CRANFIELD UNIVERSITY

GRAHAM JOHN BURLEY



A DESIGN METHODOLOGY FOR JIGLESS AEROSPACE MANUFACTURE

SCHOOL OF INDUSTRIAL AND MANUFACTURING SCIENCE

Ph.D.

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GRAHAM JOHN BURLEY

A DESIGN METHODOLOGY FOR JIGLESS AEROSPACE MANUFACTURE

Supervisor: PROFESSOR JOHN CORBETT

March 2005

This thesis is submitted in partial fulfilment of the requirements for the Degree of Doctor of Philosophy

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To
My lovely wife Anne
and my four beautiful daughters.
That they too will reach for the moon.

ABSTRACT

Between 10% and 40% of the overall cost of an aerostructure can be directly attributed to the cost of type specific, hard-tooling. Hence, any attempt to reduce the cost of aerostructure must eventually focus on reducing the need for type specific hard-tooling.

The tooling is one of the major investments made during the development phase of an aircraft programme, accounting for more than a third of the development cost of a civil aircraft and nearly a quarter of the development cost of a military aircraft. The development phase for civil aircraft typically lasts two to four years and the tooling cost represents a multi-million pound forward investment with a long pay back period. Consequently, reducing the need for type specific hard-tooling will significantly reduce development costs and the time from concept to market.

This thesis describes a new design-for-assembly JAM Methodology that reduces the need to manufacture and build with type specific hard-tooling.

The Methodology was developed by identifying, utilising and developing existing design methodologies, and by identifying and applying enabling technologies. The methodologies are integrated to create a design algorithm that identifies and draws on the enabling technologies to achieve minimal hard tooling assembly concepts. Included in the methodologies is an innovative systems analysis tool. This enables the comparison of alternative assembly concepts ahead of the detail design, and the prediction and control of the total assembly error at the design stage.

The first part of the thesis describes the development of the JAM Methodology and explains the function and purpose of each step. The second part of the thesis demonstrates, and tests, two slightly different forms of the Methodology in the re-engineering of an existing aerospace structure, and in the designing of a new aerospace structure.

Publications relating to this research thesis include eleven authored, and co-authored, refereed conference papers, one journal article, and two EPSRC final reports.

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NOMENCLATURE

α	Coefficient of linear thermal expansion
$\overline{X}$	Process mean
C_L	Lift Coefficient
Cp	Process potential index
Cpk	Process capability index
σ	Standard deviation

GLOSSARY OF TERMS AND ABBREVIATIONS

ADR	Auto-Drill Riveter. A machine tool having an automated cycle for clamping, drilling, adding anti-fretting compound, inserting and squeezing rivets, and shaving rivet heads.
Advanced Composite	A constructional material consisting of load carrying fibres encapsulated in a thermosetting or thermoplastic resin matrix.
Airbus	Airbus, is an EADS joint Company with BAE SYSTEMS. It is the leading global manufacturer of civil aircraft. The Airbus design and production sites are grouped into four wholly-owned subsidiaries, Airbus France, Airbus Deutschland, Airbus España and Airbus UK.
AKCs	Assembly Key Characteristics. The features during each assembly stage on the product, tool, fixture or procedures that significantly affect the realisation of a product KC at the next higher assembly process level during the assembly process.
AMCAPS	Affordable Manufacture of Composite Aircraft Primary Structure. Two Airbus UK led research projects investigating the feasibility of alternative, composite, manufacturing techniques and processes.
Anisotropic	Any material whose physical properties depend upon direction relative to some defined axes in the material.
Anodise	To subject (a metal) to electrolytic action as the anode of a cell in order to coat with a protective or decorative film.
ANSI	American National Standards Institute, based in Washington DC, USA.
Anti-Fretting Compound	A polysulphide compound used at the interface between contacting, highly loaded metal surfaces to prevent fretting corrosion.
Assembly Centric Design	A design process directed at ease of product assemblability.
Autoclave	A chamber that can be simultaneously heated and pressurised to cure composite materials.

AWBA	Automated Wing Box Assembly. Airbus UK technology demonstrator projects.
Braiding	The mechanised manufacture of textile compositions made with yarn thread crossing in diagonal direction. Each thread intertwines the diagonal threads it crosses one from above and one from below.
B-Staged	An intermediate, partly cured, stage in the cure of a resin.
Burr	A thin ridge or area of roughness resulting from plastic flow of the material during cutting or shaping.
CAA	Civil Aviation Authority. The aviation controlling body in the UK.
CACD	Computer Aided Conceptual Design. Computer software that assists in designing the form of a product.
Cleco Pins	Expandable, spring-loaded pins used as temporary quick-release fasteners during the assembly of sheet metal parts.
CNC	Computer Numerical Control. The control of a machine system using a computer and codified instructions.
Co-Bonding	Simultaneous bonding of parts of an assembly of composite materials.
Co-Curing	Simultaneous curing of parts of an assembly of composite materials.
Concurrent Engineering	A systematic approach to the integrated, concurrent design of products and their related processes, including manufacture and support.
Consolidation	The application of a vacuum force and sometimes heat to an uncured carbon/epoxy laminate to remove trapped air, reduce its bulk, and to improve handling.
CRT	Cathode Ray Tube. A computer monitor screen.
Cryogenic Shot Blasting	The preparation of cured composite parts, prior to adhesive bonding, by blasting the bonding surfaces with crystals of carbon dioxide.
Cure	To irreversibly change the properties of a thermosetting resin by chemical reaction.
Datum Feature	A part feature that is considered accurate for locating other features or surfaces.
Design Inertia	The reluctance of a design organisation to change.
DFA	Design For Assembly. The process of designing a product for ease of assembly.
DFC	Datum Flow Chain. A graphical representation of the links between parts.
Doubler	A surface-fitting component part that increases skin thickness to provide localised stiffening and strength.
DRF	Datum Reference Frame. A feature co-ordinate system established by primary, secondary, and tertiary datums.
EADS	European Aeronautic Defence and Space Company. EADS is the largest aerospace company in Europe and the second largest worldwide. It is active in the fields of civil and military aircraft, space, defence systems and services.

Ergonomics	The study of the relationship between people and the machines they work with and the environment they work in, with a view to increasing efficiency in work and reducing injury.
Error	Any deviation from the ideal.
FDFC	Featurised Datum Flow Chain. A graphical representation of the mating features between parts.
FEA	Finite Element Analysis. A numerical technique used to solve mathematical models of solid structural components.
Fibre Placement	An automated process capable of laying directional or randomly oriented fibres in a variety of configurations with minimal waste and at cycle times which are compatible with liquid moulding. Importantly the manufactured products have through thickness re-enforcement.
Fixture	A manufacturing aid for holding, supporting, and locating parts during machining or assembly operations. It must be able to react any in-process machining or assembly forces.
Flyaway Tooling	Tooling that becomes part of the finished structure.
Fraying Surfaces	Surfaces face to face and liable to fretting corrosion.
Fretting Corrosion	Corrosion damage at the asperities of contact surfaces. This damage is induced under load and in the presence of repeated relative surface motion.
FSW	Friction Stir Welding. A process that joins nonferrous metals by plasticizing and then consolidating the material around the joint line.
Gaugeless Tooling	The creation of hard tooling direct from a solid model.
GD&T	Geometric Dimensioning and Tolerancing. Symbolic drawing standards produced by ANSI and the ISO.
Hand Lay-Up	Manual laminating of composite parts.
Hard Tooling	Traditional metal tooling having a physical existence.
Integrated Tooling	Reference and tooling features that are designed into the parts.
IPD	Integrated Product Development team. A multi-disciplinary design team.
ISO	International Organisation for Standardisation, based in Geneva, Switzerland.
Isotropic	Any material having properties that do not vary with direction.
JAM	Jigless Aerospace Manufacture. A new design, manufacturing and assembly philosophy to help reduce the present reliance on dedicated hard tooling.

Jig	A manufacturing aid that holds a part, or locates off a fixture or a part. It is fitted with devices to guide a cutting tool, so ensuring the correct relationship of the machining operation relative to the finished assembly.
Jigless Assembly	The term is used throughout this thesis to describe a structure that has been specifically designed for assembly using the minimum of dedicated hard tooling.
Jigless Design	An assembly centric design methodology that deliberately seeks to reduce the use of dedicated hard tooling.
JIT	Just In Time. A production scheduling system that produces the necessary units in the necessary quantities at the necessary time.
J-Stiffener	A component part shaped like the letter 'J' and fastened to the surface of thin skins to provide stiffening.
KCs	Key Characteristics. Product features, manufacturing parameters and assembly features for which any significant variation would affect the product's compliance to quality standards, or is likely to significantly affect the customer's satisfaction.
Life Cycle Cost	The total cost of ownership over the life span of the product.
Lift Coefficient	A number, usually determined experimentally, and used by aerodynamicists to model the complex dependencies of shape, inclination, and some flow conditions on lift.
Liquid Shim	A filled epoxy resin compound used to fill gaps and offsets at the structural assembly stage.
LMC	Least Material Condition. The condition in which a feature contains the least amount of material within the stated limits of size. Eg. Maximum hole diameter, minimum shaft diameter.
M/T	Machine Tool. A power-driven machine that cuts, drills or otherwise shapes metal, wood, or plastic.
Machine Vision	A computerised vision system used to control the logic and positioning of an Industrial Robot.
MKCs	Manufacturing Key Characteristics. Machine process parameters and/or workpiece fixturing features that significantly affect the realisation of a product or an assembly process KC at the part feature level.
MMC	Maximum Material Condition. The condition in which a feature contains the maximum amount of material within the stated limits of size. Eg. Minimum hole diameter, maximum shaft diameter.
NIOSH	Acronym for the, (American), 'National Institute for Occupational Safety and Health'.
PDS	Product Design Specification. A document that formally lists the objectives and restraints that applies to the attributes of the product being designed.

Peel Ply	A finely woven rayon fabric supplied treated to prevent it bonding with epoxy. Laid up and cured on top of the lamination; after curing it is peeled off to leave a clean bondable surface.
PFD	Penetrant Flaw Detection. Crack detection using a penetrant fluid that fluoresces when irradiated with ultraviolet light.
PKCs	Product Key Characteristics. A products' geometric features and material properties that are highly constrained or for which minute deviations from nominal specifications have a significant impact on the product's performance, function and form at each product assembly level.
Preform	A dry fiber or prepreg lamination that has some handling integrity and that will later be transferred to a mould tool for forming and consolidation.
Prepreg	Pre-impregnated composite reinforcing material having the correct volume of resin and partially cured.
Process Capability Index	The Process Capability Index, or *Cpk*, measures a process's ability to create product within the specification limits.
Process Potential Index	The process potential index, (*Cp*), measures a process's potential capability, which is determined as the allowable spread over the actual spread.
QFD	Quality Function Deployment. A formalized, graphical, method of linking customer valued attributes to the engineering, manufacturing, and process decisions.
Quality	The degree to which a product adheres to the design intent.
Rate Tooling	Additional tooling needed to enable an increase in the production rate when the existing tooling is fully utilised.
RCC	Remote Centre Compliance. A device for aiding assembly insertion operations.
Re-Engineering	Detail re-designing of an existing product to improve its assemblability and/or reduce cost.
Ref.TE	Reference Target Error. An Error Budgeting metric.
Rel.TE	Relative Target Error. An Error Budgeting metric.
Resin Infusion	A simple technique for wetting out a dry preform with resin.
Resin Transfer Moulding	(RTM). An advanced automated technique that injects resin into a dry preform clamped in a closed mould tool. Vacuum can also be applied to the mould cavity to assist resin in being drawn into the fabrics. This is known as Vacuum Assisted Resin Injection (VARI). Once all the fabric is wetted out, the resin inlets are closed, and the laminate is allowed to cure.
RSS	Root Sum of the Squares. A widely used form of statistical tolerancing employed to account for the unlikelihood that

	all of the tolerances in a stack will be at their extremes simultaneously.
SAE	(American) Society of Automobile Engineers. The aerospace division is an organisation for aeronautical engineers dedicated to the international sharing of knowledge.
SCRIM	A light, non-woven, fabric with an open mesh construction used as a resin carrier to facilitate the faster wetting out of a dry composite preform.
Sewing	The process of joining and fixing composite laminae using interlinking loops of yarn to create a dry preform.
Shot Peening	A cold working process in which the part surface is bombarded with small spherical shot.
Six Sigma	A definition of quality that equates with only 3.4 defects per million. A Six Sigma process allows plus or minus six standard deviations within the specifications limits and has a process potential index, (*Cp*), greater or equal to two.
Slat-Track Can Hole	A spar aperture that locates a slat-track can.
Slat-Track Can	A housing into which the slat-track withdraws and which prevents fuel escaping through the slat-track can hole.
Soft Tooling	Tooling that is made using rapid prototyping techniques, such as Stereo Lithography. They are usually an interim product towards the fabrication of a hard tooling.
Solid Model	A computerised representation and manipulation of three dimensional shapes. A solid model has virtual volume and mass.
Solution Treatment	A normalising process carried out by soaking the light alloy in a salt-bath at approximately 450^0C for 30 minutes and then quenching in water. After about 1 hour the material starts to age harden.
SPC	Statistical Process Control. A statistically based system that monitors the consistencies of processes.
Spreader Plate	A component part fastened across two or more components to keep them a set distance apart.
SRIM	Structural Reaction Injection Moulding. A process in which a dry preform is located in the lower half of a matched tool, a precisely measured quantity of resin is poured over the preform and the mould closed. The pressurising effect of closing of the tool, ensures equal distribution of the resin through the preform.
Tape Layer	A fully automated CNC process that laminates composite parts from carbon/epoxy strips 75mm or 150mm wide.
TSE	Total System Error. An Error Budgeting metric.
Type Specific Tooling	Hard tooling that is specific to a particular type of aircraft or variant and can not be used for other types or variants.
UTE	Ultimate Target Error. An Error Budgeting metric.
Vacuum Forming	The process of vacuum forming a B-staged laminate.

VALISYS	Commercial tolerance analysis software that studies the effect on component and assembly variation caused by the sequence of assembly and sub-assemblies, fixturing, etc.
VOC	Voice of the Customer. An early stage in a product design process when the potential customer explains their requirements.
Warp Fibres	The lengthwise threads or fibres in woven cloth.
Weaving	The manufacture of woven cloth by passing threads under and over the threads of a fixed warp.
Weft Fibres	The crosswise threads or fibres in woven cloth.
Wing Chord	The straight line distance joining the leading and trailing edges of an airfoil.
Wing Span	The maximum distance laterally from tip to tip of an airplane.

1.0 INTRODUCTION

1.1 Definition of Terms

The terms jigs, fixtures, and tooling, are often used loosely and incorrectly. Their definitions vary from one industry to another and between different manufacturers. In this thesis, the following specific definitions are used:

Tooling - Tooling is the generic name for jigs and fixtures, and the master gauges, and tools set from the master gauges for calibrating jigs and fixtures.

Jig - A jig is a manufacturing aid that either holds a part or is itself located on the part. It is fitted with devices to guide a cutting tool ensuring the correct location of the machining operation relative to the part.

Fixture - A fixture is a manufacturing aid for holding and locating parts during machining or assembly operations. They do not provide definite guidance for the cutting tools.

Type Specific Tooling - Hard tooling that is specific to a particular type of aircraft or variant and can not be used for other types or variants.

JAM - Is a new design, manufacturing and assembly philosophy to help reduce the present reliance on type specific hard tooling.

1.2 Traditional Method of Building Aerostructures

The process of building an aerostructure using type specific manufacturing and assembly tooling goes back to the 1930s and the first all metal airplanes. The tooling was necessary to hold together the matrix of small sheet metal parts in the correct relationships prior to drilling, deburring, and fastening by riveting. The individual component parts were variously formed by bending, stretching, pressing, explosive forming, and routing, (Ref. 1). The forming processes were not precise and the parts varied both dimensionally and geometrically. The assembly process compensated for this by allowing fettling and the forced compliance of individual parts to make them fit the tool. The quality of the finished structure was resident in the tooling and not the individual parts. The assumption was that the finished structure would reflect the quality inherent in the tooling.

This did not happen in practice and unique aircraft were produced with no interchangeability of major components.

Seventy years on and the aircraft are a lot bigger, the designs are more advanced, the manufacturing processes have changed and improved but the cost of the tooling now adds about 10% to the overall cost of the structure, (Ref. 2). This means that if a set of Airbus A320 wings sell for £6million then the hidden cost of the tooling is £600,000.

Further, the use of hard tooling does not guarantee that sub-assemblies and assemblies will be of the desired quality, or that they will fit, or that they will be interchangeable.

1.3 Cost Considerations

As the aircraft have increased in size, so have the costs of the tooling. During the production run the tooling is expensive to own, occupying expensive floor space and needing regular maintenance and calibration. If the aircraft fails to achieve the forecast rate of sales the tooling is under-utilised, further extending the payback period. If the aircraft sales exceed the forecast rate, then additional sets of tooling, (Rate tooling), are needed. This inevitably causes a long delay before the increased manufacturing capability is in place and the company is able to meet the demand for the aircraft. Additionally, the inflexibility of dedicated hard tooling inhibits product mid-life design changes, and makes it difficult for manufacturers to respond to customer requested upgrades.

The tooling is one of the major investments made during the development phase of an aircraft programme. It accounts for more than a third of the development cost of a civil aircraft and nearly a quarter the development cost of a military aircraft, (Ref. 3). The development phase for civil aircraft typically lasts two to four years and the tooling costs represent a multi-million pound forward investment with long pay back periods. Consequently, reducing the amount of dedicated hard tooling will significantly reduce costs and the time from concept to market.

1.4 The Need for Change

Political and economic considerations now result in very large commercial aircraft no longer being built entirely on a single site, or by a single manufacturer, or even in a single country. This, co-production, requires that parts and sub-assemblies are manufactured to drawing and are interchangeable.

The traditional method of assembling aerospace structures is now recognised as being technologically inadequate and commercially unviable in a very competitive business environment. (Ref. 4).

1.5 JAM – Jigless Aerospace Manufacture

The JAM acronym does not accurately describe the scope of the research, and JAM is better defined as being, 'A new design, manufacturing and assembly philosophy to help reduce the present reliance on type specific hard tooling'. (See Section 1.1).

It aims to reduce the reliance on large quantities of type specific hard tooling through the;

- Transfer of tooling functions into component design and manufacturing processes, (Ref. 5).
- Development of design methodologies, (Ref. 6).
- Application of enabling technologies, (Ref. 7).

1.6 Background to the JAM Project

Starting on 1st June 1998, JAM, (Ref. 8), was a three-year EPSRC/IMI collaborative project between four industrial companies and four universities, (*Table 1*). The project had three objectives:

1) To address significant scientific, technological and economic issues to enable a new design, manufacture and assembly philosophy to minimise product specific tooling and fixtures during assembly of aerostructure.
2) To develop methodologies to improve the efficiency of product development processes in the aerospace sector.
3) To increase the flexibility and productivity of product manufacturers and assembly through the utilisation of new assembly technology.

Project Partners

Industrial:	Academic:
• Airbus UK	• City University
• BAE SYSTEMS MA&A	• Cranfield University
• BAE SYSTEMS Sowerby Research Centre	• Nottingham University
• Bombardier Shorts Aerospace	• Salford University

JAM Project Partners *Table 1*

The four universities each contributed to the overall project objectives through individual, but interrelated, research programmes, (*Table 2*).

Areas of Research Speciality

• City University	- In-Process Measurement and Metrology
• Cranfield University	- Design for JAM, Manufacture and Assembly Processes
• Nottingham University	- Evaluation of TI^2 System - Robot & Photogrammetry - Product Modelling Environment
• Salford University	- Analysis of Kinematic Restraint and Handling.

University Research Areas *Table 2*

1.7 The Cranfield JAM Objectives

Cranfield University's specific objectives were;

- The development of a JAM methodology for assembly centric design
- The creation of a Feature Library for part-to-part assembly using structurally integrated features
- The creation of a Process Capability Database to enable JAM
- The development of a methodology for three-dimensional Error Budgeting
- Re-Engineered design of an existing structure
- New Conceptual Design of an existing structure
- Costings Analysis comparing the re-engineered design to the existing design

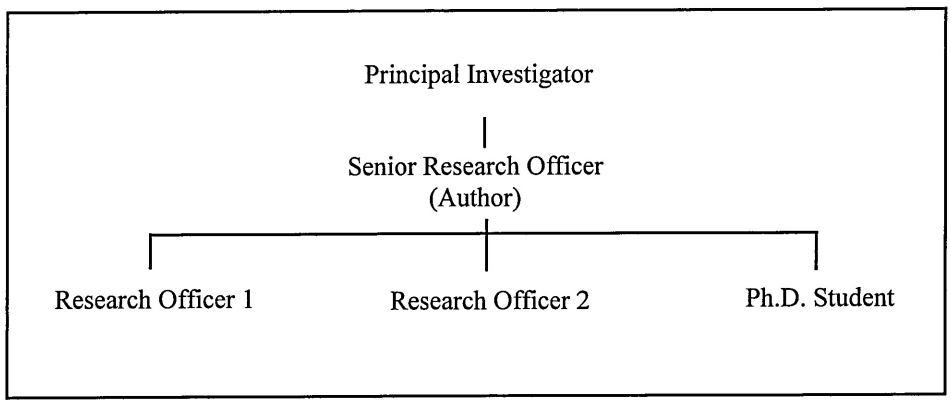
1.8 The Cranfield JAM Team

The Cranfield Team consisted of four researchers under the direction of a Principal Investigator.

Each team member, (*Figure 1*), had a collective overall responsibility plus areas of primary research;

Senior Research Officer (Author)	-	Project planning and management, Development of the JAM design methodology, Process capability, Re-Engineered design, New Conceptual design
Research Officer 1	-	Three-dimensional error budgeting
Research Officer 2	-	Cost modeling
PhD Student	-	Feature library, Feature selection, and Cost modeling

Other areas of the programme were undertaken collectively by the researchers.



Members of the Cranfield JAM Team *Fig. 1*

1.9 Thesis Aims and Objectives

The work described in this thesis is the author's contribution to the JAM Research Project. It has the following aims and objectives;

Aims:
Development and demonstration of a JAM assembly centric design methodology with particular emphasis on the importance of incorporating process capability data.

Objectives:
- The development of an assembly centric design methodology for JAM.
- To identify and utilise the enabling technologies.
- To identify and utilise applicable design methodologies.
- To bring process capability data into the design process.
- To demonstrate the efficacy of the JAM methodology through case studies

To achieve these objectives the following work was undertaken:

- A literature search to identify enabling technologies and design methodologies, and to establish the 'State of the Art'
- Interviewing specialists in the areas of design, manufacture, and assembly to obtain their opinions and suggestions
- Visits to relevant companies to gain an appreciation of working conditions and practices
- Development of a JAM assembly centric design methodology
- Case Study evaluation of the JAM design methodology through the re-engineering of an existing structure
- Case Study evaluation of the JAM design methodology through a new conceptual design

1.10 Methodology

JAM was a real world problem-solving research project, (Ref. 9), and finding a solution required the application of a number of different engineering disciplines.

JAM was preceded by a smaller, pilot project, 'Cranfly – A Novel Approach to the Design of Aerospace Structures'. The knowledge gained from Cranfly led to the formulation of the JAM research objectives, (Section 1.7).

These objectives were then carefully thought through and broken down into a series of clearly defined work packages, (*Figure 2*). The degree of difficulty in achieving each task was assessed, and an estimate made of the required man-hours. Achieving the project milestones, (Appendix A), was considered important, as late delivery would affect the opportunity to interact effectively with the other university research groups, *(Table 1)*. At the same time, it was appreciated that the programme needed to be flexible, as by their very nature research projects can neither be guaranteed to meet delivery dates, or even, to be successful.

Since JAM was clearly going to be a multifaceted research programme with the different research packages feeding and influencing each other the interpretive research model, (Ref. 10), where data collection and analysis are entwined was followed as against the scientific model that would have required all of the data to be collected before any analysis.

The interpretive research model is based on the belief that science is driven by human interests and that the research should;

1. Focus on meanings
2. Try to understand what is happening
3. Look at the totality of each situation
4. Develop ideas through induction from data

Suggested research methods include;

1. Using multiple methods to establish different views of phenomena
2. Investigate small samples in depth or over time

This process fitted well with the work plan and the need for multi-disciplinary interaction between the different research groups and the collaborating companies.

