IAS was the first stage on the final assembly track. It was basically a fixed site designated to the aircraft's structural 'boxing' (assembly of all the major structures i.e. wings, fuselage sections (nose, centre and rear), tailplane and rudder) and 'equipping' (installation of all the systems, for example, electrical, air conditioning, fuel, hydraulics etc.). There were four IAS sites on the track.

4. Finals and Flightline

The activities that were carried out in Finals and Flightline were:

- customisation, which involved:
  (a) installation of internal furnishings, i.e. baggage bins, wall panels, seats, galleys, toilets and wardrobes;
  (b) external painting;
  (c) other miscellaneous customer specific requests;
- installation of all high cost items, for example, engines, avionics suites etc.;
- functioning and testing of all the systems;
- production test flying.

As part of the Build to Order initiative (see Appendix 4) Avro's production process underwent a significant re-design. It is now split into two phases: Structural Build and Completions. Figure A3.2 illustrates how the major work packages are grouped.

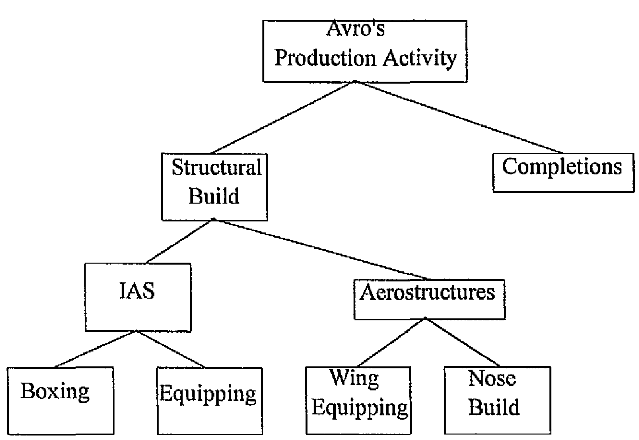


Figure A3.2 Organisation of Major Work Packages

Structural build includes Aerostructures and IAS. Aerostructures is now the collective name for the nose sub-assembly and wing equipping sites. Completions is the new name for the 'Finals and Flightline' activities.

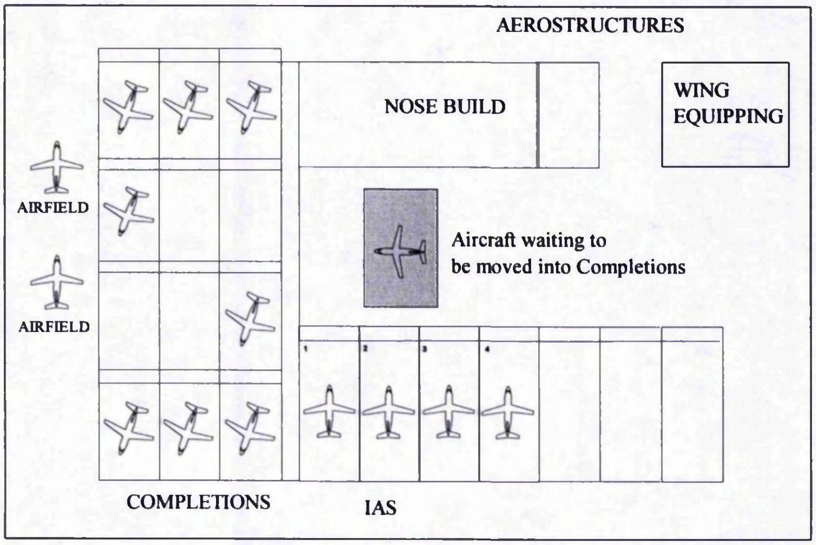


Figure A3.3 Factory Layout – Today

The aircraft currently spends 6 weeks in IAS and 9 weeks in Completions. This is expected to come down, in the near future, to 4 weeks and 7 weeks respectively.

Avro currently produce 18 aircraft sets per year.

Appendix 4 – The Build to Order Initiative

Up until 1994 Avro operated a push based production philosophy where aircraft were built to forecast. In other words Avro were committing to specific product configuration (i.e. customisation options and series type i.e. RJ70/85/100) so far in advance of known customer information that it could be seen as largely speculative and very risky.

This production philosophy invariably led to the production of unsold aircraft or "white tails". The interest payments associated with unsold aircraft were a major cause for concern and as the RJ came in three series types, there was also a further risk associated with producing the wrong type (i.e. a series that did not meet the next customer order). The production of such white tails was becoming financially unacceptable. To eliminate this situation the Build to Order ("BTO") production operating rationale was adopted.

The essence of BTO is quite simple, it is about matching supply to demand and consequently minimising the company's exposure to financial working capital. Figure A4.1 illustrates the BTO concept using the "P-D" model developed by Mather (88).