Each of the University research teams was assigned a senior industrialist to be their 'Champion' to guide them through the intricacies of company red-tape, to aid them in acquiring proprietary information, and in identifying experienced practitioners that would be able to explain specific aerospace practices and procedures.

1.11 Background Theory

The Background Theory stage was a period of widespread, data gathering. The new knowledge provided background information and helped with the conception and development of hypotheses.

The Literature Review, (Chapters 2, 4 and 5), was augmented by site visits and interviews with company specialists in aerostructure design, manufacture and assembly. The interviews provided the opportunity to test and further develop hypotheses, and the interviewees supplied specific background information together with their personal opinions and suggestions. (Appendix B).

Every interview had a specific and individual purpose. To achieve that purpose the research team met ahead of the interview and crafted a series of pertinent questions. Follow-up questions were based on the answers received.

It was thought possible that the practitioners from different disciplines would vary in their interpretation of aerospace practices and that there could be potentially embarrassing disagreements. For that reason the private, face to face interview was considered to be the most effective way to elicit the information sought, (Ref. 11).

As each interview was specific and individual it was not possible to prepare a standard pro-forma list of questions, however the following are typical of the primary questions addressed to a tooling designer;

1. What is the tooling design process?
2. What datum/referencing system is used on the assembly drawings?
3. What datum/referencing system is used on the tooling drawings?
4. How are the datums chosen?
5. What type of tolerancing system is used?
6. How are the tolerances derived?
7. What are the differences between manufacturing and assembly tolerances?
8. What is the purpose of the tooling?
9. Are parts manufactured and assembled using the same datums?

Hypotheses were often developed and explored during the interviews. Later at the University the research team used 'Brainstorming' techniques, (Section 5.3.1.1), to further analyse the information and explore the hypotheses.

The site visits provided the opportunities to see aerostructure being built, and to gain an appreciation of working conditions and practices, (Appendix C). In the later visits,

attention was concentrated on the selected demonstrator structure, (Chapter 3), and in identifying the actual, as compared to the supposed, role of the tooling.

Informal discussions with both the parts-manufacturing and the airframe assembly technicians revealed a number of ongoing problems dealt with on the factory floor, and not reported to the management. Attempting to identify the causes of these problems further helped in the development of hypotheses.

The site visits and interviews enabled the developments of professional friendships and increased the confidence that BAE and Airbus UK staff had in the researchers. The friendships formed proved invaluable in cutting through the red tape and in reaching a non-disclosure agreement that then allowed the release of engineering drawings, photographs, assembly sequences, and design manuals.

1.12 Focal Theory

The developing hypotheses gave direction to the research and resulted in the work being concentrated into very specific subject areas. These have been grouped together under two main headings - enabling technologies and design methodologies.

The design methodologies have been arranged into a logical sequence to form an, 'Algorithm for Assembly Centric Design'. This is then combined with the selected enabling technologies to create a holistic, 'Design Methodology for Jigless Aerospace Manufacture'.

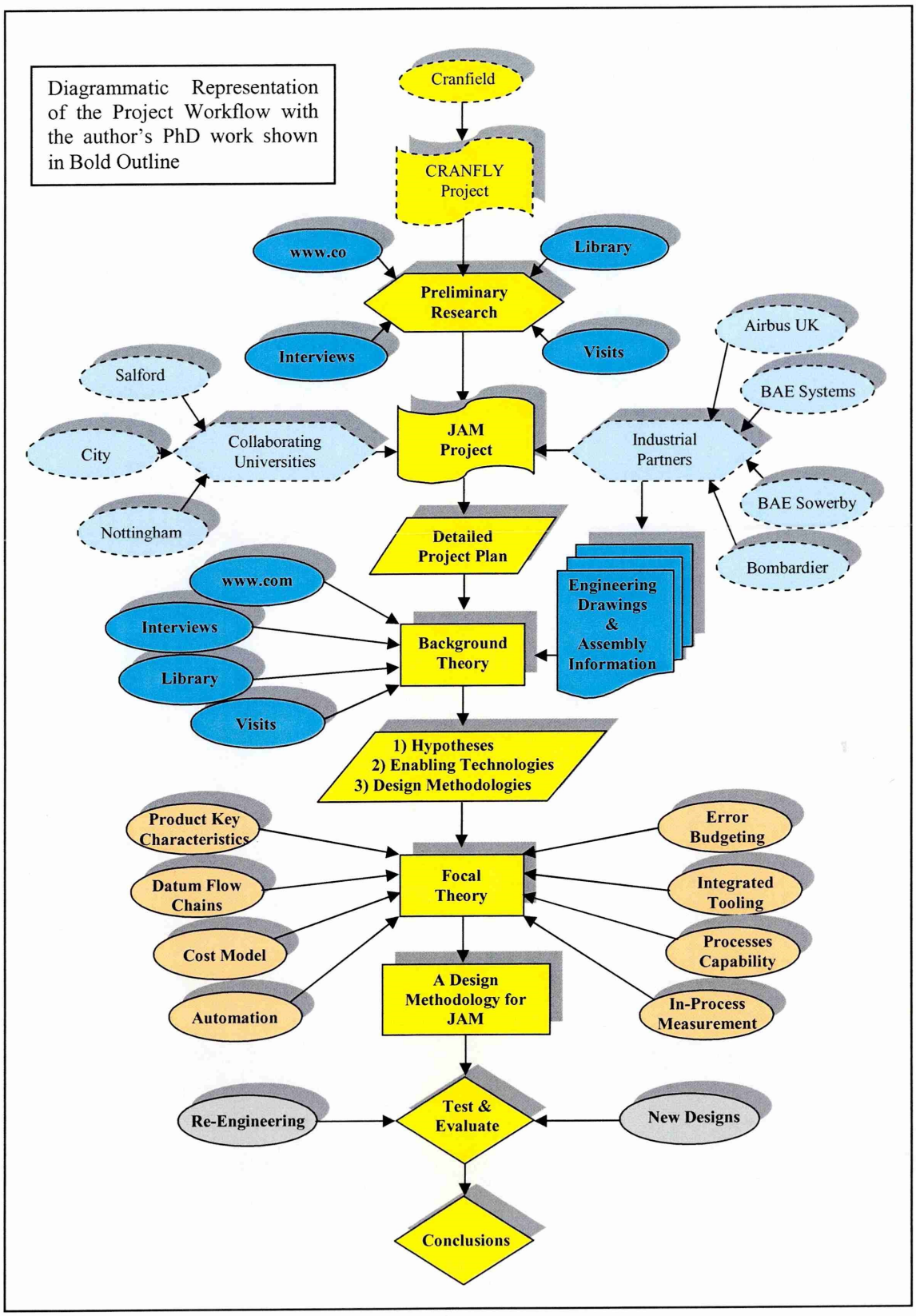
1.13 Testing and Evaluation

Two slightly different forms of the methodology were developed and evaluated. The first is for the creation of new and original designs, (See Section 6.1), and the second is for the re-engineering of existing structures, (See Section 6.2).

Following agreement between the University research teams and the industrial collaborators, the criteria for success were defined as;

1. A reduction in the use of type-specific tooling.
2. A reduction in overall cost of the finished structure.
3. No reduction in quality of the finished structure.

- As compared to the current assembly process.



The Project Workflow *Fig. 2*

2.0 LITERATURE REVIEW 1 – THE STATE OF THE ART

The facilities of the Cranfield University Kings Norton library were used to accomplish a wide-ranging literature search aimed at identifying the enabling technologies and at achieving an understanding of the design process including DFA and DFMA methodologies. The initial, broad, search was made very early in the project with much of the information on basic technologies and design methodologies being obtained from text books held by the library. More focused searches followed with relevant data bases being identified and searched, to establish current thinking, and the 'State of the Art', of Jigless Aerospace Manufacture.

A regular flow of current information was also obtained by reading relevant periodicals, from the company visits, and from interviewing equipment suppliers, specialist researchers, and aerospace practitioners, (Appendices B and C).

This thesis is presented having the actual logical flow of research, hypotheses, and developments, (*Figure 2*), and consequently the literature review researches three distinct subject areas in three separate chapters;

Chapter 2 The State of the Art
Chapter 4 The Enabling Technologies
Chapter 5 The Design Methodologies

This format reflects the argument by Silverman, (Ref. 12), that a literature review should mainly be written after the data analysis has been complete.

2.1 The State of the Art

Chapters 4 and 5 look in depth, with references, at those enabling technologies and methodologies which are considered to be particularly useful in achieving Jigless Aerospace Assembly, (JAM). This section is, therefore, limited to establishing the, 'State of the Art'.

2.1.1 Assembly of Complex Structures

2.1.1.1 Shipbuilding

Jigless assembly is the way that large individual products such as ships and submarines are manufactured. Ships are constructed without the use of any type-specific tooling, (Ref. 13). Sheet and plate steel is CNC flame-cut or precision laser-cut, (Ref. 14), and machined-welded to create larger flat parts. These are then lifted using vacuum equipment and drape-formed over CNC profiled parts, and hand-welded to create hulls and superstructure.



Shipbuilding *Fig. 3*

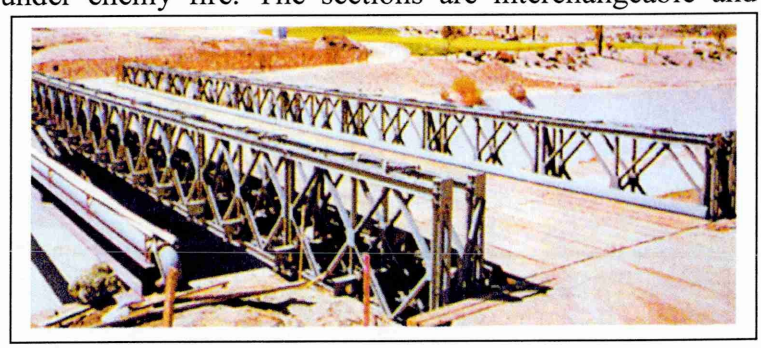
The steel plate may first be tacked or spot-welded to secure its position before the

entire perimeter is welded. Alternatively, steel plate may be welded to form erection units that are later moved and assembled to form the ship, (*Figure 3*). Welding has mostly replaced drilling and hot riveting. (Ref. 15).

Submarines are constructed from sections of very thick steel plate rolled to match the radius of a wooden former and then machined on the ends to provide features that will locate the next section of hull prior to welding. The accuracies required by the ship yards are achieved using plumb lines, lasers, and non-contact measuring equipment.

2.1.1.2 The Bailey Bridge

In 1940, Sir Donald Bailey designed his famous panel bridge, (*Figure 4*), for ease of assembly by troops whilst under enemy fire. The sections are interchangeable and joined together by bolting through matching female jaws and male eyes. No tooling or fettling was needed in the assembly of a Bailey bridge, although a considerable quantity of dedicated hard-tooling was used in its wartime construction. The modern version by Mabey and Johnson Ltd makes full use of solid modelling, FE and virtual assembly analysis, CNC drilling, profiling, and robotic welding. The result is a reduction in manufacturing tooling and an improvement in manufacturing capability. On-site assembly is just as simple as the original bridge and, due to the improved manufacturing accuracies, the modern version no longer needs turnbuckles to tension the finished structure, (Ref. 16).



A Bailey Bridge *Fig. 4*

2.1.1.3 Erection of Structural Building Frames

With increasing concerns over Health and Safety issues associated with the assembly of high-rise, steel framed buildings, (*Figure 5*), the building industry is looking to a future using automated construction cranes. This requires a move away from on-site fettling and hole-to-hole assembly to the use of integrated assembly features that will enable automated part-to-part assembly. The features under consideration are variations of the standard woodworkers mortise and tenon joints with tapered lead-ins to aid initial location, (Ref. 17).



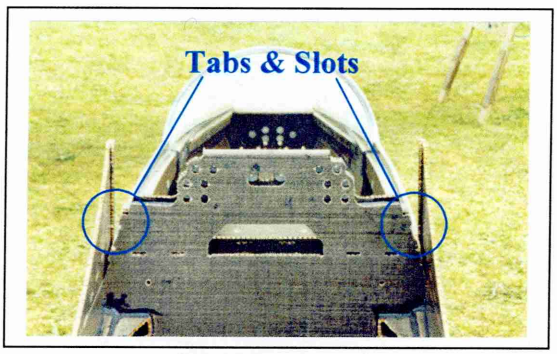
The High Rise Buildings of New York *Fig. 5*

2.1.1.4 Self-Tooling Assemblies

The Edgley EA9 Optimist glider, (*Figure 6*), is designed for home assembly and delivered in a flat-pack containing CNC, composite sandwich, machined panels with tangs and slots, (mortise and tenon joints), for easy assembly. The components form a self-tooling structure and are first dry assembled, (*Figure 7*), then bonded together using a foaming adhesive, (Ref. 18).



Edgley EA9 Optimist *Fig. 6*



Dry Assembly *Fig. 7*

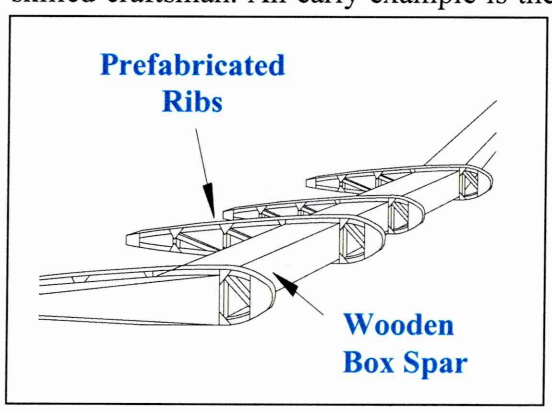
In other areas too, designers have been innovative in designing self-tooling assemblies. Composite Optics of California has developed a method of building satellites from flat, water-jet cut, panels of carbon composite, (Ref. 19). The panels are cut with tabs and notches for locating to the neighboring parts giving a method of assembly that is apparently similar to a model chuck-glider.

AMS Radar Systems, (See Appendix C), use similar features to assemble the egg-box stiffening structure on the rear of large radar antennae.

Home-build aircraft designs have to be carefully thought through to allow them to be built in a reasonable time by enthusiasts that are not necessarily highly skilled craftsman. An early example is the 1947 French designed Jodel range, (Ref. 20), (*Figure 8*), which like similar wooden home builds, features a continuous wooden box spar running from tip to tip and forming the pilot's seat as it passes through the fuselage. The prefabricated ribs, (*Figure 9*), are slotted onto the spar and bonded in position. The spar is the assembly tooling for the wing. If the spar is correct, then the remainder of the wing assembly is relatively easy.



Jodel D11 *Fig. 8*



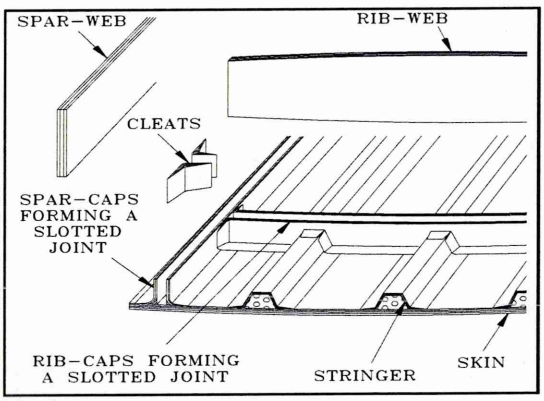
Jodel Wing Construction *Fig. 9*

2.1.1.5 AMCAPS Wing-Box Design

The AMCAPS research project into the Affordable Manufacture of Composite Aircraft Primary Structure resulted in the development of a number of innovative manufacturing processes, and the manufacture and assembly of a three metre long demonstrator wing-box representative of an Airbus A320 outer wing, (*Figure 10*). An assembly centric approach was adopted and the final design was very nearly self-tooling with the only external tooling being a steel structure that established the correct relationship between the two aerodynamic surfaces. Matching pairs of rib-caps and spar-caps co-bonded to the interior surfaces of the wing-skins created deep slots for locating the rib-webs and spar-webs on final assembly. The normal composite manufacturing variables are absorbed in the depth of the slots and the thickness of the bond-line, (*Figure 11*), (Ref. 21).



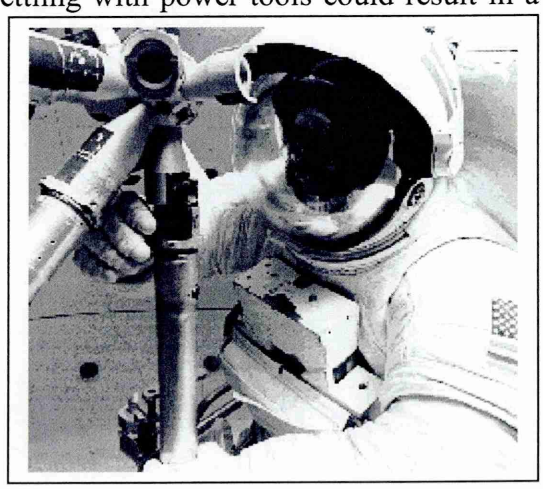
AMCAPS Demonstrator Wing-Box *Fig. 10*



Self-Tooling Assembly *Fig. 11*

2.1.1.6 Assembly of Large Structures in Space

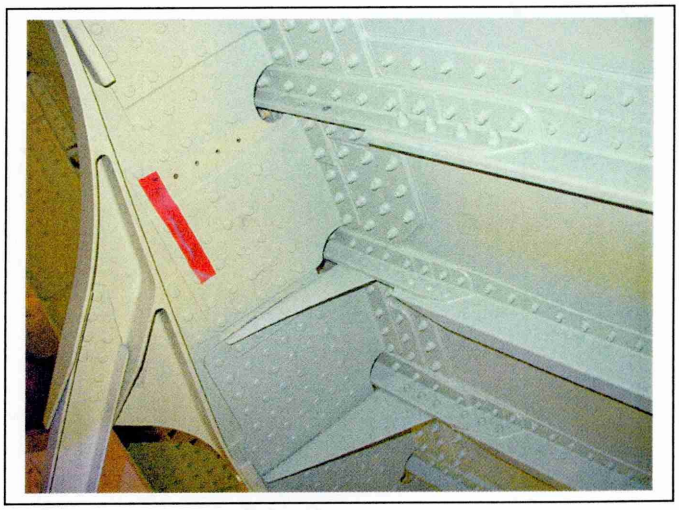
Jigless assembly is necessary for the assembly of large structures in space, where extra vehicular activity, (EVA), is dangerous and fettling with power tools could result in a damaged space suit and is, therefore, an unacceptable risk. While NASA Langley has concentrated its efforts in recent years on the in-space assembly of high-precision deployable instruments, a decade ago the task was to design and build much larger structures for possible integration into the space station programme. Because of their size, these structures are designed to be assembled by astronauts in space during EVA. From their research, NASA engineers developed a quick-attachment joint for high-performance structures which allows one-handed operation through spring-load latch bolts, and a tapered tongue-and-groove design to eliminate free play, (*Figure 12*). CNC machining has made it possible to fabricate joint hardware which gives consistent repeatable performance, (Ref. 22).



Precision Node and Strut Joint *Fig. 12*

2.1.1.7 One-Way Assembly

The traditional reasons for the aerospace industries relying so heavily on type specific tooling are explained in Section 1.2; and one of the reasons given is the need to drill fastener holes in-situ through several different component parts, (*Figure 13*). The parts must then be separated for de-burring, cleaning, adding anti-fretting compound, and finally relocated in the tooling for final assembly with the addition of the permanent fasteners, (Ref. 1).

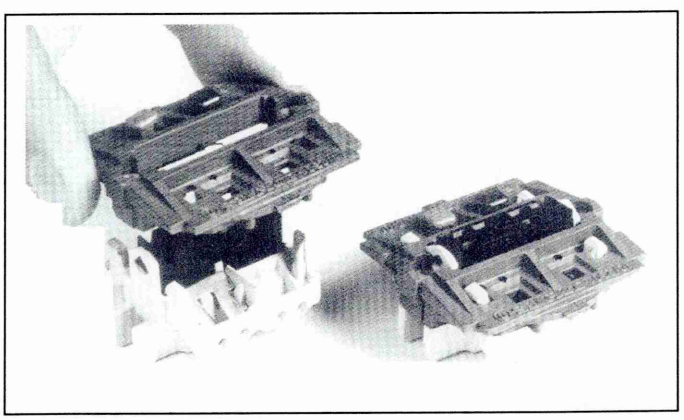


A380 Fuselage Frame to Stringer and Skin joint *Fig. 13*

Simplification of the process will eradicate the need for much of the tooling and there is research being conducted into what the industry calls 'one-way', or 'one-sided assembly'. One-Way assembly research includes burr-free hole production, fasteners incorporating a small sack of anti-fretting compound, welding, adhesive bonding, reconfigurable and flexible tooling, use of industrial robotics, real time machine vision, solid modelling, and FE analysis to determine the effect of the clamping forces and the most effective positioning of the clamps, (Ref. 23).

2.1.1.8 Snap-Fit Assembly

The elastic properties of plastics have been long been exploited by manufacturers of toys, construction kits, and electronic components. Children are able to assemble large and complex models by pushing together individual Lego bricks, (Ref. 24), and older modellers can assemble scale model aircraft, cars, and buildings without adhesive by simply snap-fitting the parts together, (Ref. 25).

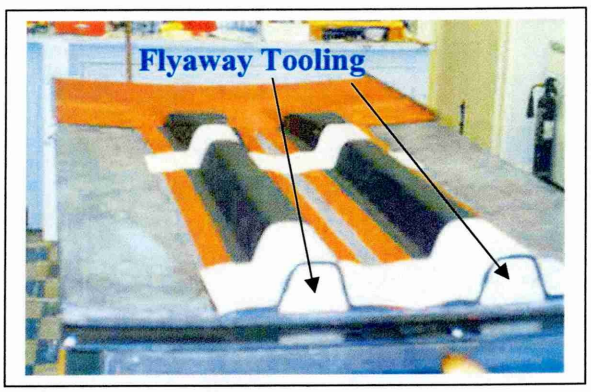


Snap-Fit Assembly *Fig. 14*

Serious applications of the technology are found in the electronics industry. Sensitive components are encapsulated in moulded plastic enclosures having barbed prongs that locate into holes and slots in a mother component, (*Figure 14*), so ensuring integrity of restraint but also allowing easy removal and replacement should the embedded electronics fail, (Ref. 26).

2.1.1.9 Flyaway Tooling

The terminology 'Flyaway Tooling' has a specific meaning within the aerospace industry and is described, 'as tooling that remains in-situ to become part of the finished structure'. In that sense, it has particular relevance to an advanced composite structure where it is possible to reduce the need for mould tools and assembly tooling by covering a preformed foam core with a composite skin. The foam core remains in-situ after curing as an integral part of the structure and may contribute to the engineering properties of the finished structure.



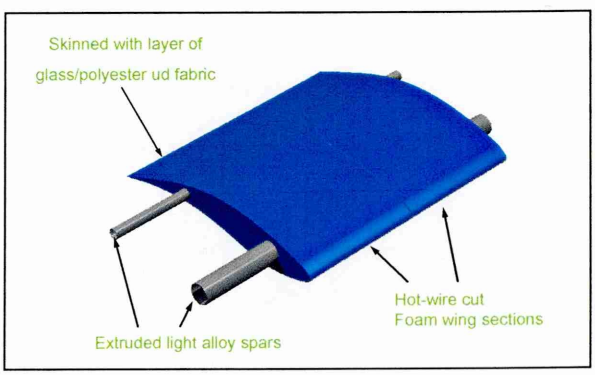
Flyaway Tooling *Fig. 15*

The author's paper, (Ref. 4), on the subject proposed several theoretical applications and described a number of current examples. These included an application found in both the boat building, and the light aviation industry, where pre-formed top hat shaped sections of rigid foam core, are embedded within composite skins to create integral stiffener elements. This allows co-curing of the skin and stringers without the need for internal tooling to react the autoclave pressure, and avoids the problems associated with extracting very long rubber mandrels, (*Figure 15*).



Rutan Varieze *Fig. 16*

Burt Rutan in his revolutionary Varieze aircraft, (*Figure 16*), (Ref. 27), designed for the home-build market, exploits a variation of this technique. The wing is a single spar structure onto which are threaded pre-formed hot-wire cut plastic foam wing sections, (*Figure 17*). A finishing layer of unidirectional glass fibre applied by hand provides structural integrity. Construction is very easy, (hence the name of the aircraft), no form tools are required and the spar is the assembly tooling.

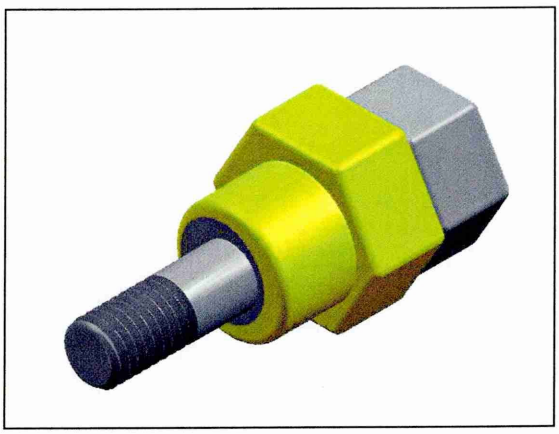


Easy Build Wing *Fig. 17*

2.1.1.10 Part-to-Part Assembly

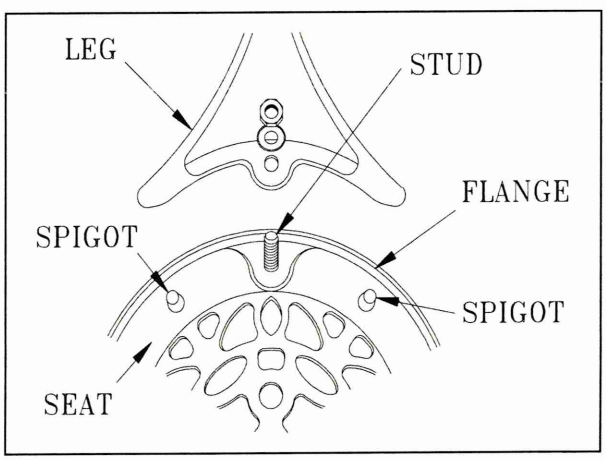
Successful Part-to-Part assembly requires that the parts are manufactured with the necessary accuracy. They can then be located such that the resulting assembly accuracy, is a function only of the component

accuracy, and the ability of the location and fastening features, to locate one component kinematically and accurately against another, (Ref. 5).



Double Eccentric Alignment Fitting *Fig. 18*

Short Brothers of Belfast have succeeded in virtually eliminating all external tooling from the cabin door assembly of the Bombardier Global Express aircraft. The door structure and the complex closing and locking mechanism are assembled with parts locating off each other on a part-to-part basis. Double eccentric alignment fittings are used to achieve correct fitting of the door locking bolts to the more flexible fuselage assembly, (*Figure 18*), (Ref. 5).



Part-to-Part Chair Leg Assembly *Fig. 19*

Other industries, such as the 'home assembly' furniture industry are also well advanced in this technology. An example is a cast-aluminium garden chair leg-to-seat assembly. The chair leg locates against the curved seat flange with two spigots preventing it from rotating. The casting draft angles of the spigots and the flange are used such that as the single fixing bolt tightens on the base of the leg, the leg slides down the angles and is forced hard against the seat flange, locking it in position, (*Figure 19*).

2.1.1.11 Boeing 777 Fuselage

Boeing claim to have achieved jigless production with the assembly of fuselage sections for the Boeing 777 aircraft coming from five different Japanese manufacturers, (*Figure 20*). They claim that by coupling automated drilling systems with calibrated temperature scales they have achieved the tight tolerances necessary to realise hole-to-hole assembly of the barrel sections, (Ref. 28). Information is sketchy, but consideration of the holes positional and diametrical tolerances to achieve true hole-to-hole assembly for several



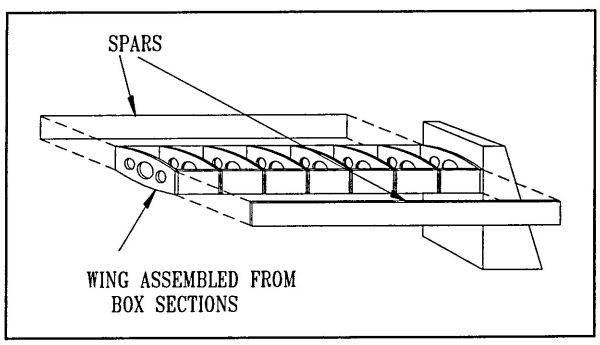
777 Fuselage Assembly *Fig. 20*

hundred rivets at each radial joint makes it easy to be sceptical. However it may be that the pre-drilled holes are pilot-holes and that they are positioned sufficiently accurately to allow reaming with minimal metal removal on final assembly.

2.1.1.12 Blue Sky Concepts

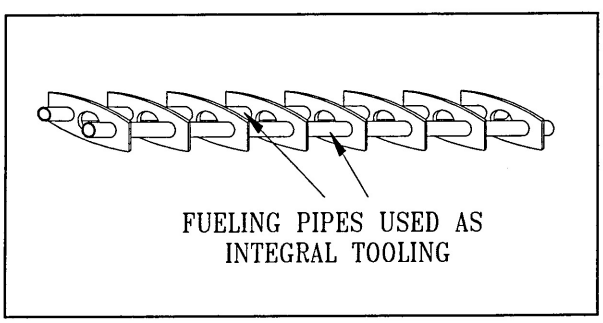
Four 'Blue Sky' concepts were developed during discussions among other researchers and published in the first of the JAM technical papers, (Ref. 4).

1) The Box Build concept is the final assembly of a wing from a series of stiff boxes having features to kinematically locate to other boxes and parts, (*Figure 21*). In its simplest form, the wing is divided into boxes of one rib bay width. During construction, the wing is cantilevered from a wing-root plug and each box section is suspended on wires of adjustable length that enable the builders to control the amount of wing-droop. As the box sections are fastened or bonded together the full thickness of each rib is realised, and the sub-structure assembly is completed with the fastening or bonding into position of the two half-thickness full length spars. The concept assumes that the process capabilities are adequate to support box-to-box assembly.

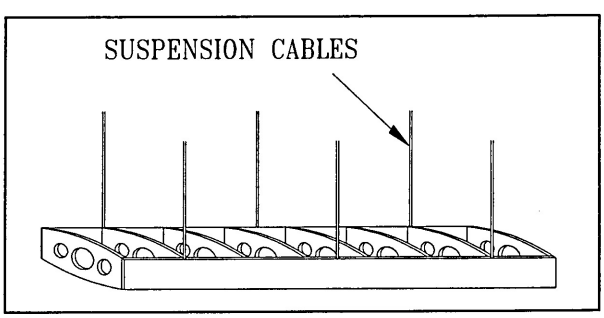


Box-Build Concept *Fig. 21*

2) The Integrated Tooling concept is based on the applications described in Section 2.2.1.4. Looking at schematics of Boeing and Airbus wings it is clear that they have features that with thought can become integrated tooling and still perform their original function. The wings of both manufacturers have, for example, large diameter fuel pipes running through them. It may be possible to redesign and utilise these so that they also act as tooling for locating and supporting the ribs prior to the fitting of the spars, (*Figure 22*).



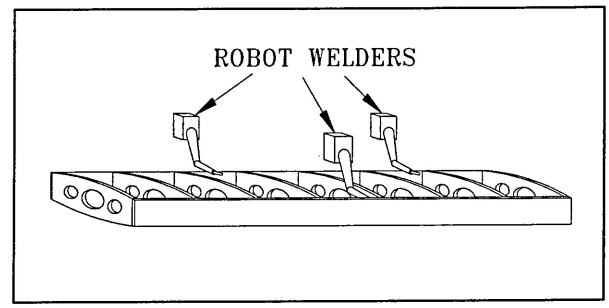
Integrated Tooling Concept *Fig. 22*



Use of Suspension Cables *Fig. 23*

3) The idea of using Suspension Cables or adjustable length rods arose after a visit to the Advanced Technologies Group at Cardington and seeing the use of cables to support an airship gondola during construction. It is a minimal tooling concept, with the ability to be rapidly reconfigured for a different size or type of structure, (*Figure 23*).

4) All Welded Structure. An all welded structure has the advantages of weight saving and part reduction. It is not just the rivets that are eliminated but also all the tooling associated with them. The welding process can be automated, (*Figure 24*), and can compensate for any slight mismatch between parts with the filler rod material. There can be problems of strength and distortion with all welded structures, however, the technology is being intensively researched[1] and is becoming better understood.



All Welded Wing *Fig. 24*

2.2 Analysis

Quite clearly there is no shortage of jigless examples. Therefore, jigless assembly is not a new concept and is already reality, or is close to becoming reality, in many branches of engineering; but that reality eludes the major aerospace companies.

There is also a common thread running through the examples and demonstrates that necessity is still the mother of invention.

a) There is no way that a ship yard could afford to build a one-off ship using dedicated hard tooling; they needed to find an alternative method of building them.
b) To be built and launched under live fire conditions, the Bailey bridge needed to be simple and easy to assemble, the parts needed to be interchangeable, and they needed to fit as supplied.
c) The AMCAPS wing-box design developed out of a need to demonstrate the efficacy to the CAA of a fully-bonded composite structure, and the deep slots, that make it self assembly, developed out of a need for double-lap shear joints and an increase in the bonded area.
d) The NASA node and strut joint evolved out of a need for simple and safe EVA assembly.
e) Burt Rutan was declared bankrupt after his earlier design for a wooden home-build aircraft, the Variviggen, proved too difficult for many purchasers of the kit. He needed to find a simpler method of construction, and he found it by being aware of new and emerging technologies.

Not all jigless technologies are applicable to aerospace structures. It is difficult to see, for example, how an aircraft primary structure can be snap-fitted together; nevertheless it is important that JAM designers, like Burt Rutan, be aware of alternative assembly technologies. One day there may be a quantum leap of intuition and then, maybe, it will be possible to snap-fit assemble large aerostructure.

It should also be noted that these are all original designs, designed from the outset for jigless assembly, and not re-engineered versions of existing designs. Although having

[1] CEMWAM II, 'Arc Welding Process Improvement for Airframe Applications', current EPSRC-IMRC research project at Cranfield University, Principal Investigator – S. Blackman.

said that, like Burt Rutan's history, there is probably a lot of learning experience and the odd failure behind each success story.

The major aerospace companies are unlikely to take a single step-change to JAM. Instead they are more likely to opt for a piecemeal approach starting not with a major structure but with a small, low risk structure that could be rapidly re-engineered if the JAM approach failed.

The part-to-part assembly of the complex locking mechanism for the Bombardier Global Express door was largely driven by one man, Mike Gribben, (Appendix B), and was possible because, although Short Brothers are part of the global company Bombardier Aerospace, they are small enough and have enough autonomy for one gifted engineer to be able to make an impact. Also, they were successful because they knew their manufacturing capabilities, and therefore knew that the parts would fit as delivered.

3.0 THE INDUSTRIAL BASED RESEARCH PROGRAMME

3.1 Demonstrator Structure – A320 Fixed Leading Edge

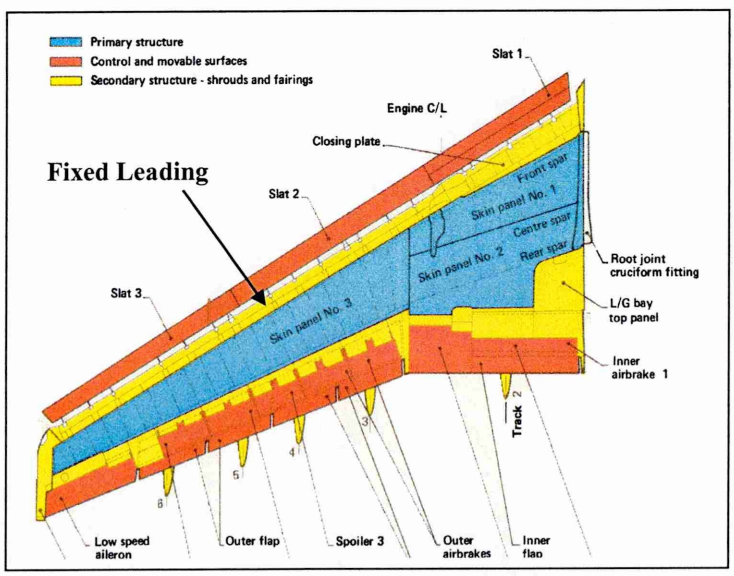
In order to provide a focus for the research, a 1.55 metre long section of the Airbus A320 fixed leading edge, inclusive of slat track ribs numbers 5 and 6, was selected as a demonstrator structure. (*Figure 25*). The selection of the A320 wing was significant, as this wing is common to the A319, A320, and A321 aircraft. In excess of 1720 A320 wingsets have been produced, (Ref. 29), with analysts forecasting future requirements for another 2000 wingsets. The wing was designed in the mid-1980's and Airbus UK recognise both a need, and the opportunity, to re-engineer the design to reduce cost and to improve competitiveness.



Leading Edge Demonstrator Section *Fig. 25*

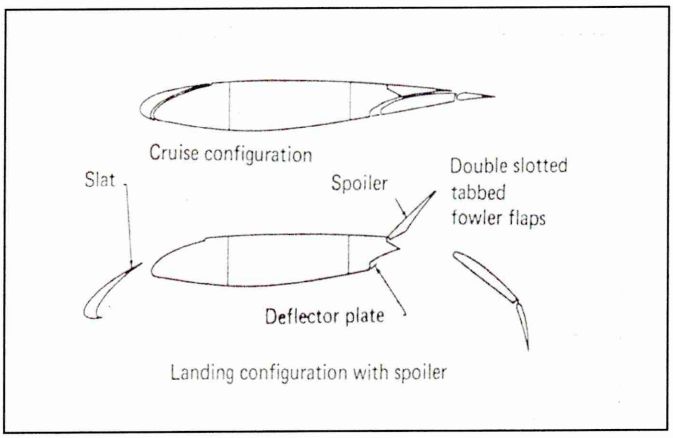
3.1.1 Description

The fixed leading edge is a metal 'D' nosed structure attached to the front spar of the main wing box, (*Figure 26*), housing the slat tracks and the slat operating mechanisms (*Figure 27*).



Wing General Arrangement - Upper Surface *Fig. 26*

It does not contribute to the wing shear, bending or torsional strength and is defined as a secondary structure, (Ref. 27). The fixed leading edge profile is aerodynamically critical whenever the wing is set to take-off or landing configuration. In the cruise configuration the nose and upper aerofoil surface of the fixed leading edge are covered by the slats, (*Figure 27*).

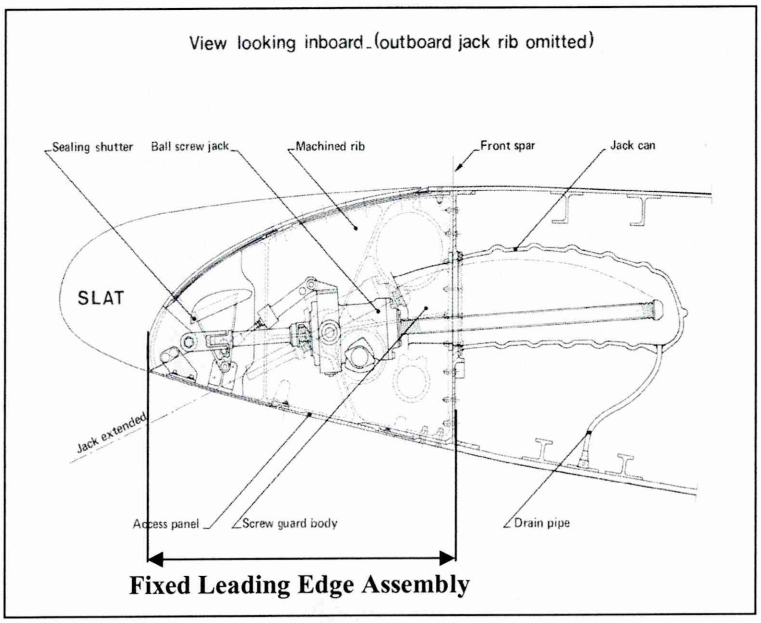


The Airbus Two-Dimensional Wing Aerofoil Fig. 27

The Airbus wing has a low speed, high lift performance provided by a combination of leading edge slats and trailing edge flaps, (*Figure 27*). The leading edge slats are approximately 18% of the wing chord and extend over the great majority of the wing span.

3.1.2 Structure

The fixed leading edge consists of pairs of cantilevered track-ribs and an inter-rib secondary structure, between the track-ribs, carrying the local air loads. The track-rib pairs provide mountings for the rollers supporting the slat tracks, and for the trunnions supporting the slat screw jacks. (*Figure 28*).



Leading Edge at Slat Track Fig. 28

The ribs at the slat tracks are integrally machined from aluminium alloy plate and incorporate bosses to support the roller loads. The track-ribs are assembled as pairs by external sub-contractors and delivered to the Airbus assembly line with temporary tooling to ensure that the alignment of the bores is maintained during delivery and handling.

The cantilever bending loads at the front spar are transmitted by bolts in shear into local extensions of the top and bottom main box skins at the rib positions.

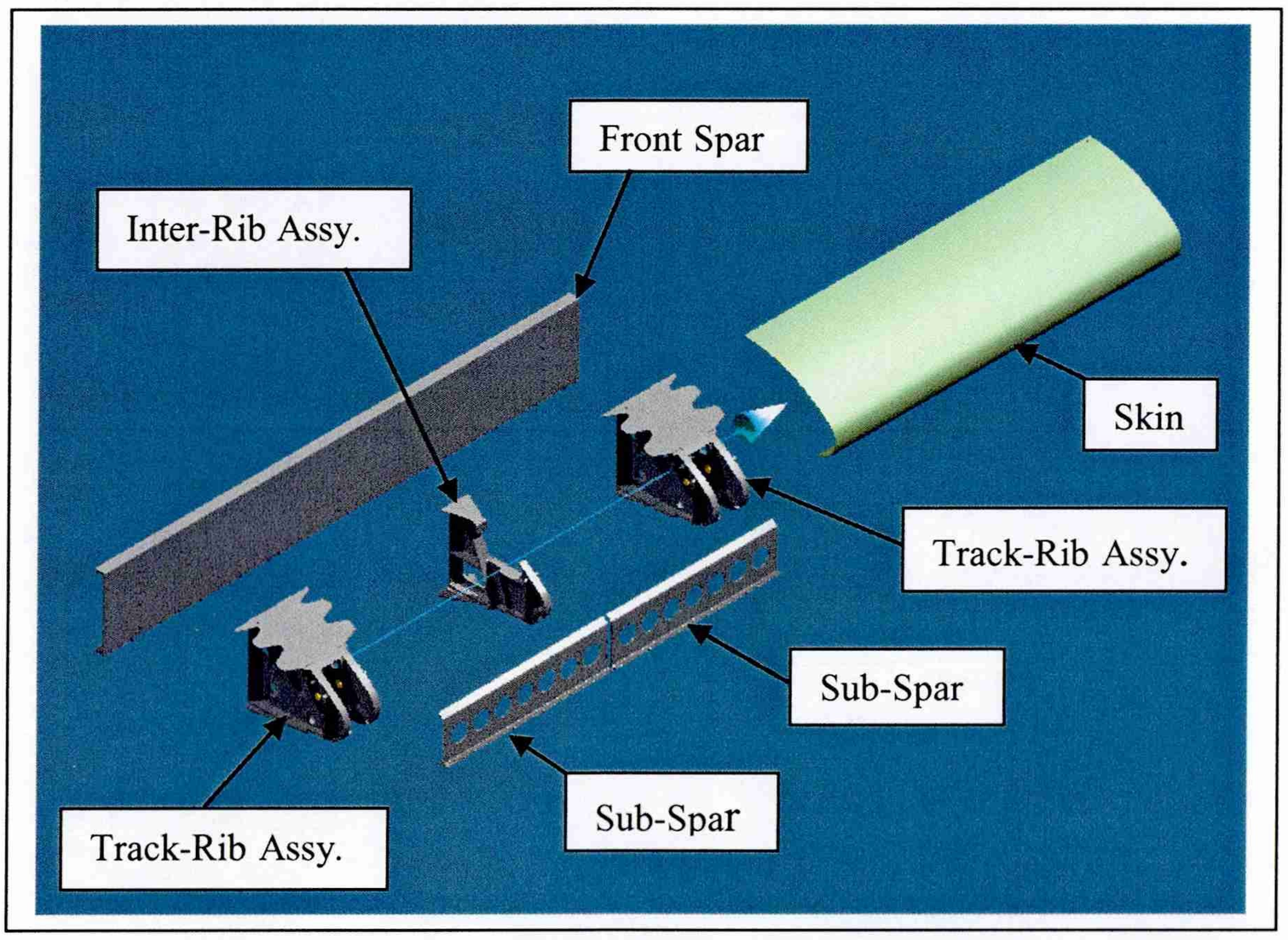
The secondary structure consists, at the front, of a span-wise diaphragm and a metal 'D' nose. Between the diaphragm and the front spar, on the lower surface, there are panels with quick release fasteners providing access for in-service maintenance of tracks, rollers and slat operating jacks, gearboxes and shafting. On the top, the panels are permanently attached.

Each section of slat is carried on curved titanium tracks attached to the slat and running on rollers in the fixed leading edge. Four rollers carry vertical loads, the lower pair being adjustable to suit the tracks. Side loads are carried by rollers running on the track side flanges. Aerodynamic seals, attached to the slats, prevent airflow between the slat and the fixed leading edge, when the slat is closed.

To avoid in-flight steps, caused by bending deflections of the wing relative to the local deflections of the slats, the slats rear edges are set 2.5 mm below the top skin level so that they are more nearly flush with the skin under cruise conditions.

Provision is made for adjusting the slats, to the wing profile, at the track positions.

3.2 Current Parts Manufacture

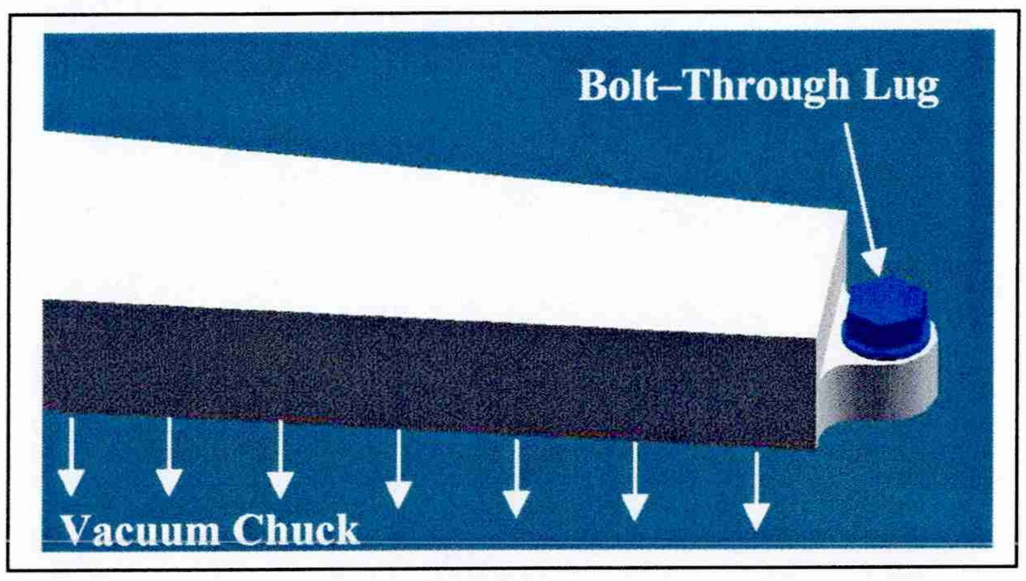


The Principal Component Parts of the Demonstrator Assembly *Fig. 29*

The principal component parts, (*Figure 29*), of the Demonstrator Assembly, are;

3.2.1 Front Spar

The front spar is a light-alloy, CNC machined, monolithic component. The material is sourced both in the USA and Europe and shipped to the UK as a planar milled billet. Historically, placement of the spar manufacture may be part of the overall Airbus sales package. This has resulted in spars being machined at a number of different sites in a number of different countries, including the USA, China, and the UK. The spar mills in use, at the time of this research, had vertical milling heads and were not climate controlled or enclosed.