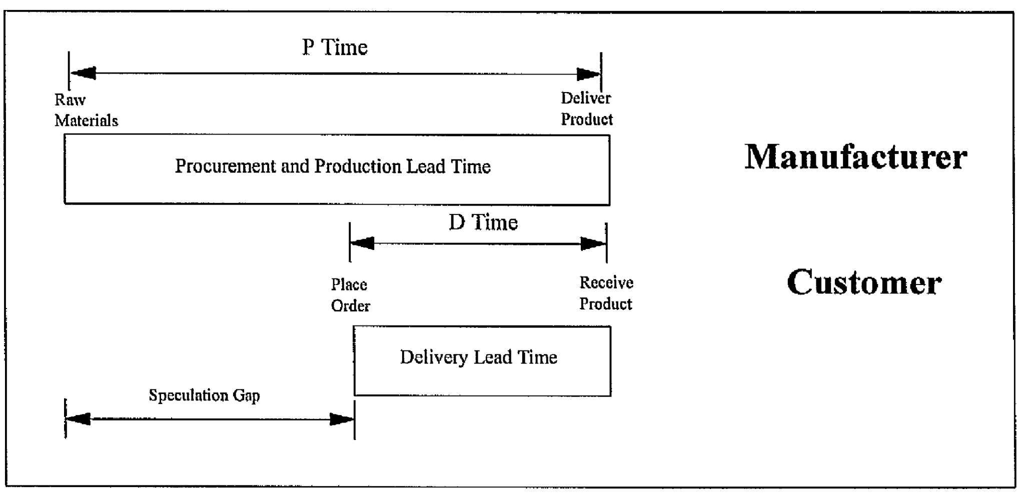


Figure A4.1 The P-D Model

Within this model the customer demand delivery lead time represents the demand element, and the product's cumulative procurement and production lead time represents the supply element. BTO increases the business responsiveness to market demands whilst maintaining working capital at a minimal level and reducing cost. The utopia is to have the P time less than the D time.

If the P time cannot be contained within the D time then the next best thing for a product that undergoes configuration to suit a specific customer, is to have at least the configured element of the production activity contained within the D time. Figure A4.2 below illustrates this concept.

The P time is made up of the time taken to produce the standard product plus the time taken to configure the product for the given customer. In the case of Avro the aircraft configuration involves two elements: (a) selection of the series type i.e. RJ70, 85 or 100; (b) the installation of customer specific equipment.

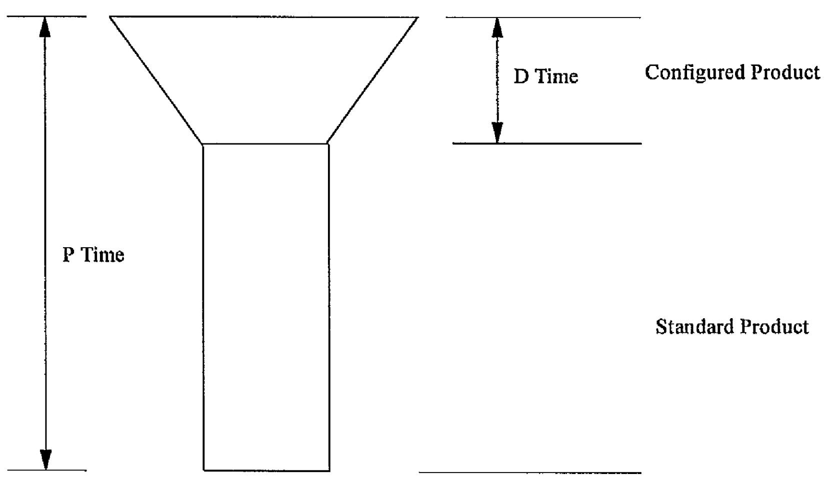


Figure A4.2 The Mushroom Model

In order to establish Avro's BTO vision, the ultimate model would display the following key principles:

- Avro's total cycle time would be within the customer's Acceptable Delivery Lead Time ("ADLT"). In other words P time = D time;
- supply would match demand in terms of rate;
- Avro would hold no stocks ahead of a customer order;

- all decisions related to commitment of product configuration would be contained within the ADLT (i.e. now Avro's total assembly process).

The figure below illustrates Avro's BTO model.

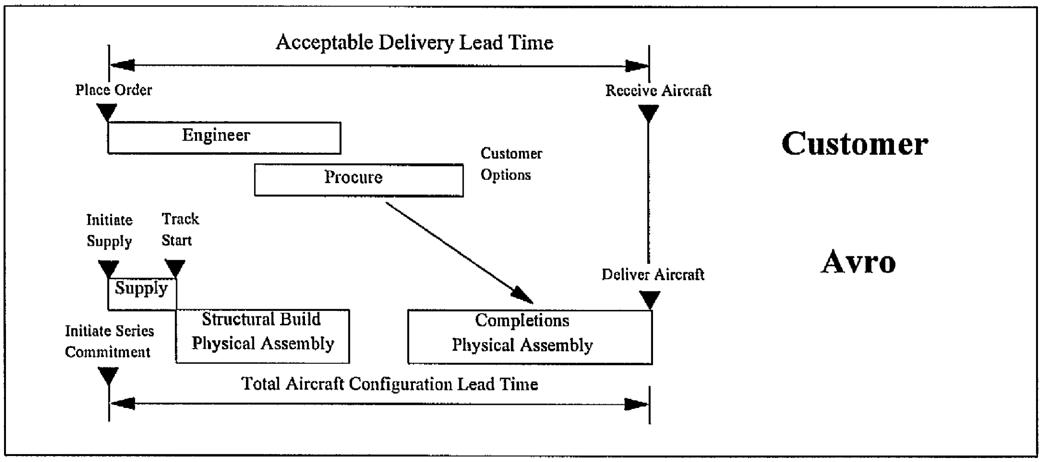


Figure A4.3 Avro's Build to Order Model

There are four phases to the development of BTO at Avro:

Phase 1 – ensuring the Completions business process cycle time is within the ADLT (see Figure A4.4)

('business process cycle time' refers to the engineering, procurement and physical assembly activities associated with customisation i.e. the installation of customer specific equipment).