Machine Tool Fixturing of Spar *Fig. 30*

The spar billets are fixtured to the machine tool table using bolt-through, sacrificial tooling lugs at each end of the billet, and pulled down along the span by a vacuum chuck, (*Figure 30*). The CNC datum is a hole on the fixture, and datum is effectively lost when the machined spar is removed from the fixture. During manufacture, over 75% of the billet is machined away and the emerging spar becomes increasingly flexible with a risk that the machining forces could cause it to bow away from, or pull into the cutter.

The spars are delivered to the assembly cell as sub-assemblies with a crack stopper and various brackets already fitted.

There is no delivery inspection of manufactured parts. The reliance is on the manufacturer to provide parts of the required quality.

Machining sequence;

- Skim one face
- Turn over
- Skim opposite face
- Finish machine using puddle-jumping technique
- Turn over and finish machine other face

- Finishing operations, (See Section 3.2.9).
- Corrective shot-peening - as necessary, (See Section 3.2.10).

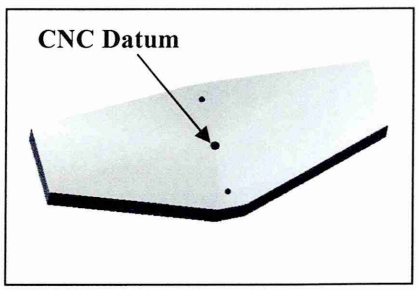
3.2.2 Track-Ribs

The track-ribs are manufactured internally by the main contractor and assembled as track-rib pairs by external sub-contractors. The track-rib sub-assemblies are delivered to

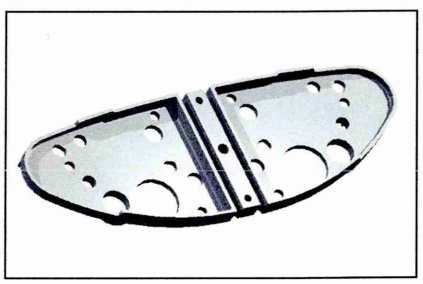
the fixed leading edge assembly cell fitted with temporary tooling to ensure the alignment of the slat track bearing holes. (See Section 3.1.2).

Machining sequence;

- The light alloy blank is supplied as a plate, sawn to approximate profile with flycut faces and pre-drilled hold-down holes. (*Figure 31*).
- Blank fixtured using bolts and vacuum chuck.
- Datum hole is in sacrificial material between the two ribs.
- Mirror pair of ribs are machined simultaneously from a single blank. (*Figure 32*).
- Six hours of CNC machining using a twin spindle Automax III, 5-axes machining centre.
- Part turned over and finish machined from both sides.
- Mask to ensure required conductivity.
- Remove from machine and de-burr.



Track-Ribs Blank *Fig. 31*



Machined Track-Ribs Pair *Fig. 32*

- Operator carries out a 10% partial inspection using an LK Co-ordinate Measuring Machine.
- Operator checks and records conductivity.
- Operator checks and records hardness.
- Operator visually checks for evidence of machine abuse. (That is heavy cutting and chatter marks that may have produced stress raisers).

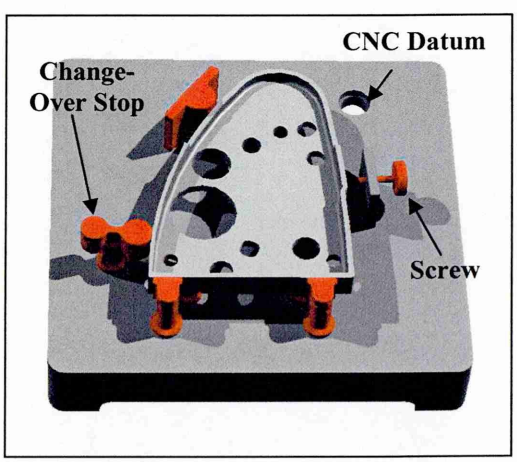
Reaming the bush housings, (*Figure 33*);

- Ribs are mounted separately on the fixtures. (This time locating off the outer profile). Use of a change-over stop allows each tool to be used for two different sizes of track ribs.
- CNC datum is established with reference to the tooling hole on the fixture.
- Ream bores. (KTM Fleximatic FM200 M/T) (Reamers have one cutting blade and two burnishing blades).

Remove from M/T and fit bushes.

- Heat ribs to 95^0C and cool bushes in liquid nitrogen, to -196^0C.
- Press into bores.
- Return to M/T and re-fixture.
- Bore bushes and skim faces.

The ribs then undergo a number of finishing operations, (See Section 3.2.9), before being transferred to the bonded store.



Fixturing for Reaming The Bush Housings *Fig. 33*

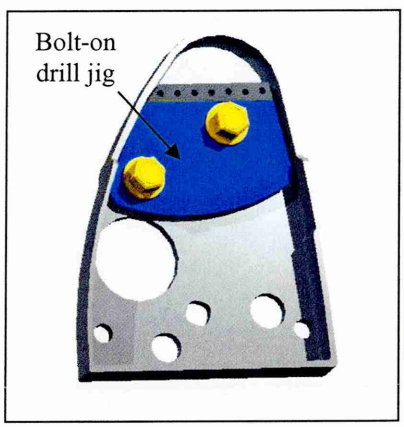
3.2.3 Sub-Assembly of Track-Rib Pairs

The track-rib pairs, (*Figure 35*), are assembled by external sub-contractors. The sub-contractors maintain kits of parts in order to achieve JIT, (Just In Time), delivery of completed sub-assemblies. All of the jigs and tools are supplied and owned by the main contractor with a twenty-week lead-time for additional, 'Rate tooling'.

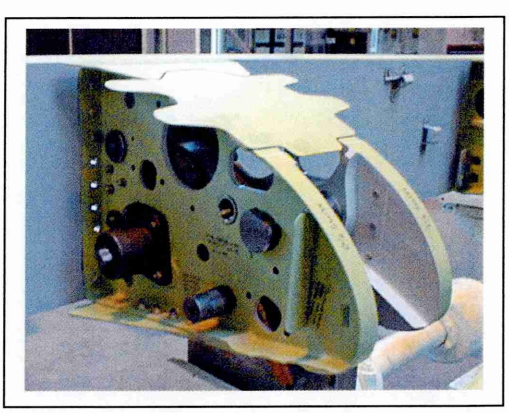
It takes approximately 260 man-hours to complete the assembly of a track-rib pair.

(Partial) Assembly Sequence;

- Attach sub-spar brackets and track stops
  - Use abrasive pads to clean fraying surfaces
  - Use drill jig, (*Figure 34*).
  - Drill 2.4-mm pilot holes
  - Final size drill
  - Cold work drilled holes, (See Section 3.2.11).
  - Disassemble and deburr
  - Reassemble with permanent fasteners
- Assemble mirror ribs pairs using alignment tools - 'dummy rollers', and spacers
- Assemble lower spreader-plate to rib-pair
  - Use abrasive pads to clean fraying surfaces
  - Clamp fixture to rib-pair
  - Clamp fixture in an engineer's bench vice
  - Centralise spreader-plate using feeler gauges
  - Back drill 2.4-mm pilot holes in spreader plate using pre-drilled pilot holes in ribs.
  - Use Cleco pins to hold in place
  - Remove tool and drill remaining holes
  - Drill final size
  - Cold work drilled holes
  - Countersink as necessary – Cleco pins are placed by the technician to prevent the accidental countersinking of the wrong holes



Drill Jig for Attaching Sub-Spar Brackets *Fig. 34*



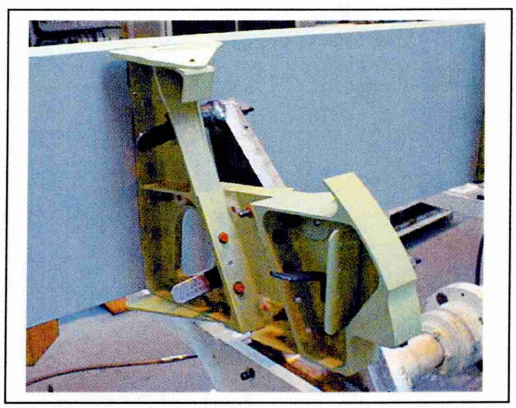
Assembled Track-Rib Pair *Fig. 35*

  - 'Superglue' the two packers together. (One thin and one thick packer)
  - Measure and mark with a soft pencil, the positions of the two packers on the track-rib pair
  - Clamp and drill through using pre-drilled pilot holes
  - Drill final size and countersink
  - Cold work drilled holes
  - Disassemble and deburr
  - Reassemble with permanent fasteners

3.2.4 Inter-Ribs

The inter-ribs, (*Figure 36*), are monolithic, CNC machined light alloy components. They are delivered to the fixed leading edge assembly cell as sub-assemblies with sub-spar brackets, stiffeners, and doublers permanently attached.

The inter-ribs are machined with tooling holes to establish location during assembly.



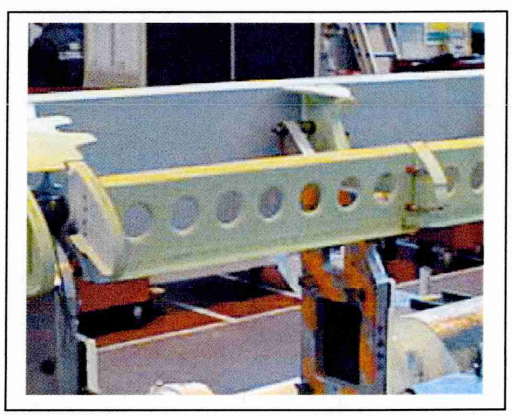
Inter-Rib *Fig. 36*

3.2.5 Sub-Spars

The sub-spars are sheet metal sub-assemblies, (*Figure 37*). They consist of three parts;

1. Spar web
2. Lower spar flange – front
3. Lower spar flange - rear

- The component parts are solution treated both before and after the drop-hammer forming processes.
- Tooling is used to ensure the correct drilling and assembly of the parts.
- A manually operated auto-drill riveter, (ADR), is used for the permanent assembly of the component parts. (See Section 3.2.6).



Sub-Spar *Fig. 37*

3.2.6 Skins

The nose skins are stretch-formed sheet metal sub-assemblies, (*Figure 38*).

Production sequence;



Nose Skins *Fig. 38*

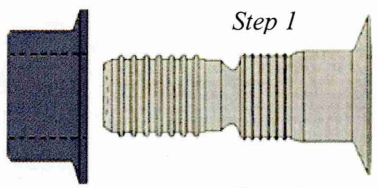
- Manually drill and screw light alloy sheet to wooden backing sheet
- Drill tooling holes
- CNC rout profiles leaving retaining webs
- Manually separate parts
- Solution annealing treatment
- Stretch form using tooling holes to locate parts
- Pull down flat for final trim - includes losing tooling holes
- Solution tempering treatment
- Attach J-stiffeners to the inner surface using a manually operated auto-drill riveter, (ADR).

The ADR requires the clamped parts to be manually moved to each rivet position. Final positioning is by sighting through an optical centering microscope onto centre-punch marks, or drawn pencil lines, or pre-drilled pilot holes. On the operator's instruction the ADR will automatically clamp, drill, add anti-fretting compound, insert and squeeze rivets, and shave countersunk heads. No separation of parts for deburring is necessary as the high clamping forces prevent burrs from growing between the sheet metal plies.

3.2.7 Permanent Fasteners

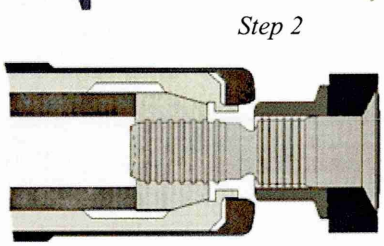
Step 1

The fastener is inserted into the prepared hole and the collar is placed over the fastener with the flanged base towards the part surface



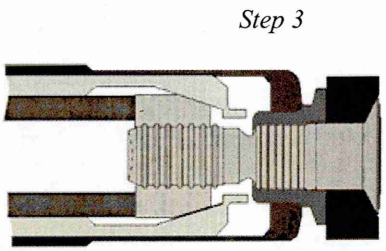
Step 2

The installation tool is placed onto the fastener and the gripper jaws engage the pintail of the fastener. The tool is actuated and the pintail is pulled against the push of the tool on the collar. This action seats the head of the fastener and begins swaging the collar



Step 3

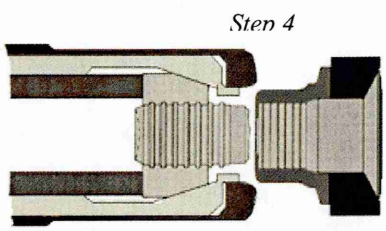
Continued swaging of the collar forces the collar material into the fastener locking grooves creating an extrusion action that stretches the collar. This results in a corresponding stretch of the pin.



Step 4

When the collar swaging is complete, the tool continues to pull until the pin separates in tension, (at a pre-determined force), at the break neck groove. The tool trigger is then released and the nose assembly with tool is pushed off the installed fastener, completing the installation cycle.

The entire sequence occurs in less than two seconds.



Principle of Swaged Head Fasteners *Fig. 39*

1) Automatic riveting machines use solid cylindrical, slug type, rivets. Access is required to both sides of the structure and the riveting tool sets both heads.
2) Rivets that are set using manually held riveting guns are of the solid, single headed varieties.
3) Higher strength permanent fasteners are of the swaged collar type. (Ref. 31). A manually guided autonomous tool grips and pulls on the grooved pintail of the fastener. Simultaneously the nose of the tool reacts against the collar, swaging it

onto the parallel threaded shank of the fastener. At a predetermined tensile stress the pintail breaks at the groove completing the fitting process. (See *Figure 39*)

3.2.8 Removable Fasteners

Two types are used;

1) Floating nut assemblies for securing removable inspection and maintenance panels.
2) Standard design bolts and nuts for securing replaceable and maintainable components.

3.2.9 Finishing Operations for Machined Parts

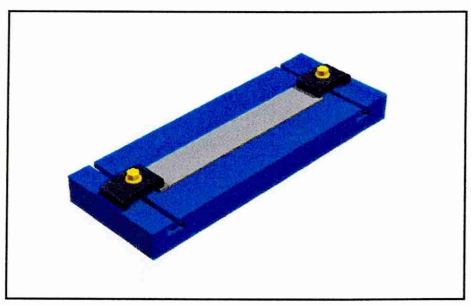
1. Penetrant flaw detection, (PFD) - crack detection using ultra-violet light.
2. Shot-peening – (See Section 3.2.10).
3. Anodising - this opens up the surface grain and parts must be painted within 16 hours.
4. Mask specified areas - to ensure required conductivity.
5. Prime painting.
6. Gloss painting.
7. Part identification marking.

3.2.10 Shot-Peening

Shot-peening is used to;

- Form the main wing-skins, (Ref. 32).
- Correct distortion of machined parts, such as wing-spars.
- To introduce compressive stresses into the surfaces of machined parts, so as to increase fatigue strength and prevent stress corrosion.

Type specific tooling is not normally needed. The shot-peening of machined surfaces is an automated, repetitive process. Parts are laid horizontally and shot-peened one side at a time. A test strip is used to establish the degree of compressive stress introduced into the part surface.

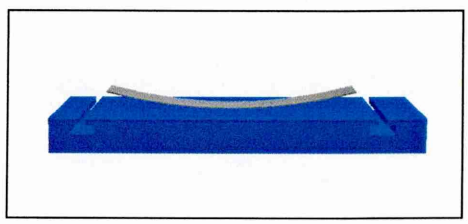


Shot Peening Test *Fig. 40*

Test:

- Peen test strip, *(Figure 40).*
- Release clamps.
- Measure height of arc.

The height of the arc is directly related to the compressive surface stresses. (*Figure 41*).



Peened Testpiece *Fig. 41*

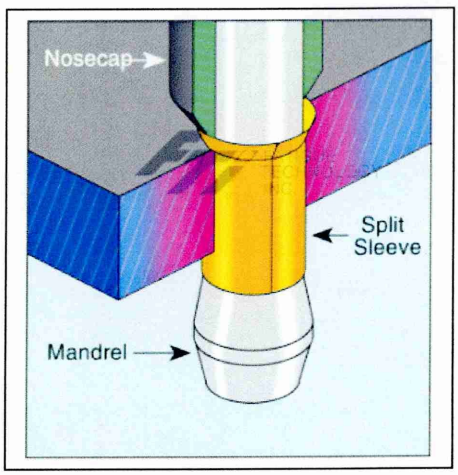
It is claimed that there is no measurable change in the part-dimensions.

The steel shot, up to 3-mm diameter, is fired by compressed air. After each run the shot is conditioned, and damaged shot, that could cause stress raisers, is filtered out using a helical slide.

3.2.11 Cold Working Drilled Holes

The cold working of drilled holes is a single-sided operation that involves pulling an expandable, tapered, mandrel through the hole, *(Figure 42).* The process produces a radial zone of residual compressive stresses that protect the hole from surface imperfections or material flaws and minimises the effects of applied cyclic loading.

The process results in, approximately, a 4.0% increase of the hole diameter for aluminium and mild steels, and 5.5% for higher strength metals. The cold expanded hole is normally finished by reaming to obtain the desired hole diameter and tolerance. (Ref. 33).



Cold Working of Drilled Holes *Fig. 42*

3.3 Current Assembly Process

The assembly process is divided into three stages to allow more efficient utilisation of the tooling and more flexibility in the rate of manufacture.



Stage 1 Assembly of Fixed Leading Edge *Fig. 43*

3.3.1 Stage 1 Assembly Operations

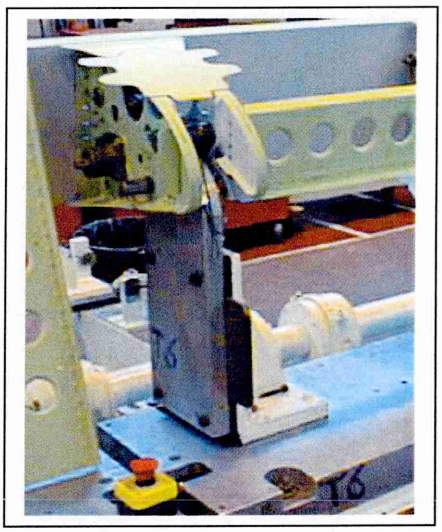
Stage 1 uses a full wing-length fixture tool designed to establish the slat-track hinge line as the main build datum. (*Figure 43*). This is to ensure correct operation of the slats in service.

The tool consists of a horizontal steel box structure, carried on cast iron pillars. It has 23 fixed tooling arms to hold and locate the track-ribs and inter-ribs, and 11 movable arms

to hold and locate the spar. The movable arms are mounted on a single hydraulically driven axle and can be rotated from the horizontal into the vertical position.

Assembly Sequence:

1) Each track-rib pair is mounted onto a specific fixed tooling arm. Location is hole-to-hole via the slat track bearing holes in the ribs, to tooling holes in the fixture. (*Figure 44*). The technician uses 'feeler gauges' to ensure that the rib pair is central on the fixture. He also checks that the rollers can be rotated. This establishes that the track-rib pair are correctly mounted on the tooling.



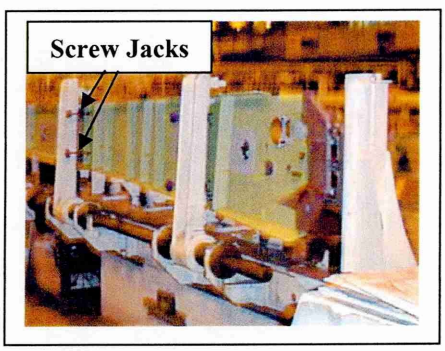
Track-Rib on Tooling Arm *Fig. 44*

2) Each inter-rib is mounted onto a specific fixed tooling arm. Location is hole-to-hole via tooling holes in the ribs to tooling holes in the fixture. (*Figure 36*).

3) The hinged arms are rotated into the horizontal, and the spar is lowered into position.

4) The spar is very flexible and is handled by an overhead crane with a lifting beam having seven pairs of hooks that locate under the edges of the spar flanges. (*Figure 48*).

5) Spanwise, the spar is located on the slat-track can hole at track-rib position five, and laterally by screw jacks spaced out along the length, coincident with the rib positions.



Lateral Adjustment of the Spar *Fig. 45*

6) The hinged arms are activated and the spar rotated into the vertical and adjusted using manually operated screw jacks so that it abuts against the track ribs. (*Figure 45*).

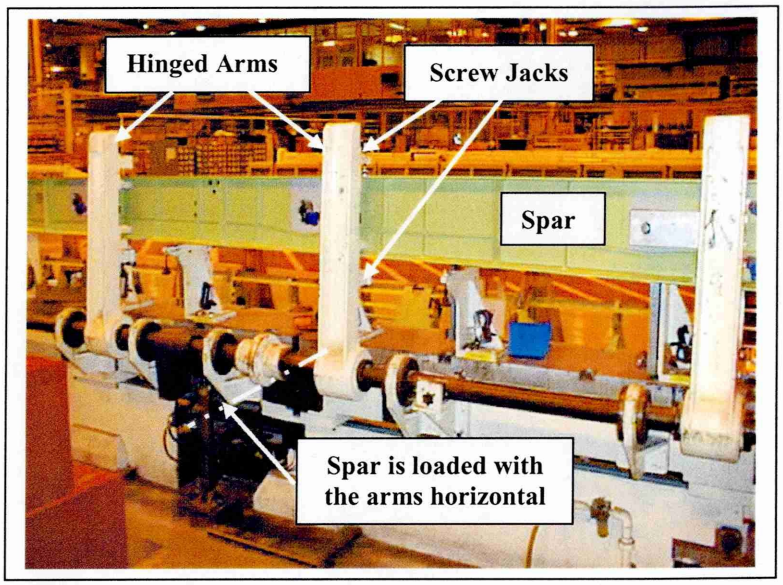
7) Manually operated screw jacks are also used to vertically adjust the spar at each rib position, (*Figures 45 & 46*). The technician uses a position-specific steel step gauge and 'feel,' to establish the correct step height between the upper aerodynamic surface of each rib and the upper spar flange.

8) Rib-to-spar fastener holes are drilled manually using bolt-on drill jigs to ensure correct hole positioning, (*Figure 47*). (Each drill jig is unique to a specific rib position).

9) The drill jigs are removed, the spar rotated back into the horizontal, and the drilled holes manually deburred.

10) The spar is rotated back to the vertical and the screw jacks adjusted to re-establish the correct step height between ribs and spar flange.

11) The ribs are sequentially removed, from the tooling and the fraying faces painted with anti-fretting compound.



Vertical Adjustment of the Spar *Fig. 46*

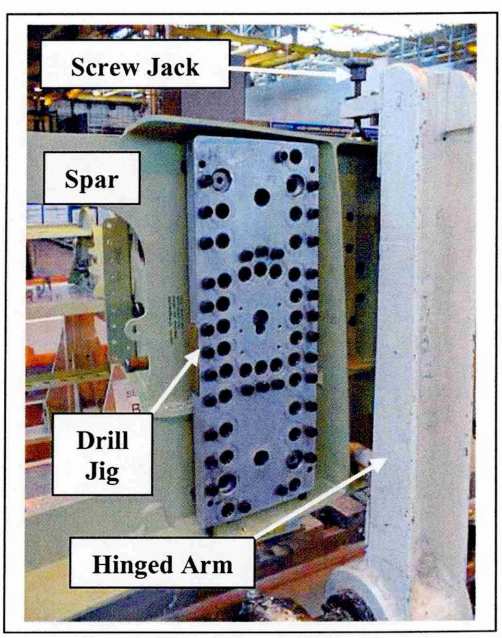
12) The ribs are refitted to the tooling and permanently attached to the spar using swaged collar fasteners. (See Section 3.2.7).

13) The spar is released from the tooling and the hinged arms are lowered to provide better access for the assembly technicians.

14) Next, the sheet metal sub-spars are approximately positioned on the sub-spar brackets, and temporarily fastened with G-clamps. Final positioning is achieved manually by visually equalising the end-gaps, and by setting the sub-spars flush with the top aerodynamic surfaces of the ribs.

15) Sub-spar fastener holes are drilled-off from the pre-drilled brackets.

16) The sub-spars are removed, the drilled holes deburred, and the fraying faces painted with anti-fretting compound.



Drill Jig Mounted on Spar *Fig. 47*

17) Cleco pins are used to temporarily relocate and retain the sub-spars prior to permanent fastening with counter-sunk rivets.