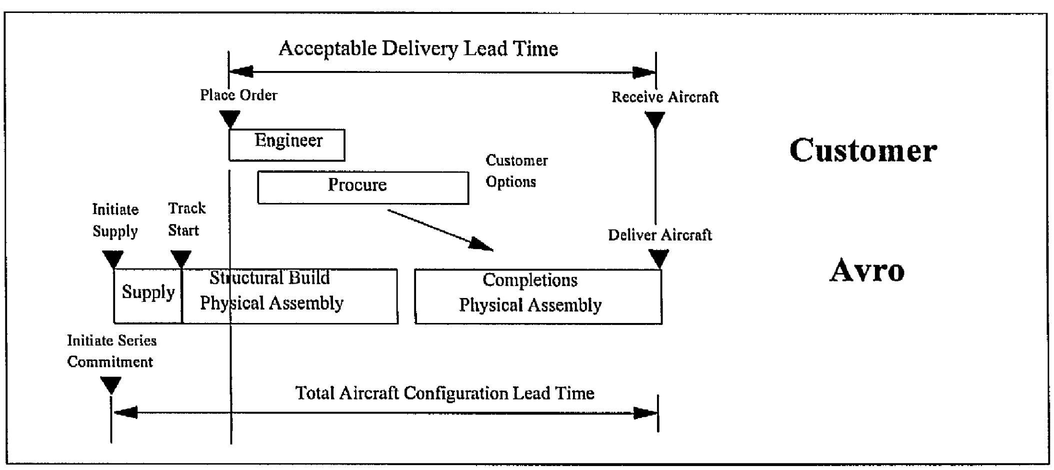


Figure A4.4 Phase 1 to Achieving BTO at Avro

Phase 2 – ensuring that both the Completions business process cycle time and Structural Build physical assembly cycle time falls within the ADLT (see Figure A4.5).

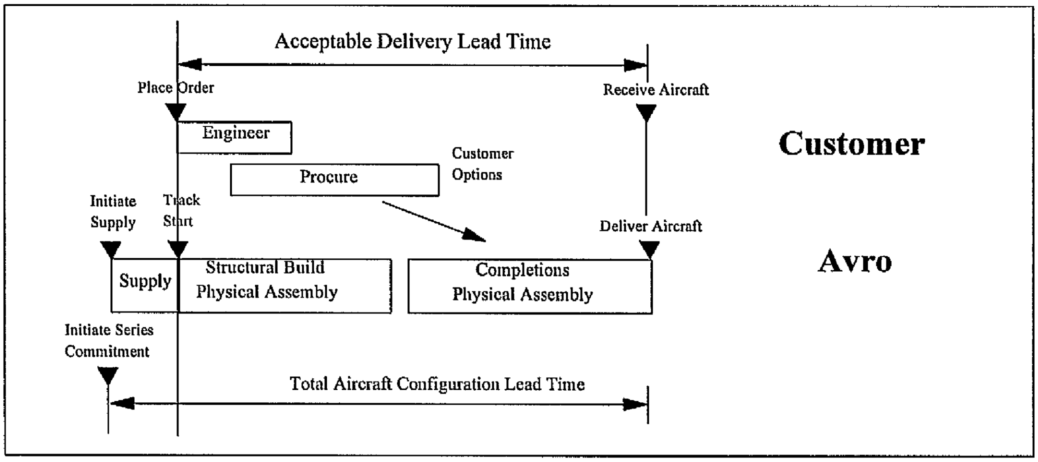


Figure A4.5 Phase 2 to Achieving BTO at Avro

Phase 3 – ensuring the series configuration options lead times are included in the ADLT (see Figure A4.6).

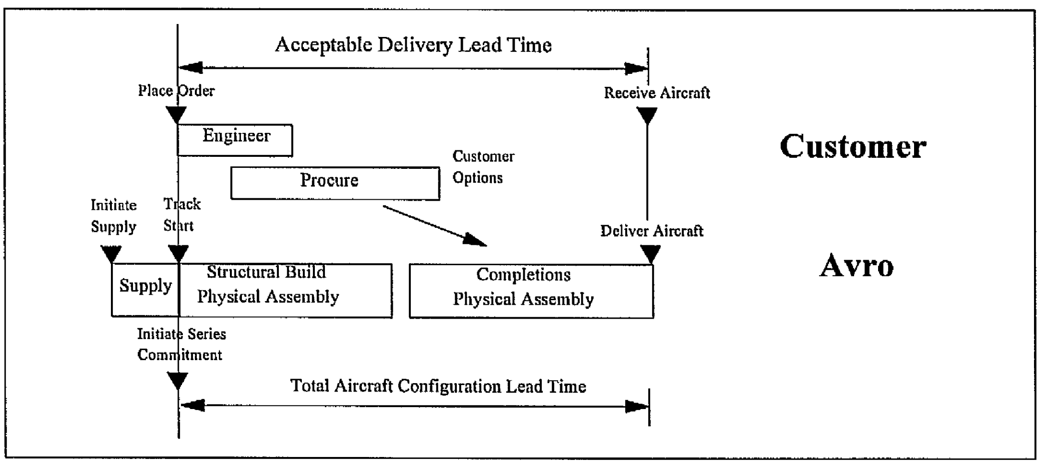


Figure A4.6 Phase 3 to Achieving BTO at Avro

Phase 4 – ensuring all the supply process lead times are within the ADLT; this is the utopia (see Figure A4.7).

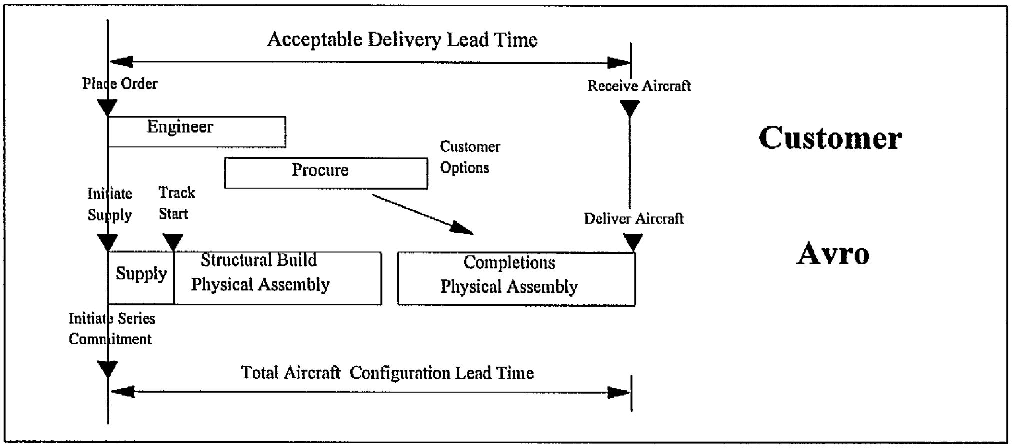


Figure A4.7 Phase 4 to Achieving BTO at Avro

The BTO initiative began in 1994 and following improvements have been achieved to date:

- the physical assembly lead time has been reduced from >18 weeks to 11 weeks;
- the series decision point prior to track start has been reduced from 52 weeks to 15 weeks, hence a speculation gap reduction from >61 weeks down to 19 weeks;
- series standardisation of the rear and nose sub-assemblies.