This completes the Stage 1 assembly operations.

18) The partially completed fixed leading edge assembly is released from the Stage 1 tooling and lifted across to the Stage 2 build tool.

The lifting beam is suspended from an overhead travelling crane and has seven pairs of hooks for locating and lifting under the spar flanges. (*Figure 48*).

The positions of the hooks do not relate to the positions of the track rib pairs.



Using the Lifting Beam *Fig. 48*

3.3.2 Stage 2 Assembly Operations

Stage-2 is where the nose skins are added to the assembly. The Stage 2 build tool is a full-length, steel support tool, (*Figure 49*). It provides straightness and rigidity but not precision location.

The skins are delivered to Stage 2 as ADR prepared sub-assemblies, (See Section 3.2.6), without any pre-drilled, or machined, assembly features.



Stage 2 Assembly *Fig. 49*

Assembly Sequence:

1) The technician locates the skins with respect to the track ribs and spar, using strap clamps to temporarily fasten and pull down into profile.

2) Manual edge fettling is usually necessary to achieve correctly toleranced gaps between skin sections. (The gaps help to reduce panel buckling caused by wing flexure).

3) The technician uses drill jigs to locate and drill-off the numerous rivet and fastener holes.

4) The skins are removed, the drilled holes deburred, and the fraying faces painted with anti-fretting compound.

5) Cleco pins are used to temporarily relocate and retain the skins prior to permanent fastening with counter-sunk rivets.



Stage 2X Finishing Operations *Fig. 50*

This completes the Stage 2 operations.

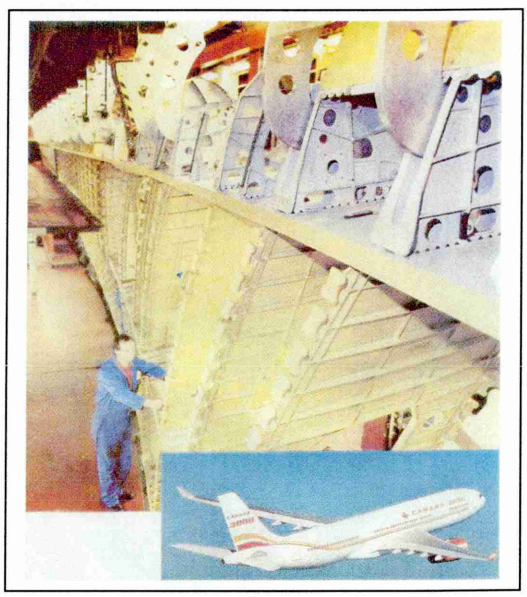
The fixed leading edge sub-assembly is lifted from the Stage 2 build tool and moved across to the Stage 2X station for the finishing operations.

3.3.3 Stage-2X Finishing Operations

At Stage 2X, the leading edge is finished and prepared ready for shipping to the customer.

The operations include final inspection, and minor tasks, such as adhesively bonding packers to correct any steps between the rib-flanges and the lower spar flange, and re-finishing any bare surfaces.

Type specific tooling is not needed and the leading edges are supported on wooden trestles. (*Figure 50).*



Stage 01 Assembly of An Airbus A330 Wing *Fig. 51*

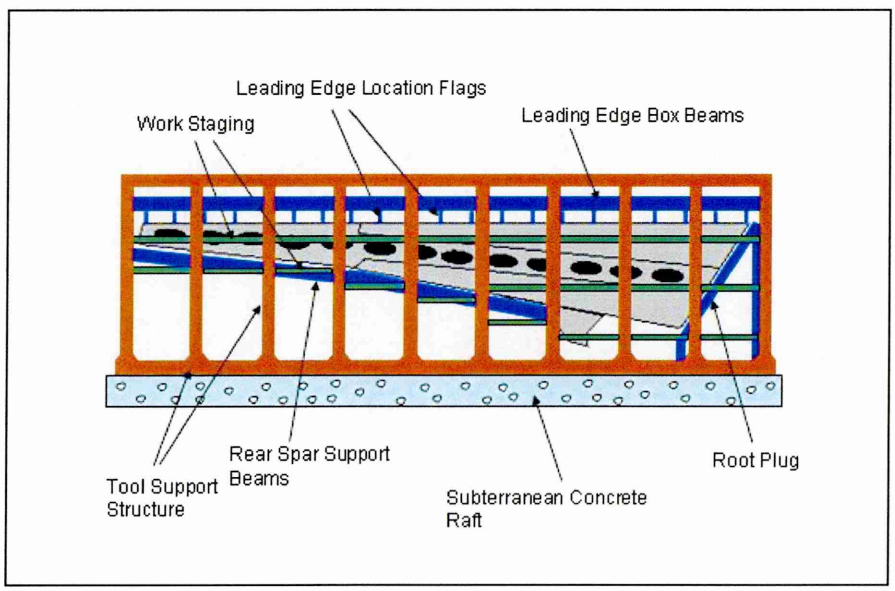
3.3.4 Transportation

The completed sub-assemblies are loaded into protective wooden transport trolleys for road transportation to the main wing-build and assembly site.

The assembly is supported on seven sets of wooden blocks corresponding to every other track rib and at both ends.

3.3.5 Building into the wing

The fixed leading edge sub-assembly is loaded into the A320 01-Wing Assembly tool, with the tool picking-up on the slat track hinge line, (*Figure 51*).



Stage 01 Assembly Tool *Fig. 52*

The leading edge and trailing edge sub-assemblies are first located in the Stage 01 tool and effectively define the shape of the finished wing. The ribs are then located in the tool and their position finely-adjusted to align with the leading and trailing edges.

The wing-build is vertical with the leading edge at the top. This allows simultaneous access and multi-level work staging to both sides of the wing, improving access and reducing the build cycle time. The datum plane for the assembly is established by a dummy wing to fuselage, root plug, joint.

The wing-box components are located to light alloy flags using hardened pins and bushes. The location flags are mounted to light alloy expansion slabs to reduce the effects of differential thermal expansion. The pins provide location in the X and Y axes. Location in the Z axis is by GO-NOGO setting slips and is the main method of wing build quality control and inspection. (*Figure 52*).

The completed wing is removed from the fixture by:
a) Hinging up the staging panels adjacent to the skin,
b) Fitting lifting collars suspended from overhead cranes,
c) Disconnecting the tooling locations and the wing root plug.
The lifting collars also act as turn-over fixtures, so that once the wing is clear of the tooling it can be rotated into the horizontal plane for final completion.

3.3.6 Manufacturing Problems

The assembly cell technicians drew attention to a number of regularly re-occurring problems. These have been broadly categorised into either manufacturing or assembly in origin, although it is also recognised that some of the current problems may originate from dimensional errors in the original drawings.

a) Spar dimensional variability
The technicians reported that the spar flanges varied in depth between spars by up to several millimetres, necessitating the use of hand-screw height adjusters to achieve alignment of the spars with the upper surface of the track-ribs.

Consideration of this problem suggested that the following possible causes should be investigated;

- Variability due to place of manufacture.
- Unreliable and unrepeatable machine tool fixturing.
- Unreliable and unrepeatable assembly tool fixturing.
- Datum shift between machining and assembly (See Section 3.2.1, and 3.3.1 assembly sequence 5).
- Inadequate machine tool accuracy or repeatability.
- Inadequate control of the overall manufacturing process.
- Workpiece warpage caused by residual stresses.

Further investigation suggested that the main cause of the apparent spar dimensional variability results from the datum shift between machining and assembly fixturing.

A slat-track can hole is a poor choice for an assembly datum as it is a clearance fit with the can and is not closely toleranced. Any variation in the hole dimensions will result in a variation of the spar positioning, exasperated over the length by the spar taper.

3.3.7 Assembly Problems

a) Skin Edge Gaps

The 'D' nose skins often require manual edge fettling to achieve a dimensionally acceptable constant width gap between adjacent sections of skin. The gaps are necessary to prevent skin-buckling due to wing-flexure and constancy of width is required by the end users for attractiveness of appearance.

Consideration of this problem suggested that the following possible reasons should be further investigated;

- Repeatability of the stretch forming process.
- The ADR, (Auto-Drill Riveter), sub-assembly process.
- Repeatability of the routing process.
- Loss of datum between machining and assembly (See Sections 3.2.6 and 3.3.2).
- The fixturing for the routing.
- The fixturing/location on the leading edge sub-structure.

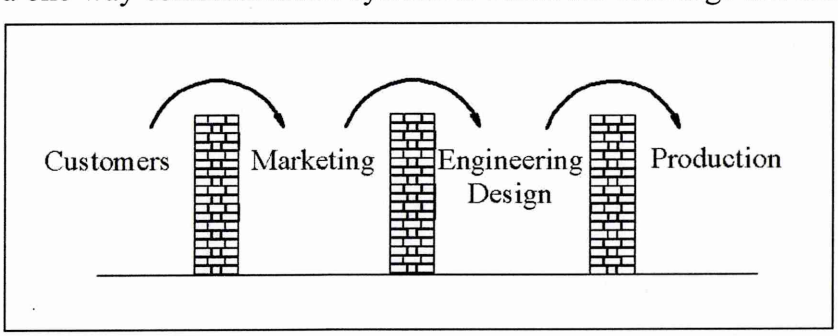
b) The technicians do not trust the Stage 2, strap-on, drill jigs as using them often places the rivet holes too close to the edge of the nose-ribs resulting in consequential scrapping of parts. The preferred alternative is to mark out the hole positions manually using a rule and a soft pencil.

Possible causes could be;

- The tooling is wrong.
- The skins are not sufficiently dimensionally repeatable.
- Parts dimensional-variability.
- Sub-structure dimensional-variability.

3.4 Design Philosophy

The A320 is the product of a traditional, 'Over the Wall', aerospace design process as described by Ullman, (Ref. 34), (*Figure 53*). The 'Over the Wall' design process is effectively a one-way communication system in which the drawings and manufacturing

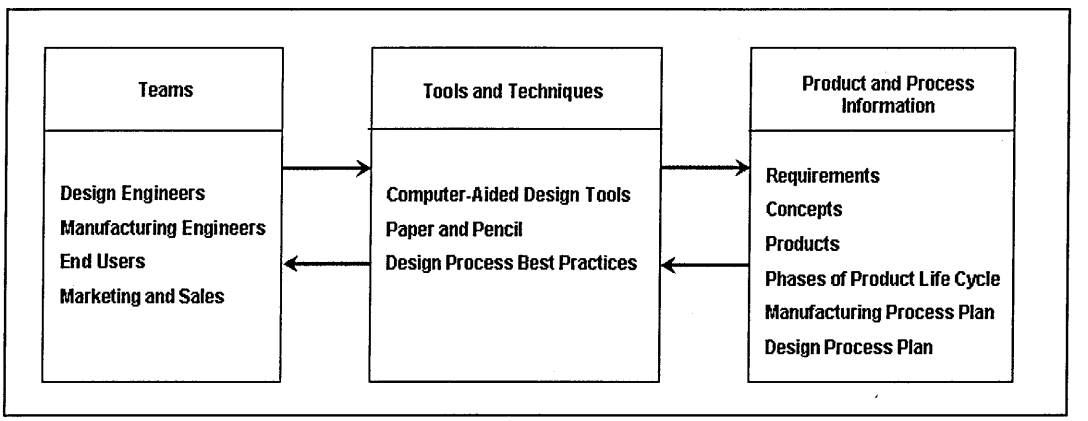


The Over-The-Wall Design Method *Fig. 53*

specifications are, colloquially, thrown over the wall for manufacturing to produce.

The lack of interdisciplinary dialogue can result in designs that are almost impossible to manufacture, and in unrealistic and unachievable tolerancing exacerbated by the aerospace practice of 'blanket tolerancing' parts by category.

The inefficiencies of the 'Over-the-Wall' system are well recognized and the current approach to design utilizes the joint philosophies of 'Integrated Product Development' teams and 'Concurrent Engineering', (*Figure 54*).



The Concurrent Engineering Method *Fig. 54*

The aircraft design reference system creates a point in space that is the aircraft datum point. This is usually within the centre of the fuselage on the fuselage centre line. The wing and the detail parts are designed and dimensioned with reference to the aircraft datum and the wing neutral axis.

Eventually in the manufacturing process, for example CNC machining, these absolute dimensions have to be converted to a local coordinate system centred about a localised datum, resulting in a 'datum shift' and a possible source of error.

3.5 Tooling Philosophy

3.5.1 Static Sites

The manufacture and assembly of Airbus wings up to and including the A330/A340 relied on the use of static site master references. A static site is a full sized, physical representation of those elements of an aircraft structure that must be geometrically and dimensionally controlled. A static site represents a financial investment of several million pounds and must be maintained throughout the product lifecycle. Gauges set from the master reference established the quality of the assembly tooling and hence the build quality of production airframes.

3.5.2 Quality of Manufactured Parts

This build philosophy means that airframe components need not, generally, be subject to extensive dimensional checks. The parts either fit the tooling, or they do not. As a result there has never been a need to collect complete process capability data, and the tooling acts as a 'crutch' for poor quality parts by absorbing some manufacturing variations and inaccuracies.

3.5.3 Fettling and Shimming

Airbus UK takes pride in manufacturing to size and achieving a part-to-part surface contact. In practice, Airbus needs to manufacture parts slightly oversize and to fettle back on assembly.

Boeing has an alternative philosophy manufacturing parts slightly undersize and accepting the need to use sheet plastic shim and liquid shim to fill gaps on assembly.

3.5.4 Use of Laser Trackers

Since 1996 the development and use of laser trackers has allowed the static reference sites to be measured and dismantled. In some instances the measurements were found to be at variance from the original two dimensional design drawings.

3.5.5 Solid Models

All new aircraft are now designed as solid models, and the static sites have been replaced with digital data derived from the solid model.

3.5.6 Over Restraint

Analysis of the tooling used for the assembly of the demonstrator structure revealed that most parts are over restrained, an example being the location of an inter-rib to a tooling arm. Three round pins plus a loading force against the side face, (Figure 36 clearly shows the visibility flags attached to the three pins), are used to locate the inter-rib when two pins with an additional side-loading force are sufficient to achieve full kinematic restraint, further, 'best-practice' requires that one of the pins should be machined with a diamond cross section to aid assembly.

Over-restraint results in different features competing to locate the part with the result that the primary location and therefore the build-quality will vary between structures.

True kinematic location uses the theoretical minimum necessary number of restraints and is not always practicable when applied to large and flexible structures. There is then a need for the tooling designer to adopt a semi-kinematic approach. (See Section 4.3).

3.5.7 Role of Tooling

The research undertaken revealed that in the manufacture and assembly of engineering structure jigs and fixtures have the following roles;

1. Correctly locate parts relative to each other, (*Figure 43*)
2. Clamp parts, (*Figure 30*)
3. Support parts, (*Figure 46*)
4. Hold several elements together in a rigid assembly, (*Figure 51*)
5. Guide cutting tools, (jigs), (*Figure 47*)
6. Fasten and position the unit on a machine tool or main assembly, (fixtures), (*Figure 33*)
7. Absorb part manufacturing variations and inaccuracies, (*Figure 45*)

In a re-engineering exercise of a twenty year old design it should be possible to eliminate some of the hard-tooling by first identifying the role of that tooling and then

either designing that role out through part-integration, or designing it in by integrating assembly and reference features into the parts.

For new designs the adoption of a JAM design approach will help to produce designs having a reduced need for type specific hard tooling.

Parallel with a reduction in the amount of product specific tooling will be reduced opportunities to absorb the manufacturing variations and inaccuracies of poor quality parts. This, then, implies that parts must fit as made and that designers must design using realistic tolerances achievable by the selected manufacturing system, (See Section 4.12). This also implies that all sources of error are identified and, as far as possible, understood and controlled.

4.0 LITERATURE REVIEW 2 - ENABLING TECHNOLOGIES

JAM will not be achieved through the introduction of a single, as yet undiscovered, technology. Instead it will result from the adoption and interaction of a growing number of 'Enabling Technologies'. Many of which are already well established elsewhere and considered, 'robust' by other industries.

The technologies reviewed in this chapter have been identified through interviewing aerospace practitioners and industrial researchers, reading both learned papers and current trade journals, talking to people on the shop floor and discovering their needs.

4.1 Environmental Control

Whilst clamped in the hard-tooling the structural sub-assembly has the inherent quality of that specific tooling. However, when released from the tool it does not always maintain that quality, it may not fit into the main assembly and, additionally it may be severely deformed.

This is in part, caused by lack of environmental control. There are other factors also causing these problems and these are considered later.

Changes, and particularly rapid changes, in ambient temperature are a major problem. Parts can be correctly manufactured at one temperature and out of tolerance when assembled at a different temperature. Differential thermal expansion between a light alloy aerostructure and its steel tooling often results in parts that are correct at the time of manufacture failing to fit the tooling.

A monolithic light alloy spar, (Coefficient of linear thermal expansion $\alpha = 23\times10^{-6}/^{0}C$), measuring 15 metres long at $20^{0}C$ will be 1.7 mm longer at $25^{0}C$, but the mild steel tooling, ($\alpha = 11\times10^{-6}/0^{0}C$), will be only 0.8 mm longer.

Changes in temperature through the working day will cause a part with features of different thickness to twist as the thin sections expand more quickly than the thicker sections.

Different parts having the same coefficient of linear thermal expansion but different masses will react at differing rates to ambient temperature changes.

Tall parts, (See *Figures 51 and 52*), will be affected by temperature gradients created by hot air rising within the assembly sheds. The sun, shining through windows and roof lights, (See *Figures 43 and 55*), creates local hot spots that follow the sun as it traverses across the sky causing a varying twisting of structures.

Problems also arise from the opening and shutting of doors; draughts from open windows and cooling fans.

The subterranean concrete rafts, (See *Figure 52*), supporting the large, ground-anchored, assembly tools will also move, (over long periods of time), with changes in both temperature and moisture content.

The α values for a granite aggregate concrete range from 1.8 to $11.9\times10^{-6/0}C$, which means that a concrete block 15 metre long at 20^0C will have expanded by between 0.135 and 0.8925mm at 25^0C. (Ref. 35).

Carbon/epoxy composites are generally described as having low coefficients of thermal expansion and are therefore less affected by temperature variations. This is true of the carbon, but not the epoxy.

Carbon/epoxy laminate is an anisotropic material with α values dependent on the fibre directions, typically ranging from -0.1 to $1.5\times10^{-6/0}C$ measured in the X and Y axes of a multi-axial laminate. In the Z axis, where there is no through thickness carbon fibres to restrict the expansion of the epoxy, the α value ranges from 36 to $100\times10^{-6/0}C$.

The aerospace industry manufactures parts and assembles structures in vast, cavernous, shed like buildings, (*Figure 55*). It is prohibitively expensive to artificially control the environment in such large buildings. Therefore, the industry seeks to lessen the problems by applying innovative engineering solutions to the manufacture and assembly of their aerostructure. (See Section 3.3.5, paragraph 3).

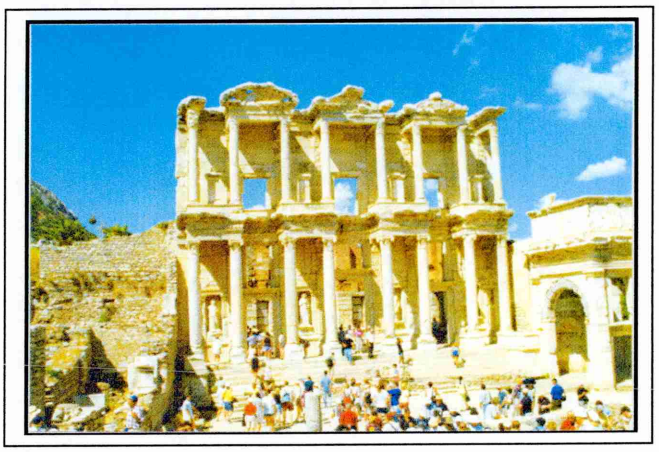


Constructing the A340-500 Stage 01 Assembly tool *Fig. 55*

Building design is outside the control of most manufacturing and production engineers and consequently is acknowledged as a fait accompli. This attitude can no longer be acceptable, and the engineers must demand buildings that are fit for their purpose. As the role of tooling is reduced then the equivalent responsibility for final build quality will move into the sum of the individual parts. Parts must be to drawing and must fit as made. This requires a holistic approach to controlling all sources of geometric and dimensional variance. Imperfectly designed buildings are one of those sources.

4.1.1 Natural Climatic Control

Architects are becoming increasingly competent at designing 'passive buildings'. That is buildings where the form and fabric is used to admit, store and distribute solar energy and other environmental resources. Surprisingly this is not a 'new technology' but an 'old technology' brought up to date with new building materials and thermal design tools using computer simulation, (Environmental modelling). Many examples of passive building design, containing elements of heating, cooling, humidity control, and lighting, are found in the ancient world. An example is the 2000 year old library at Ephesus in modern Turkey. (Ref. 36).



The Ancient Library at Ephesus *Fig. 56*

The library consists of a colonnaded façade with a semi-circular, thick stone cavity back wall with external earth banking. (*Figure 56*). The earth banking and the thickness of the wall moderate the internal temperature and humidity. The air gap and the air circulating through the cavity wall prevent condensation forming on the interior surface. The semi-circular plan-form reduces the surface to volume ratio aiding a stabilised environment and eradicating thermal bridging at the corners which can cause dampness and the growth of moulds. The roof overhang at the front shielded the interior of the building from direct solar radiation.

The result is a passive building having temperature and humidity control, and other features, which protected the valuable papyrus scrolls.

For new buildings, altitude, latitude, and the prevailing climate determine the passive climatic control requirements. Other factors that are considered are the site, the effect of water and landmasses, building orientation, solar angle, arrangement and shape of other buildings, position and sizes of openings, and the selection of building materials.

The average energy consumption of every new passive building monitored by the US Department of Energy up to 1995 was nearly 50% below that of its conventional equivalent. Savings from retrofits to old buildings were even higher, averaging over 60%, although their final performance did not equal that of purpose designed buildings. (Ref. 37).

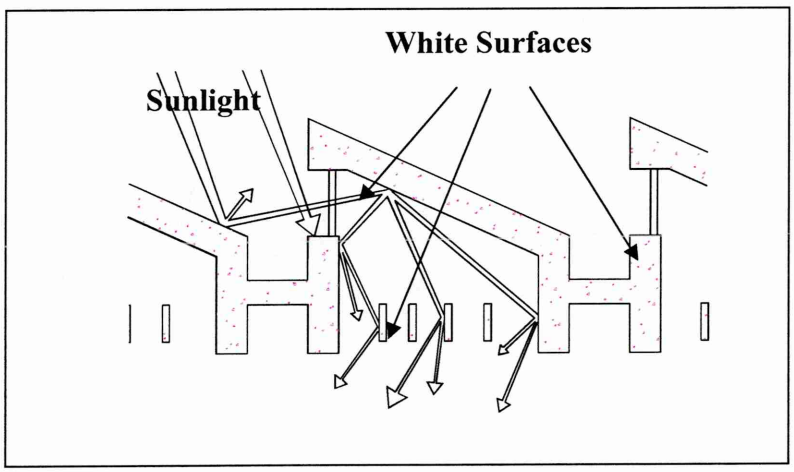
Reducing overall energy requirements is obviously worthwhile, as this in turn enables a reduction in manufacturing costs. However, the main aim is to use the structure of the building to stabilise the manufacturing environment, particularly, fluctuating ambient temperature.

Direct sunlight entering through roof-lights, (See *Figures 43 and 55*), and windows creates local hot-spots on tooling and aerostructure. The hot-spots track with the sun

causing structural warpage. This will vary from structure to structure and will be dependent on the strength of the solar radiation and the stage in the build-cycle that the sun came out.

This was observed as happening on the 01 final assembly stage of the wing. The light alloy expansion flags are only partially effective and instead of allowing smooth movement created sudden shudders as the structure expanded or contracted. (See Section 3.3.5).

This is obviously a problem best solved. A 'quality' justification can be established using Finite Element thermal analysis. This will reveal the effect of localised heating and thermal gradients on fixtures, machine tools, and aerostructure. (See Section 4.5).