Appendix 5 – Four Corners Project Plates

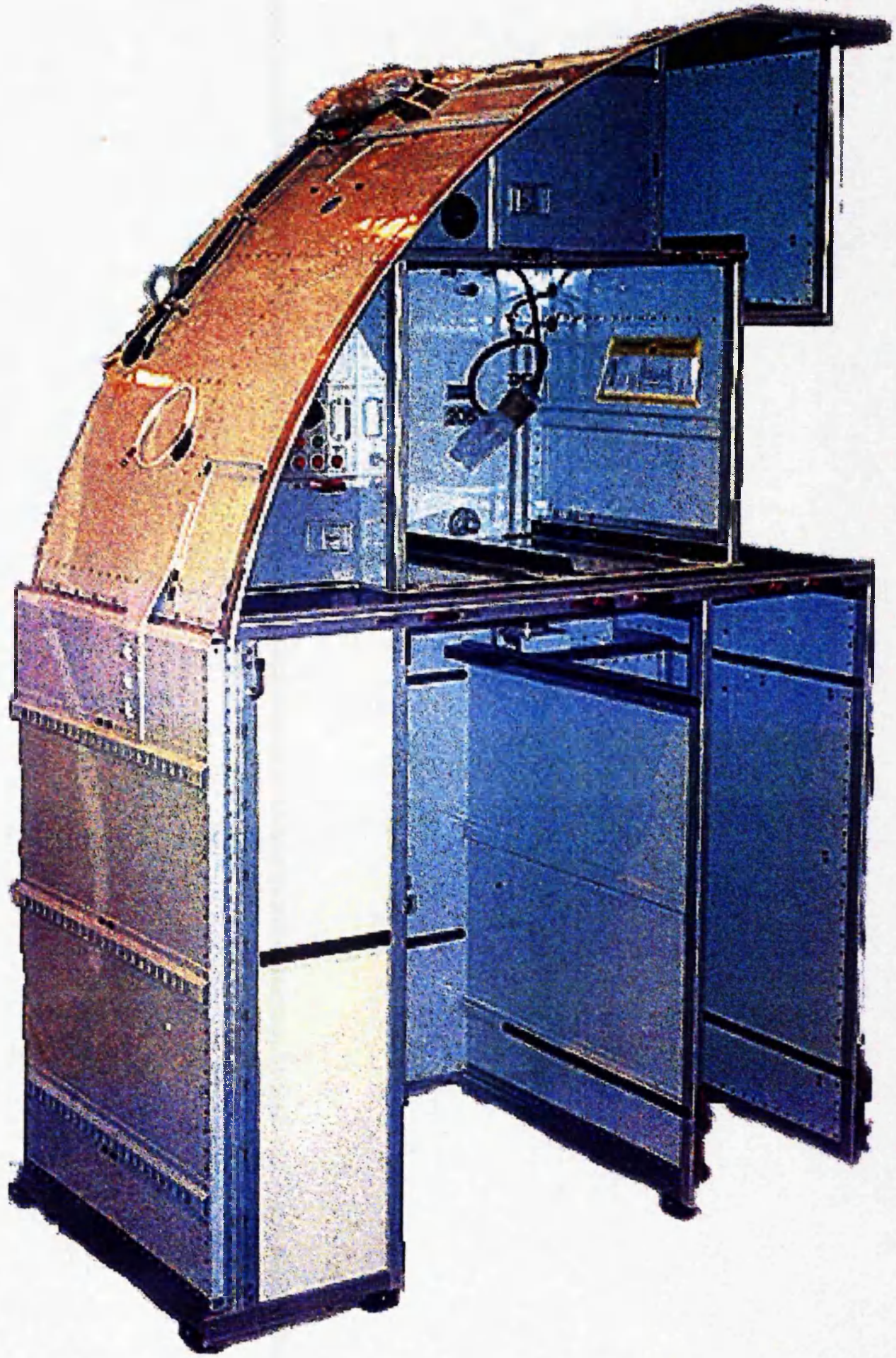


Plate A5.1 - A Typical Galley Unit

Plate A5.2 - 3R Modular Underfloor Support Structure

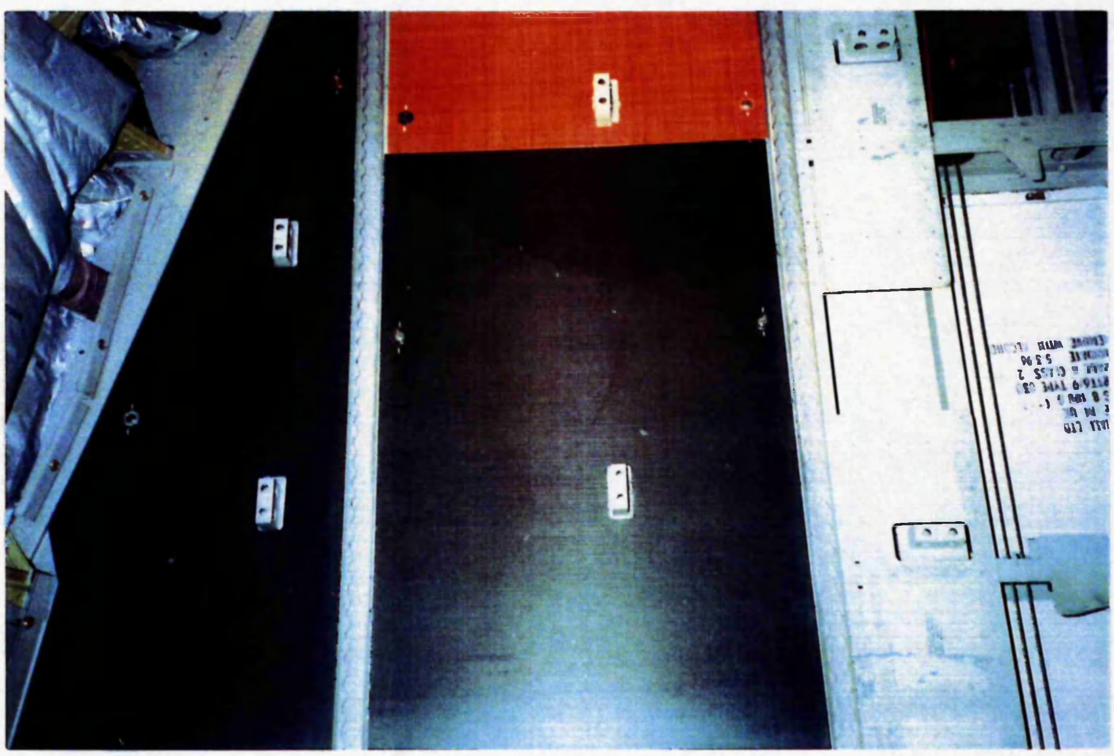


Plate A5.3 - 3R Galley Attachment Brackets

Appendix 6 – Galley Variation Survey

Table A6.1 Galley Variation Survey

Description	CES Number (Marketing)	CSC Number (Marketing)	Installation Drawing No.	AVRO Galley Drawing No.	Rumbold Part No.	Structure Lbs	Contents Lbs	AUW Lbs	AX Inches	AY Inches	Mod. No	Centre of Gravity X	Y	Z
STOCK 1R GALLEY (cold)	CES02-0141	N/A	HC253H0472	HC007H3422	C11161-001-013	129	273	402	183.15/163.65	12	40299Q			
STANDARD OPTION 1R GALLEY (ho	CES02-0242	25.01.01	HC253H0315	HC007H3186	C11216-001-005			494	183.15/163.65	12	40299K			
1R GALLEY AIR UK			HC254H0249-006		C11202-001	115	277	392	183.15/163.65	12	40299A			
1R GALLEY LUFTHANSA	CES02-0410	25.LH.204	HC253H0476	HC007H3439	C11278-001-00	127 (127)	426 (563)	553(690)	183.15/163.65	12	60415G	*9.67*	*17.68*	*29.91*
1R GALLEY SAM			HC253H0472	HC007H3422	C11161-001-01	129	273	402	183.15/163.65	12	40299Q			
1R GALLEY CROSSAIR			HC253H0426	----------------	746-101	106	307	413	183.15/163.65	12	60365G			
1R GALLEY AIR MALTA	CES02-0386	25.KM.08	HC253H0315-012	HC007H3377	C11275-001-00	156 (122)	235 (449.2	391 (571.2	186.63/163.65	12	60408G	*10.87*	*17.06*	*30.52*
1R GALLEY TURKEY	CES02-0242	25.01.01	HC253H0315	HC007H3186	C11216-001-005	159	251	410	183.15/163.65	12	40299K			
AND			HC253H0249						183.15/163.65	12	40299A			
			"Stock build 1R"		*C11161*	*125*	*507*	*632*	*183.15/163.65*	*12*		*10*	*16.8*	*31.1*
			"Alternative stock build 1R"		*C11216*	*135*	*494*	*629*	*183.15/163.65*	*12*		*10.11*	*17.62*	*30.57*
STANDARD OPTION 2R GALLEY														
100MEAL (RJ 70/85)	CES02-0245	25.02.02	HC253H0419	HC007H3147					217.7/253.1	18	40263F			
(100/115)	CES02-0245	25.02.02									40263G			
32 MEAL	CES02-0208													
2R GALLEY AIR UK			HC253H0238	HC007H2235	C11173-001-001	204 (200)	579 (670)	783(870)	*216.25/251.65*	*17.5*		*16.25*	*18.63*	*29.2*