Clerestory Roof Light System for Diffusing Sunlight *Fig. 57*

Passive design features to eliminate the effect of direct solar radiation, include clerestory roof light systems for diffusing direct sunlight, (*Figure 57*). These allow an increased use of natural lighting without the excessive heating effects of direct sunlight and artificial lighting. In reality, hybrid systems are needed; incorporating automatically operated artificial lighting and blinds, to maintain a constant light level.

The planting of tall trees around an assembly shed will provide shading from direct solar radiation and reduce the cooling effect of wind on the structure. The overall result is an insulating wall of more stable air, and the creation of a microclimate adjacent to the building.

Insulation on walls, roof, and floor, with special attention being paid to the large hangar doors, will decrease heat losses or gains through conduction. The insulation can be purpose designed to simulate the performance of a thick stone wall, storing heat during the day and dissipating it during the cooler night.

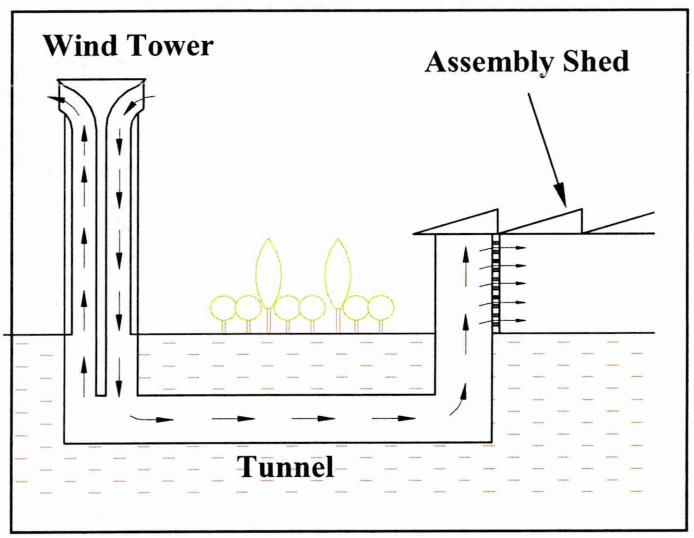
The application of heat mirror films to the inside or outside of an assembly shed will decrease the heat losses or gains through radiation.

The uncontrolled leakage of air from a shed can be reduced by double entry side doors or air locks, and the use of internal roller doors to divide off the assembly area when the large end doors need to be opened.

The shed housing the 01 final assembly tools is fitted with double doors with the space between them used for preparing the finished wings for transit. (See Section 3.3.5).

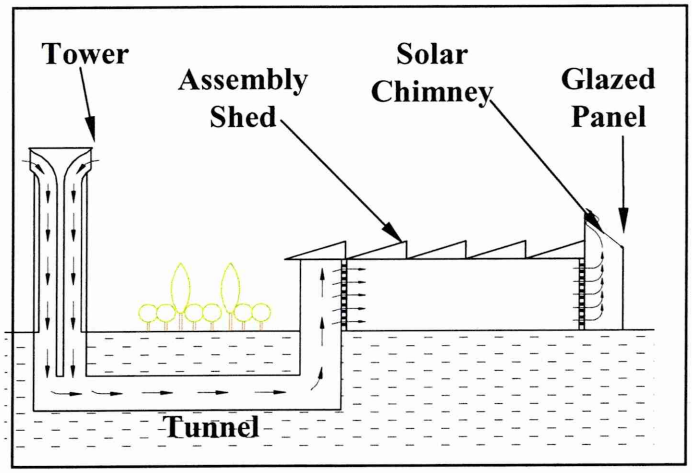
The leading edge assembly cell described in Section 3.2.4 is in direct line with the hangar doors and there is no air-lock. This means that every time parts are shipped in and product is shipped out the stabilised ambient temperature of the shed is lost and the assembly cell is exposed to sudden blasts of hot or cold air.

The construction of a traditional Middle Eastern wind tower, (*Figure 58*), can be used to create a controlled flow of warm or cool air through the shed, providing passive air conditioning and helping to reduce the effect of a heat gradient from the floor to the roof.



Wind Tower *Fig. 58*

The wind tower is provided with vents that can be opened into the face of the prevailing wind. The air flows down the tower and along a deep, cool, stone lined, underground tunnel before entering the building through louvered openings. These systems can be made more effective by passing the air over water or using a sprinkler system in the tower to promote evaporative cooling, (Ref. 38).



Solar Chimney *Fig. 59*

In areas where solar radiation is more reliable than wind, a variation on the wind tower, the solar chimney, is more applicable, (*Figure 59*). The air inside the chimney is heated by solar radiation to draw air through the building. This is the principle behind the glass atrium fronting many modern buildings.

4.2 Solid Modelling

Two-dimensional engineering drawing is a graphical language that conveys the ideas and intentions of the designer to the craftsman in such a manner that the product can be manufactured with accuracy and as rapidly as possible. The process is not a 100% reliable as two-dimensional drawings can often be ambiguous, also it takes skill, which not everyone is able to acquire, to interpret a two-dimensional drawing and then to visualise it as a three-dimensional entity.

The drawing process is also repetitious as each engineering discipline needs its own set of drawings conveying information specific to its requirements. The more repetition, the greater the risk of making and perpetuating mistakes.

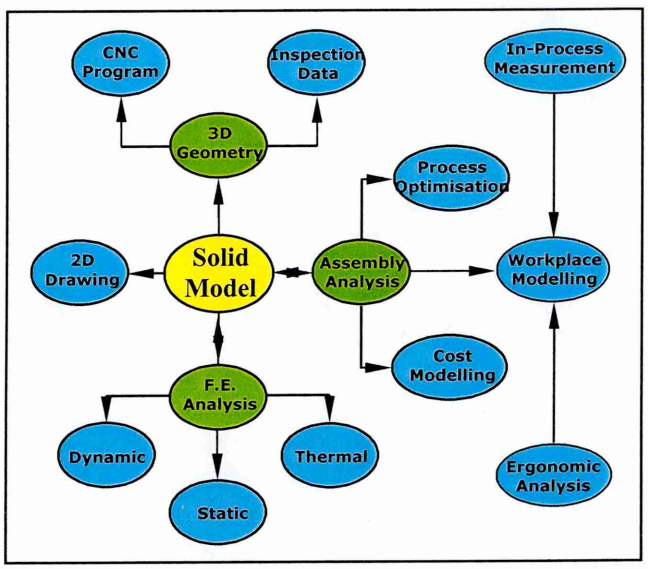
Typical errors resulting from the use of two-dimensional drawings will be significantly reduced as companies change to three-dimensional solid modelling as the solid model provides a common language and a single data base that is shared by the different engineering disciplines.

The current releases of three-dimensional solid modelling packages provide near photographic quality surface display, enabling the designer and the engineer to easily visualise the final product.

Solid modelling is the computer representation and manipulation of three-dimensional shapes. Once created the solid model has virtual volume and for a given material density, it's mass, centroid, and products and moments of inertia can be determined by the software.

Parts can be combined into sub-assemblies and large, complex assemblies with specified associative relationships between parts.

It can quickly and easily provide data for input to other integrated software packages to create a 'Virtual Engineering' environment.



Virtual Manufacturing *Fig. 60*

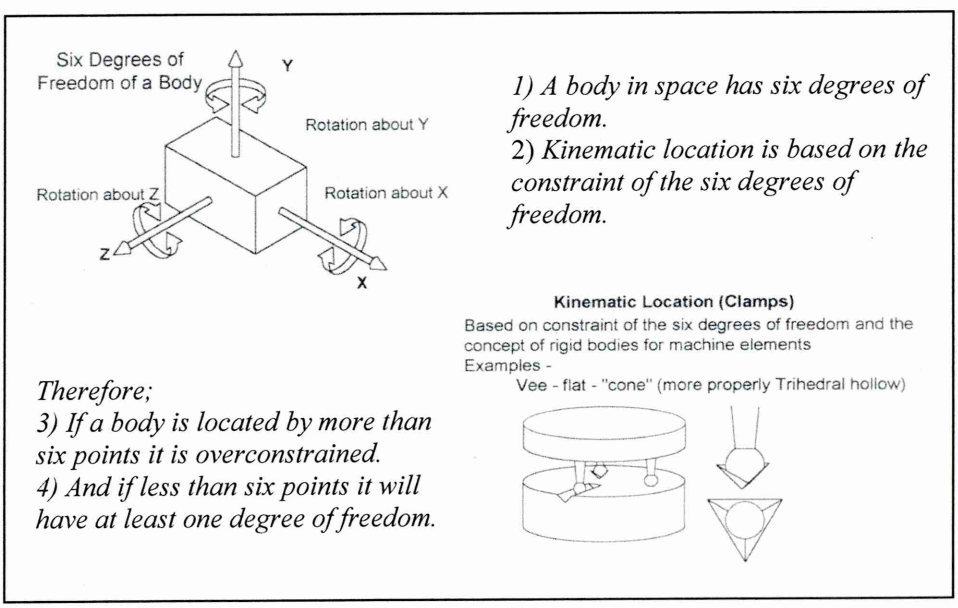
4.2.1 Virtual Engineering

Under this general title is included all those computer assisted engineering tools that aid the production of more efficient designs, (*Figure 60*), and assist in, 'getting it right first time'.

Fully integrated suites of digital manufacturing solutions are already available from software companies such as Delmia, (Ref. 39).

4.2.2 Interference Analysis

Solid models of individual parts can be assembled together to form complex component assemblies. As the software is able to perform interference analysis calculations between parts and sets of parts, (Ref. 40), the risk of the designer incorrectly sizing parts is considerably reduced, and therefore, so is the risk of failure on assembly.



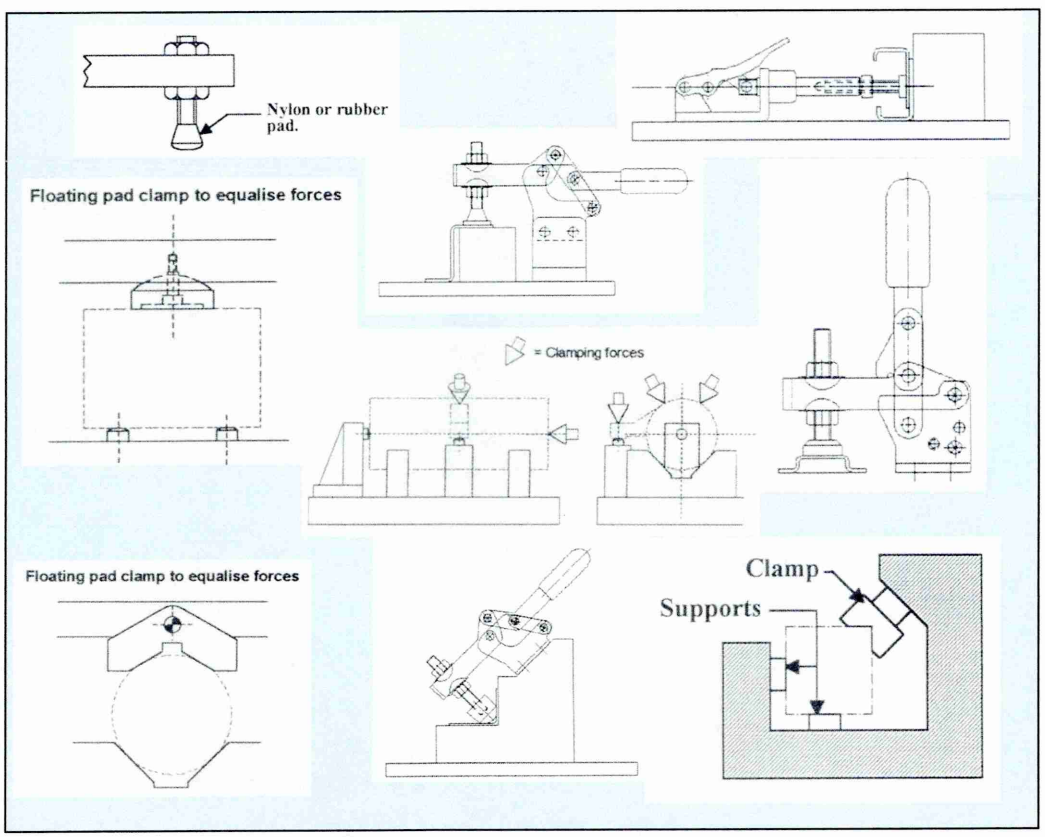
Principles of Kinematic Restraint *Fig. 61*

4.3 Kinematic Analysis and Minimal Restraint

Relationship commands fully position parts in a solid model assembly using combinations of mating, alignment, and connect definitions.

The process of building assemblies from solid modelled parts forces the designer to think in terms of minimal kinematic restraints, (*Figure 61*), and to be aware of the actual process of physical assembly.

Analysis of the existing assembly tooling, (Section 3.5.6), revealed that many parts are over restrained with the result that several different features compete to locate the part. This results in errors of location, and part stressing, which can ultimately result in distorted, poor quality assemblies.



Clamping Systems *Fig. 62*

Minimal necessary restraint is achieved by kinematic analysis, of how best to restrain the six degrees of freedom of each part in space. In practice, due to contact loads and part stiffness, tool designers often need to compromise on the principles of pure kinematics and adopt a semi-kinematic system, (Ref. 41). In discussions it was apparent that some tooling designers had only a sketchy idea of kinematic restraint and there is no mention of it in the, 'Tool Design Handbook', (Ref. 42).

A closing, clamping, force is usually needed to hold the part against the locating features. (*Figure 62*). Ideally, the clamping force should act along a direct line between the clamp and the stop and should be no more than is necessary to put the component into compression. It must not be sufficient to deform the component or the tooling.

Clamps and clamping principles are covered in the, 'Tool Design Handbook', (Ref. 43).

4.4 Assembly Analysis

Solid modelling can be used to create a very realistic solid model of the workplace, which together with kinematic software tools creates a dynamic assembly sequence, enabling the analysis of different assembly strategies, and optimisation of the process, (*Figure 4.9*).



Workplace Model *Fig. 63*

4.4.1 Assembly Access

The movement of component parts and tools into and out of the assembly can be visualised by the generation of swept paths, allowing the engineers to be certain, that access is not restricted by tooling and parts already assembled, (Ref. 44).

With the build quality of the final structure being reliant on the collective sum of the parts it is necessary to include in-process inspection procedures to check that the reference dimensions are within tolerance and that parts are aligned correctly.

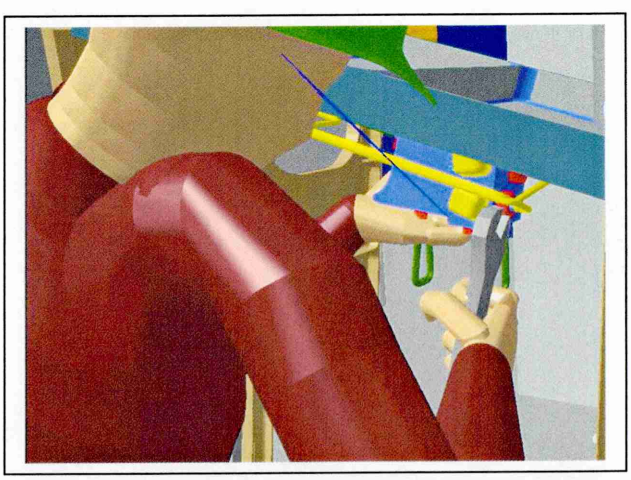
4.4.2 Line of Sight

The alignment and rotation of the solid model on the computer CRT display allows the designers and the inspectors to visually ensure that the line of sight is maintained for in-process assembly checks that may require the use of laser interferometers, laser trackers, sighting telescopes, autocollimators, theodolites, and Photogrammetry, (See Section 4.10).

4.4.3 Ergonomic Analysis

The workplace model enables ergonomic analysis to ensure safe and comfortable, working conditions for the technicians. The expectation is that a safe and comfortable workforce will produce fewer human errors during assembly.

Anthropometrical elements help the planner to layout and evaluate a workstation using human models of different nationalities, gender and anthropomorphic data.



Ergonomic Analysis *Fig. 64*

Ergonomic analysis, (*Figure 64*), allows the designer to

- Determine that parts can be reached
- Provide vision field analysis
- Calculate maximum forces and torques
- Perform NIOSH, (National Institute for Occupational Health and Safety, (Ref. 45), lifting analysis
- Obtain a comprehensive workplace design checklist. (Ref. 46).

4.4.4 Three-Dimensional Simulation

The three-dimensional dynamic workplace model is an important training tool that allows the managers and technicians to become familiar with the processes before they go on-line. This reduces the amount of on-job training and the expectation is that better trained personnel will produce fewer human errors during assembly.

Three dimensional simulations improves communication at all levels in the company and is a useful experimental tool for trying out new ideas and line-tuning without the need or the risk of shutting down production.

4.4.5 Assembly Tolerance Analysis

Manually performed tolerance analysis of a complex structure is very time consuming and too complex. Instead the solid model should be analysed using integrated assembly tolerance tools such as Valisys™ Assembly, (Ref. 47), or VSA®-3D, (Ref. 48). These are able to calculate the build-up of tolerances and to statistically predict which tolerances must be tightened and which may be relaxed without penalty, (Ref. 49).

This has particular importance for JAM where the sum of the integrated part-assembly features delivers the final build-quality of the finished assembly.

4.4.6 Cost Modelling

A cost-model is an invaluable tool for analysing the effect on costs of different designs, manufacturing processes and assembly techniques.

A cost-model is essentially a manually developed spreadsheet. The most time consuming part of the process and the task that presents the modeller with the most difficulty is the collection of meaningful data.

The cost-model is supportable by integrated computer-based simulation models of the machines and processes, with highly realistic engineering representation and visualisation, (*Figure 63*), (Ref. 50), enabling the engineer, cost estimator and manager to communicate their insights and to optimise the final processes, (Ref. 51).

4.5 Finite Element Modelling and Analysis

Finite Element, (FE), analysis enables the 'virtual' testing of a design. The basic principle of analysing a simple framework was first described by Navier in 1862, but it has only really become a practical tool with the development of fast and powerful computers.

The solid model (the continuum) is, interactively with the programmer, sub-divided into an equivalent three-dimensional mesh of discrete elements joined at nodes. For a given applied force, displacement of the nodes can be calculated, and hence the elemental stresses and strains. Any design concept can be checked for a variety of loading conditions, ranging from linear static, to dynamic analyses as well as thermal analysis, (Ref. 52).

The adoption of JAM will significantly reduce the amount of hard-tooling and therefore the support that it provides during the assembly of a structure. FE analysis can simulate the structure's response to any external loading that is identified as a possible source of error, (Ref. 53).

The research discovered two examples, one in Sweden and the other in the UK of large, expensive, and complex sub-assemblies that passed the manufactures final inspection but failed the customers. In both cases, the end customer traced the problem to part distortion resulting from incorrect handling.

It is important to understand and, if necessary, compensate for the effects on the parts and assemblies, of handling, gravity, and in-situ machining forces. FE analysis enables this understanding, and FE thermal analysis enables the determination of the thermal, dimensional stability of a structure.

4.6 CNC Part-Programming

Part-programming is the interpretation and codifying of an engineering drawing into a sequence of instructions that are the high-level controlling medium of a CNC machine tool.

Part-programming can be entirely manual for small simple parts or computer-assisted for larger and more complex parts. The process is onerous and both methods are prone to 'human error', resulting in expensive 'first-off' mistakes.

Solid modelling enables full automation of the part-programming process reducing the lead-time and resulting in a significant increase of part-programs being 'right first time'.

The surface of a solid model provides Cartesian co-ordinate information suitable, after post-processing, for direct input to the control systems of CNC machine tools, programmable work-fixturing, Co-ordinate Measuring Machines, robots, and in-process measurement systems.

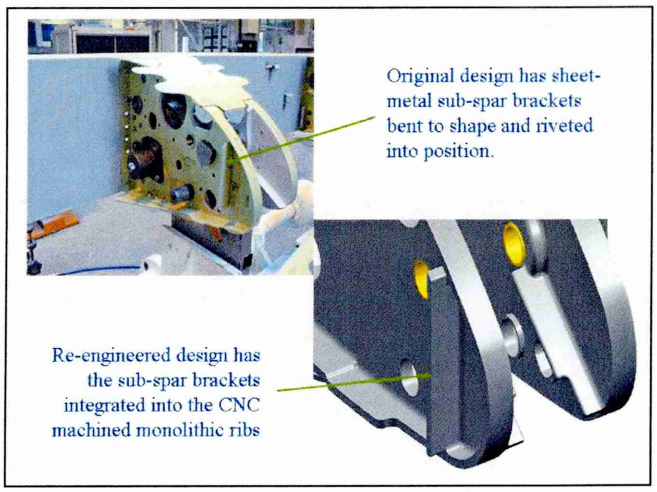
The part-programming software also enables the virtual machining of a component helping to reduce the lead-time and the risk of very expensive errors.

4.7 Parts Manufacture

Part-to-part assembly without the use of an assembly tool requires that parts are manufactured consistently with sufficient accuracy to ensure assembly.

The risk of failure on assembly is eliminated by integrating parts into a single monolithic component.

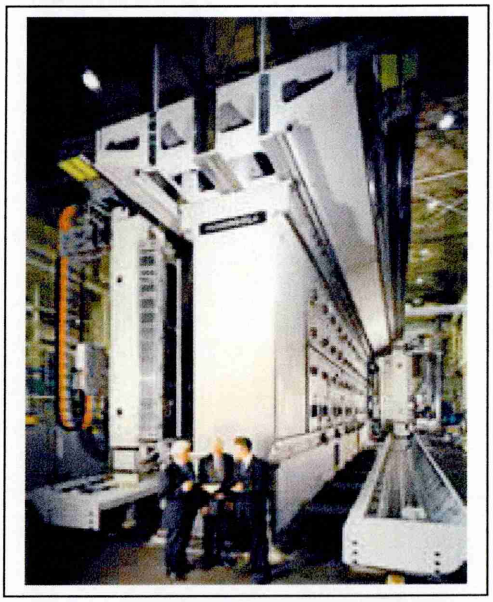
Computer numerically controlled machine tools enable designers to considerably decrease the number of parts, and hence the number of assembly jigs and fixtures, by re-designing many sub-assemblies as monolithic components. (*Figure 65*).



Parts Integration *Fig. 65*

Ideally parts should also be designed for machining in a single setting. This reduces the risk of random quality errors, and reduces, or may even eradicate, the need for work-holding fixtures. It is preferable to use a multi-axis machine if this enables a part to be machined in a single setting. The research revealed that management pressure is often exerted to ensure that work is fed to existing three-axis machines in order to keep them fully utilised. This can be a false economy if it results in a work piece being reset a number of times using a number of different fixtures. Financially this can be clarified with the use of a simple cost-model, but a single setting is always to be preferred for consistency of quality.

CNC machines work hard and need to be regularly maintained and calibrated to ensure that parts are of consistent quality and dimensions. Assembly problems caused by parts of inconsistent quality have occasionally been traced back to poor machine tool maintenance. The complexity of a modern CNC machine probably means that anything other than daily maintenance is outside the skill range of the factory maintenance team, and external specialists should be used. (*Figure 66*).



Ingersoll CNC Spar Mill *Fig. 66*

Conventional slideways, bearings and leadscrews wear unevenly and machine induced manufacturing errors are not always obvious. Machine tool manufacturers are continuously improving their products, and many of the techniques originally developed for very high precision machines can now be specified for more general purpose machines.

Hydrostatic guideways, enable high accuracy motion through low thermal effect, low friction, high stiffness, and an averaging effect over guideway irregularities.

Systematic machine tool errors, (not random - the machine must be repeatable), can be corrected through three dimensional error measurement and software compensation by the control system, (Ref. 54).

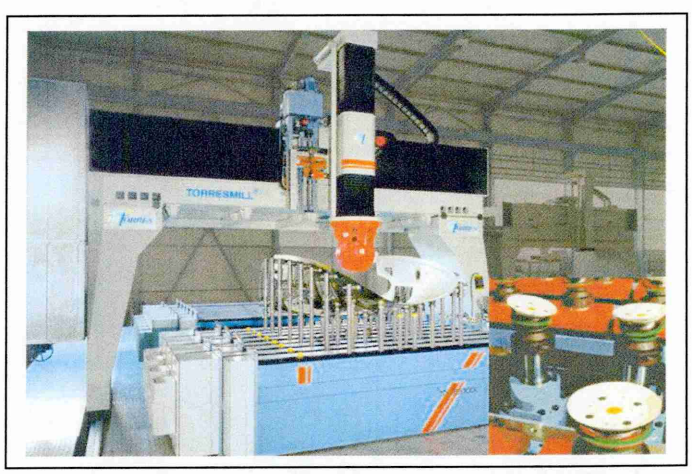
The development of porous ceramic water hydrostatic bearings for high speed spindles, now in excess of 15,000 rpm, enable rapid stock removal, with reduced tool wear, and lower spindle temperatures, (Ref. 55). The result is reduced local heating of the work piece and hence, less induced stress and, therefore less distortion when the work piece is released from the work holding device.

Enclosures are common on small and medium sized machines to contain the swarf and coolant and to protect the operator. They can, and should, also be fitted to the larger machines such as spar mills, (See Section 3.2.1). With thoughtful design, access to the machine will not be too restrictive. Temperature controlled air blown over the table and the use of temperature controlled coolant will provide a good degree of environmental stability. The enclosures should be large enough to store a number of queued components so that each work piece has sufficient thermal soak out time before being fixtured and machined.

4.8 Re-Configurable Tooling

The standard machine tool vice in its multifarious guises is probably the most versatile re-configurable work-holding device ever conceived.

However a vice is not suitable for holding complex, contoured monolithic components or flexible parts such as pre-formed sheet metal skins. Traditionally, pre-formed sheet metal parts are either pulled by vacuum onto a form tool and then routed to final profile, or like the nose skins, (See Section 3.2.6), pulled back into the flat before the final trim. An alternative reconfigurable tooling system, with the potential for full automation, has been developed by a number of different companies.



Re-Configurable Tooling *Fig. 67*

Typical is the TORRESTOOL®
manufactured by the Spanish Company of 'M. Torres'. The system consists of a matrix of adjustable, automated, pneumatic actuators with vacuum end-effectors. (Ref. 56). (*Figure 67 - The small inset picture is a close-up of the vacuum end effectors*). The control electronics are integrated with the machine tool CNC controller allowing programmable adjustment of the individual actuators. Any slight misalignment of the work piece can be automatically compensated with a three-dimensional shift of the CNC co-ordinate system.

A similar system is manufactured by CNA in the United States. Their largest installation is a three-cell unit at Northrop Grumman in Hawthorne, California. The cell measuring 3 metres by 30 metres, contains 900 programmable actuators and is used for the drilling and routing of 747 fuselage skins. CNA claim that this installation has replaced more than 100 traditional vacuum chucks each measuring 3 metres by six metres. (Ref. 57).

Flexible systems can obviously cope more easily with engineering design changes, (See Section 1.3, paragraph 1), and allow a mix of parts to be manufactured without the need to clean down and reset the machine. Unlike dedicated hard tooling the individual actuators can be programmed to retract out of the way, for example, of a riveting head, and to reattach once it has passed.

The use of flexible tooling systems will;

- More easily allow product mid-life design changes
- Considerably reduce setup times
- Eliminate dedicated tooling, associated storage and floor space requirement
- Reduce the number of tools needed
- Eliminate the need for an operator to add and subtract clamps during machining
- Reduce machining times
- Reduce material inventories
- Be scalable, flexible and universal for current and future requirements

4.9 Advanced Joining Technologies

There are a number of advanced joining technologies that are identified as 'Enabling Technologies'.

4.9.1 Friction Stir Welding

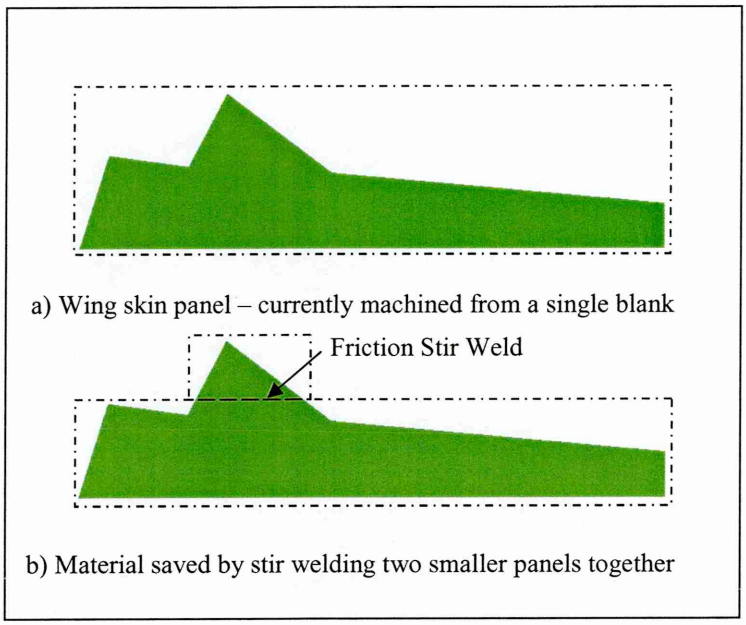
Friction Stir Welding is a relatively new process invented and patented by The Welding Institute in 1991, (Ref. 58).

In friction stir welding (FSW) a cylindrical, shouldered tool with a profiled probe is spun at high speed and slowly plunged into the joint line between the two abutting parts, (*Figure 68*). The parts must be firmly clamped onto a backing bar to prevent the joint faces from being forced apart during the process. Frictional heat is generated between the wear resistant welding tool and the material of the work pieces. This heat causes the latter to soften without reaching the melting point and allows traversing of the tool along the weld line. The plasticised material is transferred from the leading edge



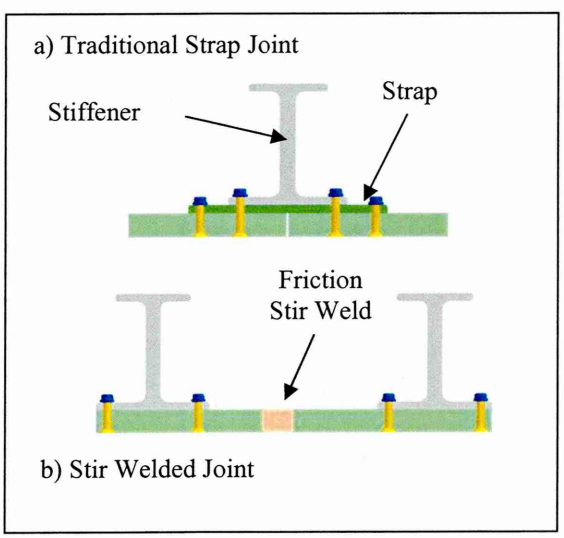
Friction Stir Welding *Fig. 68*

of the tool to the trailing edge of the tool probe and is forged by the intimate contact of the tool shoulder and the pin profile.



Improved Material Utilisation *Fig. 69*

The process produces a solid phase bond, (no melting). There is no heat affected zone and the weld is left in a fine-grained, hot worked condition with no entrapped oxides or gas porosity. Since traditional heating methods are not employed, the properties of the metal in the joined area are higher than those from any other known welding process and distortion is virtually eliminated.



The Reduced Complexity of a Stir Welded Joint *Fig. 70*

If this process proves to be acceptable for flying structure then considerable savings are available through improved utilization of material, (*Figure 69*), and simplified design of joints, (*Figure 70*).

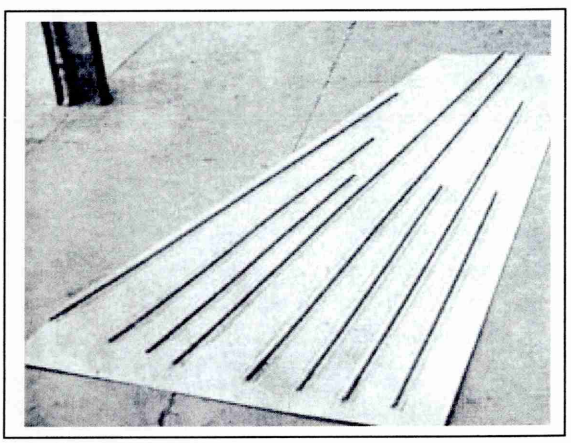
Friction stir welding is a weight saving and more cost-effective alternative to riveting or bolting.

FSW results in a reduction of;

- Recurring costs
- Material waste
- Assembly time
- Structural weight
- Number of parts
- Number of tools
- Associated storage and floor space requirement

4.9.2 Structural Adhesive Bonding

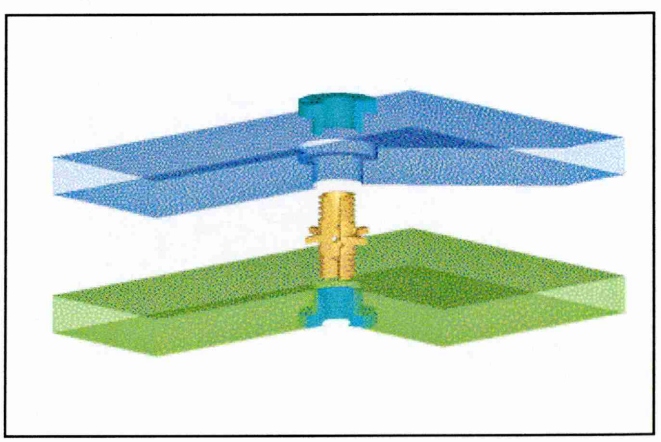
Metal to metal adhesive-bonding of aircraft structures developed during the late 1940's, (Ref. 59), with the need to produce aerodynamically clean external surfaces unmarred by rivet heads or spot-weld marks, *(Figure 71).*



A 1946 wing-skin test panel with Redux bonded stringers *Fig. 71*

Structural adhesive bonding has been used extensively, and very successfully, in the past, including on the Airbus A300 and A310 aircraft, but there have been cases of disbonding attributed to corrosion at the joint line after only a few years service, (Ref. 60). As a result, manufacturers have lost confidence in the process and structural adhesive bonding has never fulfilled its promised potential. Additionally, there is no effective method for non-destructively evaluating, (NDE), a bonded joint.

This places a very high reliance on the process control with the licensing authorities often asking for a hybrid joint that includes the addition of, theoretically redundant, fasteners, known colloquially as 'Chicken fasteners'.



AdhFAST® hybrid joint technology *Fig. 72*

AdhFAST® is a recent development in hybrid joint technology which allows adhesive to be injected through the middle of the fastener device whilst retaining the joint and controlling the bondline thickness. (*Figure 72*), (Ref. 61).

The use of AdhFAST® hybrid joint technology will;

- Reduce the quantity of jigs needed for fastener-hole drilling.
- Eliminate the tooling currently needed to locate and clamp the parts, and to control the bondline thickness.

4.10 Gaugeless Tooling

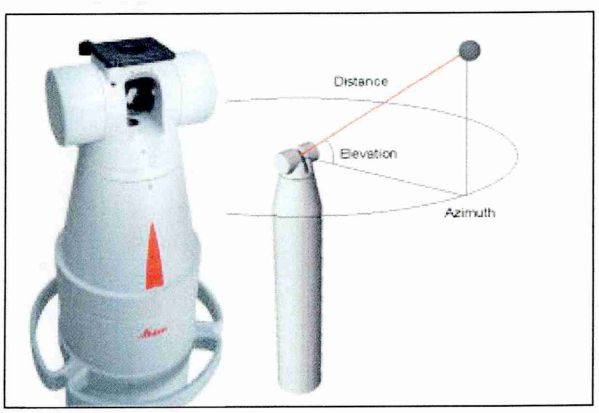
Gaugeless tooling is defined as the creation of jigs, fixtures and form tools directly from the CAD solid model without the use of master, 'hard tooling', gauges.

Manually operated optical measurement systems such as laser trackers are now being used to control the building of tools and assemblies using dimensional data derived from the CAD solid model, and presented on-line to the build technicians. (Ref. 62).

4.10.1 Laser Trackers

Laser trackers, *(Figure 73),* combine a laser interferometer for distance measurement with optical encoders to measure azimuth and elevation of a beam steering mirror. (Ref. 63).

By combining the laser interferometer with a beam steering mirror it is possible to track a moving target at a rate of about 5 m/s. Measurements are potentially to within microns over tens of metres, but changes in air temperature, air pressure and humidity will affect accuracy.



Laser tracker system *Fig. 73*

In practice the technicians walk around the cell, taking care not to break the beam, and place the retro-reflector anywhere a measurement is required.

For previous aircraft types Airbus UK has built static site master reference tooling, (See Section 3.5). The static sites are full sized hard tooling representing the major component geometry of the wing. All major tools were then correlated to the master tool to ensure a common standard.

For the A340-500/600 Airbus UK used CADDS5 solid modelling, (Ref. 64), and Leica laser tracker systems, (Ref. 65), to construct the assembly tooling, including the Stage-01 wing final assembly fixtures. (Ref. 66). These enormous fixtures are 43 metre long, 10.3 metre high and 8.3 metre wide. *(Figure 55).*

The Airbus/BAE Systems AWBA I and II, (Automated Wing Box Assembly), technology demonstrators showed that both manually operated and computer controlled laser trackers can be used effectively during assembly for the precision positioning of

components and automated equipment, including robotic handling and holding tools, and robotic drilling heads. (*Figure 74*), (Ref. 67).

The use of laser trackers and other, cheaper, more traditional metrology equipment, such as sighting telescopes, autocollimators, and theodolites, are able to;

- Ensure the correct location and alignment of parts
- Ensure the correct location and alignment of robot end-effectors



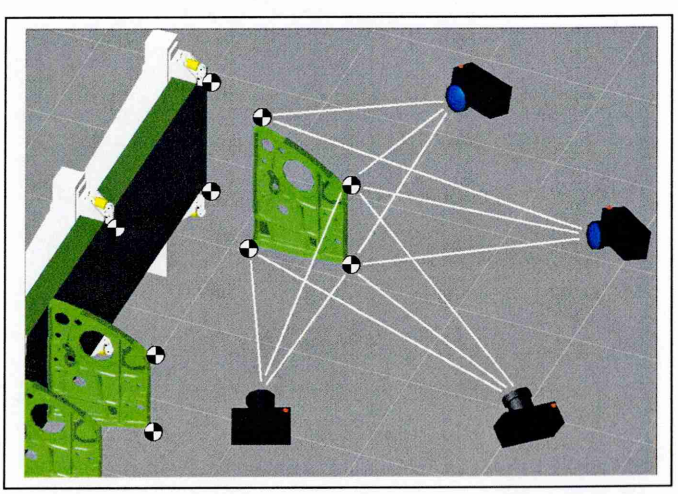
AWBA II Simulation of Automated A380 Wing-Rib Positioning *Fig. 74*

Laser trackers can be integrated into a computer controlled system as part of a fully automated process

4.10.2 Digital Photogrammetry

Photogrammetry is a three-dimensional, non-contact, measuring tool. Using one or more cameras and analytical software the process is capable of the simultaneous measurement of all points in the field of view and comparing them to the CAD solid model. *(Figure 75).*

Despite the difficulties, industrial photogrammetry is being increasingly used for the three-dimensional measurement of large structures such as aircraft and ships, (Ref. 68). The USA aircraft manufacturing industry probably has the widest use of industrial photogrammetry, with systems being used for as-built measurement of assemblies and fixtures, and tooling re-calibration.

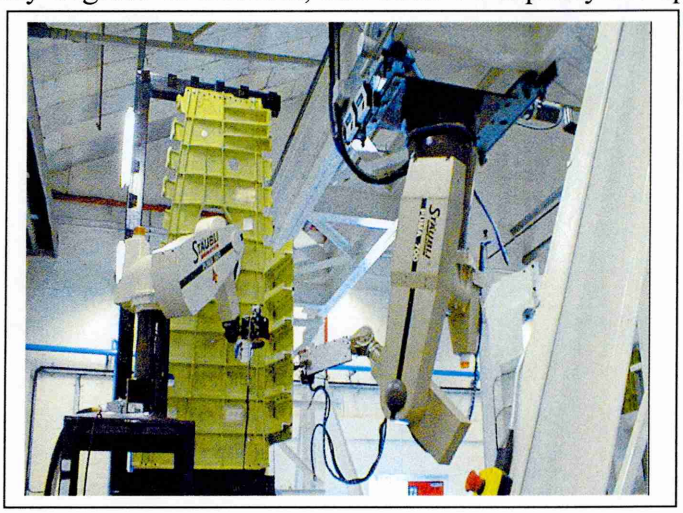


Digital Photogrammetry for On-Line Control and Component Positioning *Fig. 75*

Snapshots in time allow evaluation of the effects of a changing loading environment. So the effects of gravity, mechanical loading, thermal changes, and structural stress relieving can be measured using industrial photogrammetry, (Refs. 69, 70).

A photogrammetry system has many degrees of freedom, and must be expertly set-up and initialised before being used. The experiences of colleagues at Nottingham University, (Table 1.2), indicated that digital photogrammetry is not very, 'User friendly'. To be effective, it also requires large numbers of targets covering the parts being positioned.

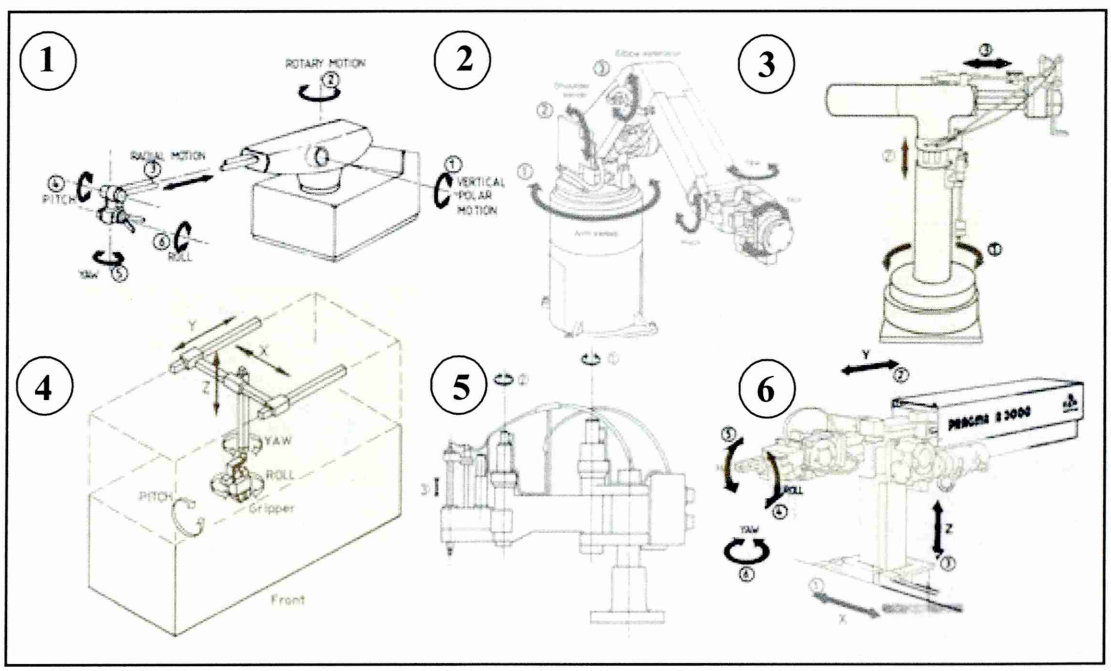
Nevertheless, the technology has huge potential and must not be ignored. It is under continual development and is expected to become easier to use.



AWBA I Technology Demonstrator *Fig. 76*

4.11 Industrial Robots

The industrial robot has come of age and already proved its worth in many different engineering environments. During the aerospace site visits, (Appendix C), it became apparent that the European aerospace industry does not yet use large number of robots, although a few were seen in production, being used for fettling, positioning parts, and drilling holes.

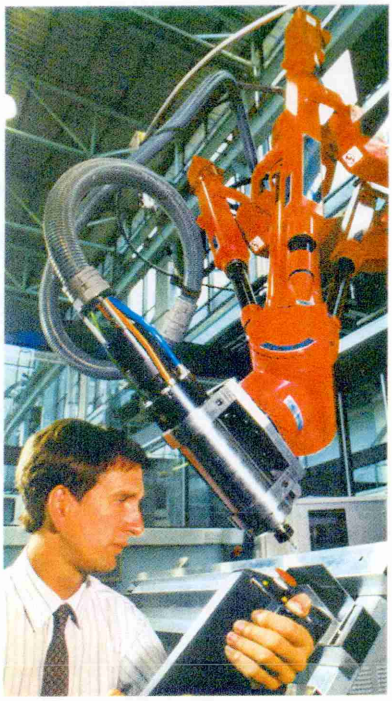


Standard Robot Classification *Fig. 77*

The AWBA I and II technology demonstrators proved that industrial robots, when integrated with external non-contact metrology equipment, can achieve the required

accuracy whilst retaining their inherent versatility, (*Figure 76*). This is particularly relevant to the main components of the Airbus A380 wing. These are too large and heavy for manual handling and an automated or semi-automated approach is necessary. (*Figure 74*).
Robots are commonly classified based on structural configuration and type of motion, (Ref. 71), (*Figure 77*):

1. Polar (spherical) robot – (5 Revolute joints + 1 Linear joint)
2. Revolute (jointed arm) robot – (6 Revolute joints)
3. Cylindrical robot – (1 Revolute joint + 2 Rotary joints)
4. Cartesian (rectangular) robot, gantry type – (3 Revolute joints plus 3 Linear joints)
5. SCARA-type robot (Selective Compliance Assembly Robot). – (2 Revolute joints plus 1 Linear joint)
6. Cartesian (rectangular) robot, sliding type – (2 Revolute joints plus 3 Linear joints).



Robot or M/T? *Fig. 78*

The anthropomorphic arrangement of the revolute, jointed arm robot, ((2) in *Figure 77*), makes it the most useful configuration for aerostructure assembly tasks, especially when combined with an XYZ Cartesian gantry system. Unfortunately, jointed arm robots are not structurally stiff and do not make good machine tools. These robots have degrees of freedom, not axes; therefore, the system stiffness and the load carrying capacity vary with the configuration of the joints. In general, they also have poor accuracy, although the repeatability is often acceptable.

The differences in performance between robots and machine tools tend to diminish when the robot system is based on the kinematic design of the Stewart Platform, (*Figure 78*), (Ref. 72). This design results in systems that are stiff and accurate, but with a reduced work envelope and a loss of versatility.

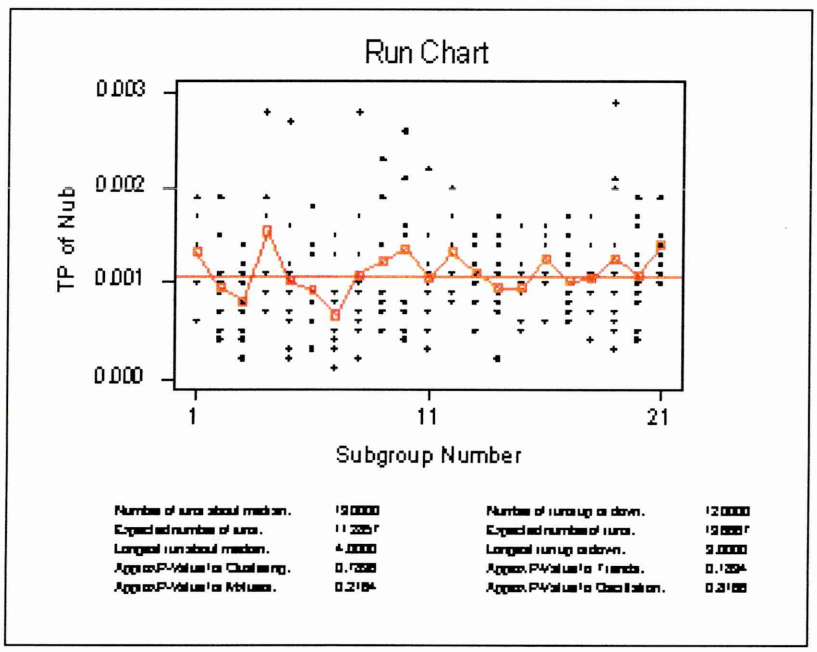
Robots are programmable off-line using data derived from the solid model, (See Section 4.6). The inclusion of photogrammetry or laser non-contact measurement in the feedback loop, (Section 4.10), ensures the correct relationship between the robot and the workpiece. Any misalignment is automatically corrected through a real-time, three-dimensional, shift of the robot co-ordinate system.