				HC007H2820	C11239-001-001				*216.25/251.65*	*17.5*	60085F			
2R GALLEY CROSSAIR	CES02-0297	25.LX.10	HC253H0427	----------------	746-201	178	301	479	243.94/217.37	11	60365H			
2R GALLEY LUFTHANSA	CES02-0411	25.LH.214	HC253H0481	HC007H3453	*C11279-001-001*	241 (241)	1153 (1119	1394 (1360	*220.55/255.72*	*6*	60415H	*16.66*	*24.55*	*33.34*
2R BULKHEAD/STOWAGE STOCK			HC252H4259	HC007H3304	C10106-001-011				*215.53/220.08*	*18.6*	60379G			
				HC007H3303	C10106-001-009				*215.53/220.08*	*18.6*	40285A			
2R BULKHEAD/STOWAGE SAM			HC252H4259	HC007H3303	C10106-001-00	67	10	77		18.6	40285A			
2R BULKHEAD/STOWAGE TURKEY			HC252H4259	HC007H3303	C10106-001-00	67	13	80		18.6	40285A			
2R BULKHEAD/STOWAGE AIR MALTA			HC252H4432	HC007H3457		22	-	22			30386A			
*****Rumbold Info.			*"Stock build galley 2R"*		*C11255*	*135*	*818*	*953*	*217.7/253.1*	*18*		17.3	17	27.8
			"Stock build frame 18 stowage"		*C10106*	*75*	*112*	*187*	*215.65/*	*18.6*		*1.63*	*17.05*	*39.4*
STANDARD OPTION 2L STOWAGE	CES04-0032	25.02.04	HC253H0460	HC007H3282	C11263-001-00	*82*	*400*	*482*	220.95/248.7	19	40503R	*13.76*	*10.39*	*27.27*
2L BULKHEAD STOCK			HC252H4231-002								40283A			
2L BULKHEAD/STOWAGE CROSSAI	CES02-0295	25.LX.10	HC253H0425			129	83	212			60365R			
2L BULKHEAD/STOWAGE LUFTHA	CES04-0032	25.02.04				129	329	458			60416J			
2L BULKHEAD AIR MALTA			HC252H4228-002			28	174	202			40090Z			
****AND '2L BULKHEAD'???			HC252H4231-002							*6.18*	40284A			
2L BULKHEAD/STOWAGE AIR UK						87	209	296						
2L GALLEY STOWAGE TURKEY	CES04-0032	25.02.04	HC253H0460-004	HC007H3282	C11263-001-00	77	450	527	220.95/248.7	19	40503R			
****AND '2L BULKHEAD'???			HC252H4231-002							*6.18*	40284A			
2L GALLEY STOWAGE SAM			HC253H0460-006	HC007H3428	C11263-001-00	78	740	818	220.95/248.7	19	60411H			
STANDARD OPTION 3L STOWAGE	CES04-0066													
3L BULKHEAD STOCK			HC252H4143								40283A			
3L BULKHEAD LUFTHANSA					*C11280-001-001*	45(75)	4(150)	49(225)	*787.76/771.51*	*19.19*	60415L	*8.42*	*13.33*	*23.83*
3L BULKHEAD SAM			HC252H4143			30	53	83		12.3	40283A			
3L BULKHEAD CROSSAIR						15	66	81						

Table A6.1 Galley Variation Survey

3L BULKHEAD TURKEY			HC252H4143			**20**	**51**	**71**		12.3	40283A			
3L BULKHEAD AIR UK						**15**	**28**	**43**						
STANDARD OPTION 3R GALLEY	CES02-0246	25.03.01	HC253H0420		C11256-001-001						40264A			
****STANDARD OPTION 3R GALLEY**	CES02-0254	25.03.05									60325F			
3R BULKHEAD LUFTHANSA						**23**	**303**	**326**			60415S			
3R BULKHEAD SAM			HC252H4144-002			**19**	**-**	**19**		13.18	40282A			
3R GALLEY AIR MALTA	CES02-0390	25.KM.09	HC253H0467	HC007H3378	C11276-001-00	**146 (210)**	**822 (781)**	**968 (991)**	661.12/693.4	12.7	60408H	*16.63*	*15.9*	*31.08*
3R GALLEY CROSSAIR	CES02-0296	25.LX.10	HC253H0428	----------------	746-301	**127**	**395**	**522**	782.9/756.01		60365L			
3R GALLEY TURKEY	CES02-0246	25.03.01	HC253H0420	HC007H3165	C11256-001-001	**170 (175)**	**717 (975)**	**887 (1150)**	844.93/881.03	12.5	40264A	*18.34*	*16.53*	*31.38*
3R GALLEY AIR UK					*C11174-001-001*	**198 (180)**	**310 (526)**	**508 (706)**	*846.0/882.10*	*15.5*		*17.87*	*12.73*	*31.29*
********Rumbold Info.***			*"Alternative stock build galley"*		*C11256-001-001*	*175*	*975*	*1150*	*844.93/881.03*	*12.5*		*18.34*	*16.53*	*31.38*
			"Stock build 3R galley"		*C11220*	*225*	*980*	*1205*	*846.0/882.10*	*12*		*18.5*	*16.8*	*31.3*
STOCK 4R GALLEY (cold)	CES02-0247	N/A	HC253H0304	HC007H3054	C11217-001-00	*175*	*475*	*650*	*821.39/841.15*	*0.65*	40265G	*9.5*	*13.6*	*31.2*
STANDARD OPTION 4R GALLEY (ho	CES02-0253	25.04.02	HC253H0473	HC007H3423	C11181-001-013			**524**	*821.39/841.15*	*0.65*	40265S			
4R GALLEY CROSSAIR	CES02-0294	25.LX.10	HC253H0429	---------------	746-401	**121**	**223**	**344**	*821.39/841.15*	0.65	60365P			
4R GALLEY AIR UK			HC253H0304	HC007H3054	C11217-001-00	**130**	**274**	**404**	*821.39/841.15*	0.65	40265G			
4R GALLEY TURKEY	CES02-0253	25.04.02	HC253H0304	HC007H2595	C11217-001	**169**	**251**	**420**	*821.39/841.15*	*0.65*	40265G			
AND			HC253H0250								40265A			
4R GALLEY LUFTHANSA	CES02-0413	25.LH.216	HC253H0477	HC007H3440	C11281-001-00	**148 (167)**	**347 (483)**	**495 (650)**	*821.39/841.15*	*0.65*	60415M	*9.5*	*15.6*	*31.2*
4R GALLEY SAM			HC253H0473	HC007H3423	C11181-001-01	**169**	**251**	**420**	*821.39/841.15*		40265S			
STANDARD OPTION 4R/L GALLEY	CES02-0400	25.04.05												
4R/L GALLEY AIR MALTA	CES02-0389	25.KM.10	HC253H0468	HC007H3379	C11277-001-00	**263 (300)**	**1190 (1022**	**1453 (1322**	727.03/746.79	*0*	60408L	*9.5*	*42.4*	*31*
********Rumbold Info.***			*"Stock build galley 4R"*		*C11181-001-005*	*160*	*530*	*690*	*821.39/841.15*	*0.65*		*9.9*	*17.3*	*32.6*
			"Alternative stock build 4R"		*C11217*	*175*	*475*	*650*	*821.39/841.15*	*0.65*		*9.5*	*15.6*	*31.2*
									729.6 (100 series)					
									915.6 (300 series)					
			"Stock build 4R galley"		*C11181*	*147*	*551*	*698*	*821.39/841.15*	*0.65*		*7*	*22*	*36.8*

Appendix 7 – Four Corners Project Financial Justification

Corner	Change	Cost in £				Total
		Design	Tooling	Parts	Assembly	
1R	Underfloor structure	44460	2000			46460
	Galley fit	8436		13000		21436
	Drip tray					0
	Seal	20520				20520
	Cockpit door post	9120		2000		11120
1L	Seal (inc fwd face tlt)					0
2R	Underfloor structure	108300	4000			112300
	Galley fit	16872		24000		40872
	Drip tray					0
	Seal (vest)					0
	Electrics	11400				
3R	Underfloor structure	68400	4000			72400
	Galley fit	11172		14000		25172
	Drip tray					0
	Seal (vest)					0
4R	Seal					0
4L	Seal					0
	General					
	3R T.I		900	5000	2500	
	Feasibility study 95	9120				9120
2L	Airstairs/Stowage Single Unit					
	Obsolete parts			36000		
	Total	307800	10900	94000	2500	415200

Table A7.1 Four Corners Project Investment Figures

Corner	Change	Cost Savings in £											
		Design		Tooling		Production eng		Parts		Procurement		Completions Assy	
		(per a/c)	(per cust)	(per a/c)	(per cust)	(per a/c)	(per cust)	(per a/c)	(per cust)	(per a/c)	(per cust)	(per a/c)	(per cust)
1R	Underfloor structure											666	
	Galley fit		3420				184	150	3000			275	
	Drip tray		2280					600	10000		2760		
	Seal							70				875	
	Cockpit door post							800			4140	375	
1L	Seal (inc fwd face tlt)							140				250	
2R	Underfloor structure		34200		4000		851				3680		
	Galley fit		7980				184	150	4000			275	
	Drip tray		2280					600	10000		2760		
	Seal (vest)							70				875	
	Electrics (rework elimination)											180	
3R	Underfloor structure		34200		4000		851				3680	3350	
	Galley fit		7980				184	150	4000			275	
	Drip tray		2280					600	10000		2760		
	Seal (vest)							70				875	
4R	Seal							70				875	
4L	Seal							70				125	
General	Birds beak							222				55	
2L	Airstairs/stowage single unit							6447				1600	
	Total	0	94620	0	8000	0	2254	10209	41000	0	19780	10926	0

Table A7.2 Four Corners Project Savings

Pay Back Period and Maximum Potential Savings

Total savings per customisation	=	£ 143,620	(without Engineering and Procurement man-hour savings; these come under the general overhead).
Total savings per aircraft	=	£ 21,135	
Total savings per year	=	£ 811,290	(assuming 3 customisations per year and 18 aircraft deliveries).
Total investment	=	£ 415,200	

Payback = (415200/811290) = 6 months = 9 aircraft sets

Appendix 8 – Company Newspaper Report – Four Corners Project

A company-wide team is focusing on giving customers the individuality they want without big cost burdens

FOUR CORNERS FINDS THE WAY

We have always prided ourselves that we meet our customers' requirements, and we have developed our customisation skills accordingly.

The problem is that customisation is expensive because each customer's specification usually demands a good deal of re-engineering, and the time taken runs counter to our build-to-order initiatives. So how do we reconcile the need to be able to offer customers an individual aircraft with the need to standardise designs to reduce costs?

A team from across the Company has been looking into the problem under the "Four Corners" project. It consists of Angus Kitney (Project Design Engineer); Les Willans, Andy Jackson, Stuart Horne, Liz Peck, Andy Redwood, Sue Riley, Howard Apps, Roger Newton, Paul Grieve (Design); Liz Clarke (Purchasing and Supply); Dave Burgess, Malcolm Ramsdale, Andy Lang and Pat Green (Manufacturing Engineering); Steve Berry (Marketing), Simon Handley (Stress), and Trevor Wade (Customisation Cell Leader).

Initially, the team is tackling galleys in three points of the aircraft, 1R, 2R and 3R (see diagram). With Marketing input, it has predicted the most popular galley requirements so that we can continue to offer a range of configurations and have designed standard modular floor structures which can meet all these combinations.

Customers will be able to order other variations but the cost advantages of sticking to the standard configur-ations will be pointed out.

So far, modular floor structures have been designed for 2R and 3R. 1R is not usually variable in any case.

The floor structure can be fitted as a standard part of the aircraft build, saving design and production engineering costs. This will mean that the 3R floor structure will be fitted by Chadderton as part of the centre fuselage drum, and 2R will be fitted during the IAS stage here at Avro. This will apply in full from set 286 - the first aircraft scheduled for Lufthansa next year, and set 271 will be the first aircraft to be retrofitted.

We have received considerable co-operation from Rumbold, our galley supplier. It suggested another idea which will save us considerable time and money - attaching the galleys to the floor using new barrel nut fittings as used by Boeing and Airbus. This will also allow us to simply drop in the drip trays, reducing scrap and waste since they have always been tricky to install.

Parts will be standardised across the new designs to save costs, and another saving will be made by using a flipper seal covering the gap between the galley top and cabin ceiling, which will be much easier to fit than the flush finish we have at the moment.

The team is also looking at 2L, the area that stores the airstairs and stowage units.

At the moment this comprises separate panel units which take eight man days in Completions.

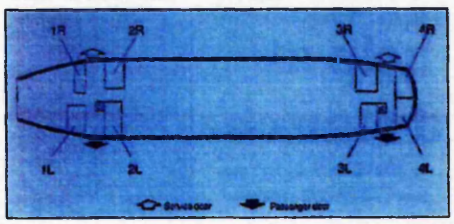
This will be changed to one modular unit which can be installed in one shift - and save 40 lb in weight.

The changes together will cost £250,000 in an eight-month design programme.

Against this, we will save £166,000 per customisation with £10,200 in parts and £13,430 in assembly labour on every aircraft - £923,000 in a year assuming three customisations and 18 aircraft.

The hours saved in each case will be 4,150 in Design, 100 in Production Engineering, 860 in Purchasing and Supply and 570 in Operations.

The Four Corners project multi-functional team in the 2L corner, l-r: Sue Riley, Liz Clarke, Les Willans, Angus Kitney, Dave Burgess and Steve Berry (Trevor Wade was absent).



Positions for the installation of cabin facilities within the passenger cabin: Right hand side - 1R, forward of front service door; 2R, aft of front service door; 3R, forward of rear service door; 4R, aft of rear service door. Left hand side - 1L, forward of front passenger door; 2L, aft of front passenger door; 3L, forward of rear passenger door; 4L, aft of rear passenger door.

Plate A 8.1 Company Newspaper Report — Four Corners Project

Appendix 9 – Company Newspaper Report – Avro/Westland Pilot Study

Working with Westland to reduce costs

Westland, our service and passenger door supplier, is another vendor working closely with us to drive down costs. We have been holding joint workshops with it to examine every part of its process, analysing basic designs, manufacturing methods, tooling and integration of the sub-assemblies.

Our team consists of Tony Harding and Steve Jackson (Cost Reduction Engineers in Purchasing and Supply), Andy Gorton and Sue Riley (Design), Brendan Morrison (Estimating) and Paul Roberts (Production Engineering), with Westland fielding people from its corresponding departments. The joint team has been using the Lucas Design for Manufacturing and Assembly (DFMA) computer system to analyse potential cost reductions in various proposed changes. The Boothroyd & Dewhurst FMA tool is also being assessed to see how the two systems compare and the one we consider more practical might well be used in similar exercises with other suppliers.

Savings of about £7,500 per aircraft set were identified after the initial four weeks. Both Westland and ourselves are confident that larger savings will be found as the project progresses.

Our picture shows the joint team., from l to r: Andy Gorton, Richard Marks (Westland), Tony Harding, Brendan Morrison, Susan Riley, Geoff Sloman (Westland), Paul Roberts and Ray Chambers (Westland).

Plate A 9.1 Company Newspaper Report – Avro/Westland Pilot Study