Multi-axes micro-adjustment between the tool flange and the end-effectors is necessary when stiction or lost motion prevents the robot mechanism from responding to demands for small amounts of movement. (Ref. 73).

Industrial robotics has a powerful role in achieving JAM and is able to;

- Fettle parts.
- Apply anti-fretting compound and adhesive.
- Hold parts.
- Position parts.
- Drill holes.
- Deburr holes.
- Insert fasteners.
- Set fasteners.

4.12 Statistical Process Control (SPC) Statistical process control (SPC) monitors the consistency of processes to ensure that a product is manufactured as designed. The purpose is to capture and keep processes under control. (Ref. 74). (*Figure 79*).



SPC Data Collecting *Fig. 79*

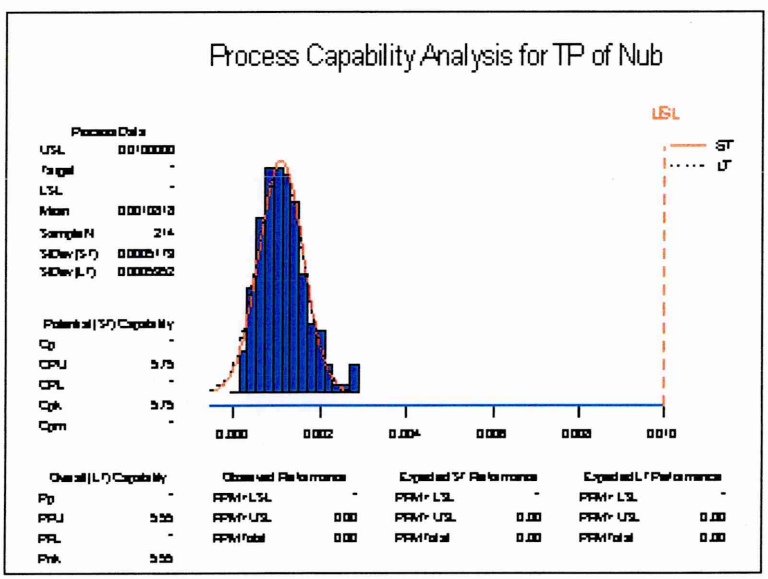
The primary SPC tool is the control chart, which is a graphical representation of specific descriptive statistics for quantitative measurements of the manufacturing process.

These descriptive statistics are displayed in the control chart in comparison to their 'in-control' sampling distributions. The comparison detects any unusual variation in the manufacturing process, which could indicate a problem with the process. Several different descriptive statistics can be used in control charts and there are several different types of control charts that can test for different causes, such as how quickly major vs. minor shifts in process means are detected. Control charts are also used with product measurements to analyse process capability, (*Figure 80*), and for continuous process improvement efforts.

(Figures 79 and 80 are typical charts and analyses used to monitor and improve manufacturing process consistency and capability, reproduced courtesy of 'The Centre for System Reliability', (CSR), Sandia National Laboratories, Albuquerque, NM, USA).

Benefits of SPC;

- Provides surveillance and feedback for keeping processes in control
- Signals when a problem with the process has occurred
- Detects assignable causes of variation
- Accomplishes process characterisation
- Reduces need for inspection
- Monitors process quality
- Provides mechanism to make process changes and track effects of those changes
- Once a process is stable (assignable causes of variation have been eliminated), provides process capability analysis with comparison to the product tolerance



Process Capability Analysis *Fig. 80*

4.12.1 Process Potential Index (*Cp*)

The process potential index, (*Cp*), measures a process's potential capability, which is determined as the allowable spread over the actual spread.

Where;

USL = *Upper specification Limit*
LSL = *Lower Specification Limit*
σ = *Standard deviation of the process*

Then the;

$$\text{Process Potential Index } (Cp) = \frac{(USL - LSL)}{6\sigma}$$

By convention, when a process has a *Cp* value less than 1.0 it is considered potentially incapable of meeting the specification. Conversely when a process *Cp* is greater than, or equal, to 1.0 it has the potential of being capable. (Ref. 75). However, a high *Cp* value

does not guarantee that a process is within the specification limits only that it has the potential to be within the defined limits.

4.12.2 Process Capability Index (*Cpk*)

The Process Capability Index, or *Cpk*, measures a process's ability to create product within the specification limits.

Where;

USL = *Upper specification Limit*
LSL = *Lower Specification Limit*
σ = *Standard deviation of the process*
$\overline{X}$ = *Process Mean*

Then the;

$$\text{Process Capability Index } (Cpk) = \frac{\text{distance mean to nearest spec. limit}}{\text{half process variation}}$$

therefore;

$$Cpk = \frac{\text{minimum}[(USL - \overline{X}), (\overline{X} - LSL)]}{3\sigma}$$

By convention, when a process has a *Cpk* value less than 1.0 it is referred to as incapable. When the *Cpk* is greater than, or equal, to 1.0 the process is considered capable of producing a product within the specification limits.

4.12.3 Six Sigma Capability

In a process qualified as a Six Sigma process, (i.e. one that allows plus or minus six standard deviations within the specifications limits), the *Cp* is greater than or equal to 2.0 and the *Cpk* equals 2.0.

However, it must be realised that many processes are prone to being influenced by known causes that will affect the overall performance of the process relative to the required specification. For example, a machine tool setter will always set a machine to either the maximum or minimum metal condition in the knowledge, that as the cutting tools wear, the distribution mean will move towards the opposite metal condition but the product will still be within tolerance.

Inherent in the statement that a process is '6 Sigma', is the knowledge that the short term capability of the process is 6 but the long term capability is 4.5, (3.4 Defects Per Million Opportunities - DPMO), assuming a shift of 1.5 Sigma.

4.12.4 Process Capability Database

A Process Capability database is essential to assist in realistic tolerance allocation, assembly feature selection, (See Section 3.5.7), and realistic analysis of Featurised Datum Flow chains, (See Sections 5.8 and 5.11).

- A Six Sigma process capability database will allow the Integrated Product Teams, (See Section 3.4), to select realistic part and assembly tolerances and to match manufacturing processes to the design tolerances.

- If the process capability database includes the uncertainties of measurement of laser trackers and other metrology equipment, (See Section 4.10), then those uncertainties can be included in the analysis of the Featurised Datum Flow Chains. (See Section 5.11).

4.13 Analysis

The industrial research programme, (Chapter 3), together with the interviews, (Appendix B), revealed that in addition to the supposed role of hard tooling it also absorbs part manufacturing variations and inaccuracies, (Section 3.5.7). Additionally the mass of the steel tooling reacts more slowly to changes in ambient temperature than the thinner light alloy aerospace parts, providing a comparatively stable base on which to assemble the aerospace structure, (Section 4.1).

For a JAM assembly solution, many of the roles of the tooling must be built into the structure itself and into the assembly process and that where hard tooling is necessary, this should ideally be flexible and not dedicated tooling. The comparative stability of the tooling also disappears and therefore it is argued that JAM must take an holistic approach and start by making the assembly sheds 'fit for purpose, (Section 4.1.1).

The seven roles of hard tooling have been identified, (Section 3.5.7), and possible alternative solutions have been researched and identified as JAM enabling technologies, (Chapters 4 and 5). These are given below:

Role 1 - Correctly, locate parts relative to each other.
JAM solutions – Integrated tooling features, (Section 5.8).
Gaugeless tooling, (Section 4.10).
Integrated monolithic parts, (Section 4.7).
CNC pre-drilled King holes, (Section 4.7).
Use hard tooling - only if necessary.

Role 2 - Clamp parts
JAM solutions – Integrated tooling features providing kinematic restraint, (Section 5.8).
Robotic clamping, (Section 4.11).
Use hard tooling - only if necessary.

Role 3 - Support parts.
JAM solutions - Re-Configurable tooling, (Section 4.8).
Integrated tooling features, (Section 5.8).
Robotic manipulators, (Section 4.11).
Use hard tooling - only if necessary.

Role 4 - Hold several elements together in a rigid assembly.
JAM solutions - Integrated tooling features, (Section 5.8).
Integrated monolithic parts, (Section 4.7).
Friction stir welding, (Section 4.9.1).
Adhesive bonding, Section 4.9.2).
Robotic clamping, (Section 4.11).
Use hard tooling - only if necessary.

Role 5 - Guide cutting tools

JAM solutions	-	CNC pre-drilled pilot holes, (Section 4.7).
		Robotic drilling machines, (Section 4.11).
		Gaugeless tooling, (Section 4.10).
		Use hard tooling - only if necessary.

Role 6 - Fasten and position the unit on a machine tool or main assembly

JAM solutions	-	Re-Configurable tooling, (Section 4.8).
		Robotic clamping, (Section 4.11).
		Gaugeless tooling, (Section 4.10).
		Use hard tooling - only if necessary.

Role 7 - Absorb part manufacturing variations and inaccuracies

JAM solutions	-	Natural climatic control
		Establish Six Sigma process capability
		Six Sigma process capability data base
		Realistic tolerancing not blanket tolerancing
		Integrated monolithic parts, (Section 4.7).
		Virtual Engineering and assembly analysis, (Section 4.2).
		Error budgeting and tolerance analysis, (Section 5.12).
		Gaugeless tooling, (Section 4.10).
		Test the design, (Sections 4.4 and 4.5).
		Use hard tooling - only if necessary.

The technologies identified are probably not a definitive list and it can be expected that new enabling technologies will continue to emerge to meet the needs of the aerospace industry. The database must, therefore, be kept live and designers and engineers must add new enabling technologies as soon as they are considered mature.

5.0 LITERATURE REVIEW 3 - DESIGN METHODOLOGIES

The main objective of the JAM research is to reduce the reliance on type specific hard tooling, through the development of design methodologies and the application of enabling technologies. (Section 1.5). The enabling technologies have already been identified in Chapter 4, and their application will reduce the need for type specific hard tooling, but unless they are applied in a logical and systematic manner as part of a total design package they will create no more than islands of JAM and the full potential of JAM will not be achieved.

There is then a need for a total design package to assist and guide in the creation of a JAM assembly.

This chapter researches the design tools for a JAM Methodology based on the knowledge gained form the industrial research, (Chapter 3), the literature reviews, (Chapters 2 and 4), and the practitioner interviews, (Appendix B). Where possible the design tools chosen are compatible with current practice within the aerospace industry.

The Chapter concludes with a listing of 'Guidelines for a JAM Solution'.

5.1 Types of Assembly Processes

Whitney, (Ref. 138), identifies two types of assembly processes. Type 1 assemblies comprise of parts, typically moulded or machined, that have their mating features fully defined by their manufacturing processes. The procedure is a passive part-to-part, kinematically constrained, assembly process and does not influence the distribution of variance in the final assembly. This approach is only feasible when the parts can be manufactured to sufficient accuracy such that the sum of their inaccuracies is within the tolerance specification for the completed assembly.

Type 2 assemblies are typical of automotive and aircraft assemblies where the parts have slip joints and the sum of the parts does not fully define the final assembly. These types of parts are commonly assembled with the use of hard tooling and the required quality of the finished assembly is embedded in the tooling. Parts are adjusted to fit the tooling.

This approach is necessary when the parts are very flexible, or when it is uneconomical or impossible to manufacture them with sufficient accuracy for Type 1 assembly.

5.1.1 A JAM Assembly

Ideally, JAM will move aerospace structure from Type 2 to Type 1 assemblies. Whereas this would previously have been impossible because of the nature of the parts and their method of manufacture, (Section 1.2), the wing of an Airbus, for example, consists mainly of a few large CNC machined monolithic components, (Fig. 51). A purpose built CNC machine should have sufficient accuracy to enable Type 1 part-to-part assembly, (Section 4.7), although in reality an aerospace JAM solution will probably be a hybrid of Types 1 and 2, with part-to-part assembly where possible and hard tooling where necessary.

This implies that a JAM design methodology must be able to determine when Type 1 assembly is feasible and when Type 2 is necessary. Therefore, the methodology must include dimensional analysis based on real process capability data.

5.2 Established DFA Methodologies

'Design for Assembly', (DFA), methodologies are of two types, (Ref. 139).

1. Quantitative – that assign time periods, costs and numerical codes to part characteristics and assembly operations to calculate a 'Design Efficiency Ratio'.
2. Qualitative – that present the designer with rules and guidelines illustrated through set examples.

Quantitative methodologies are most prevalent in industry with the three most commonly described being;

1. The Hitachi Assemblability Evaluation Method.
2. The Boothroyd & Dewhurst Method.
3. The Lucas DFA Procedure.

A detailed evaluation and comparison of these methods can be found in (Ref. 140).

5.2.1. The Hitachi Assemblability Evaluation Method

This is a proprietary method and versions can be purchased from Hitachi. The methodology is based on the principle of 'one motion for one part' and starts with determining an assembly sequence and defining the motions necessary to locate and fasten each part. Penalty points are then assigned for every motion other than a simple downward insertion. That incurs no points. The penalty scores are then manipulated to give an assembly score for each part. These are then combined with the total number of parts to give the value of assemblability evaluation score (E). The value of estimated assembly cost ratio (K) depends on the calculated value of (E) and an historical knowledge of actual costs.

The Hitachi AEM makes no distinction between automated or manual assembly and can be either paper based or computer based.

5.2.2. The Boothroyd & Dewhurst Method

The Boothroyd & Dewhurst Method is marketed by Boothroyd Dewhurst Inc. in the United States. The method draws a sharp distinction between manual, robotic and high speed automated assembly with separate analyses for each type.

The methodology consists of three stages;

1) Select the assembly method – determined by the production volume/shift, the number of parts, the number of product variations, the number of parts/product style, the expected number of design changes during the product life and the company investment policy.

2) Analyse the assembly method – by considering parts' handling, number of fasteners, the type of fasteners, the direction of insertions, insertion force, part integration.

3) Improve the design and re-analyse.

The evaluation method is based on establishing the cost of handling and inserting parts and comparing the theoretical minimum number of parts against the actual number of parts in the assembly.

The assembly efficiency for manual assembly (E) = (3 * NM)/TM
Where; NM = Theoretical minimum number of parts
TM = Total manual assembly time

The assembly rules are implied by the different weightings attached to each part.

According to Wong and Sturges, (Ref. 141), this methodology is only suitable for parts between a few millimetres and a few tens of centimetres in size and weighing no more than a few kilograms.

The Boothroyd & Dewhurst Method can be either paper based or computer based.

5.2.3. The Lucas DFA Procedure

In a similar manner to the Hitachi AEM, the Lucas DFA procedure assigns and sums penalty factors associated with potential design problems. The analysis is carried out in three sequential stages, called functional, feeding and fitting analysis.

In the functional analysis, components are separated into those that perform primary functions and those that perform secondary operations such as fastening and locating. Costs can be reduced by eradicating the secondary group and the methodology includes criteria for establishing these functions.

The feeding analysis is concerned with the problems of handling components and sub-assemblies. There is a knowledge base of feeding characteristics to ensure that the parts are compatible with the method of feeding.

The fitting analysis is divided into a number of sub-systems that include a gripping and an insertion process analysis.

The gripping analysis determines the ease with which a part may be gripped and transported and is assigned an appropriate index.

The insertion process analysis requires the generation of an assembly sequence flowchart and the assignment of a relative cost index to each insertion process.

The results of each analysis stage are entered into a table to highlight high relative cost indices and to calculate the 'Measures of Performance', (MOPs), that indicate the efficiency of the assembly process. Product redesign then takes place to eliminate the high index values and to improve the MOPs.

Miles, (Ref. 5), comments that the absence of a component manufacturing knowledge base is a shortcoming of established DFA techniques.

5.3 Analysis of Established DFA Methodologies

The three DFA techniques described in Section 5.2 are representative of current industrial practice. In summary their strengths and weaknesses are as follows:

1. All three methodologies are available as computer assisted or manual processes.
2. All three methodologies assess the ease of assembly of a product, either as a metric or an estimated cost. This then allows a comparison between alternative design proposals and competitor products.
3. The Boothroyd & Dewhurst and the Lucas methodologies both aim to reduce the number of parts and then to ease the handling and fitting of the remaining parts.
4. The Hitachi AEM methodology focuses on the fitting of the parts and the incentive for part reduction is through reducing the value of the estimated assembly cost ratio (K), but the necessity of the parts'existence is not questioned unlike the other two methodologies.
5. Only the Lucas methodology requires the construction of an assembly flowchart which can provide a visual indication of the complexity of the assembly process.
6. All three methodologies rely on the combined skills and knowledge of an Integrated Product Development team, (IPD).
7. None of the methodologies concentrate on delivering the Product Key Characteristics, (Section 5.5).
8. None of the methodologies use process capability data, (Sections 4.12.4, and 7.3), and are therefore unable to predict the accuracy of the completed assembly.

The reviewed 'Design for Assembly', (DFA), methodologies are most effective once an assembly is designed or already in existence, (Ref. 78). A common feature of DFA methodology is analysis of the product by multi-disciplinary teams, called within Airbus, 'Integrated Product Development, (IPD), teams,' (See Section 3.4). The analysis process promotes discussion and generates alternative designs and assembly concepts. As Dewhurst, (Ref. 79), points out this results in design simplification and DFA being considered simultaneously.

This is undoubtedly beneficial, but a JAM design process must apply DFA at the conceptual design stage before the expensive, and time-consuming, detailed part geometry is in existence. It must also be able to use process capability data to ascertain whether part-to-part assembly is feasible or whether hard tooling must be used to establish the high level PKCs.

This then, implies the need for a new, or modified, DFA methodology and possibly the need for new tools to assist the designers.

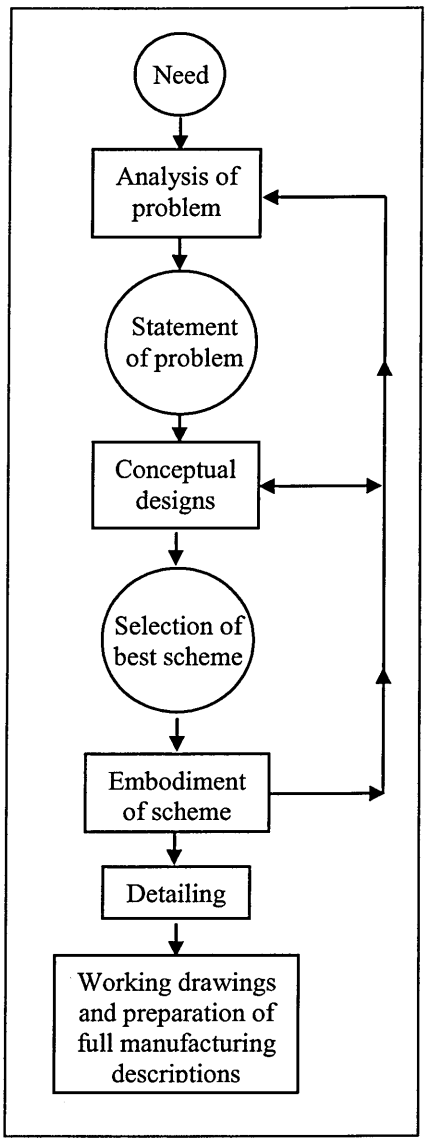
This chapter now attempts to identify the relevant design tools and their specific roles towards achieving a new JAM DFA Methodology.

5.4 Determination of Customer Requirements

The basic design process is a linear sequence of events, (Ref. 80), with feedback loops (*Figure 81*), and starts with a customer requesting a solution to satisfy a need. Unfortunately, customers are rarely able to state their needs in terms that can be easily interpreted by an engineering designer; therefore, the first task for the designer is to more precisely determine the customer's requirements and to express those requirements in engineering terminology.

There are a number of tools that can be used to help the process;

- Voice of Customer
- Product Design Specification
- Quality Function Deployment



The Basic Design Process Fig. 81

5.4.1 Voice of Customer (VOC)

As previously stated, new design starts with potential customers requesting a solution to satisfy a need. The request is expressed in abstract terms that the designer has to translate into an engineering reality.

To achieve this, the designer must listen very carefully to the customer and note and analyse what he is saying. The meetings must be well minuted to avoid any later misunderstandings and to ensure that the proposed solution will satisfy the expressed needs. This information can then be converted into a set of product characteristics expressed in explicit engineering terminology, (Ref. 81), leading to the development of a product design specification.

5.4.2 Product Design Specification (PDS)

The Product Design Specification, (PDS), is a document that comprehensively and formally lists the objectives and restraints that apply to the attributes of the product being designed, (Ref. 82). It can be a legal document forming the basis of a contract between customer and manufacturer.

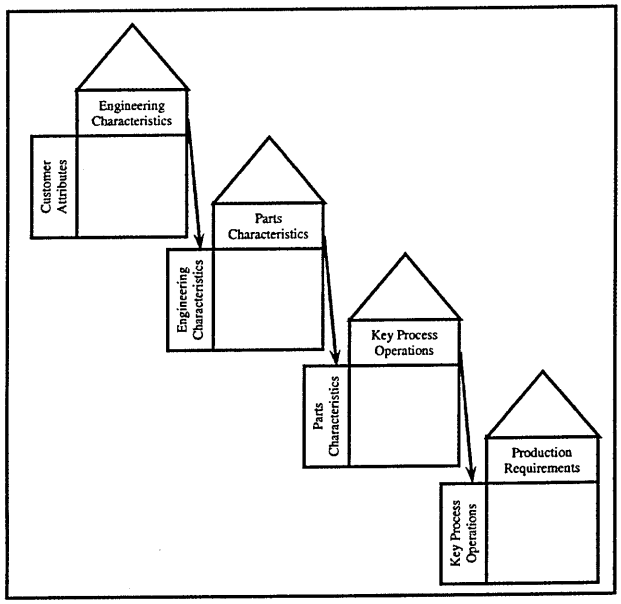
5.4.3 Quality Function Deployment (QFD)

Quality Function Deployment, (QFD), provides a formalised method of linking customer valued attributes to the engineering, manufacturing, and process decisions that companies need to make. The linkage between the requirements and engineering characteristics, part characteristics, process operations, and production requirements is established through a series of charts, (Ref. 83). However, as the proposal is to use QFD in the early stages of an assembly centric design process, there will probably be insufficient data available to construct more than the first one or two charts, (*Figure 82*).

5.4.4 Analysis

A JAM design methodology must begin in the same way as the traditional design process by determining the needs of the customer, and that this is achievable through using a combination of VOC, PDS and QFD.

The interviewed aerospace engineers are used to working from a very detailed Product Design Specification and this has been selected as the main tool to start the JAM DFA process.



Linked QFD Charts *Fig. 82*

5.5 Key Characteristics

Knowledge of the customer valued attributes makes possible identification of the product's Key Characteristics, (KCs). KCs are a concept developed by Dr. Daniel Whitney and his research students at the MIT, (Ref. 84), to capture the important characteristics of an existing product and to differentiate them from the large number of unprioritised tolerances that also appear on an engineering drawing.

This concept can equally be applied to new designs and is particularly valid for JAM assembly centric design.

Key characteristics are expressed first as high level customer requirements, (The first of the linked QFD charts – See *Figure 82*), and then translated into engineering specifications supporting manufacture and assembly.

There are a number of different definitions in use for Key Characteristics; the one used in this thesis is;

Key Characteristics are product features, manufacturing parameters and assembly features for which any significant variation would affect the product's compliance to quality standards, or is likely to significantly affect the customer's satisfaction. (Ref. 85).

Key Characteristics can be further divided into three fundamental categories, (Ref. 49);

Product Key Characteristics (PKCs) are a product geometric features and material properties that are highly constrained or for which minute deviations from nominal specifications (regardless of manufacturing capabilities) have a significant impact on the product's performance, function and form at each product assembly level. (Ref. 86).

Assembly Process Key Characteristics (AKCs) are the features during each assembly stage on the product, tool, fixture or procedures that significantly affect the realisation of a product KC at the next higher assembly process level during the assembly process.

Manufacturing Process Key Characteristics (MKCs) are the manufacturing machine process parameters and/or workpiece fixturing features for machine tools and equipment that significantly affect the realisation of a product or an assembly process KC at the part feature level.

5.5.1 Analysis

The following points result from considering and analysing Section 5.5:

1. The identification of KCs is very similar to the current Airbus practice in which the tooling designers first identify those product features that must be most closely controlled during assembly, and then design the tooling to achieve that. The recognition and designation of KCs places this practice into a formal framework and is eminently suitable as the starting point for JAM assembly centric design.

2. As the realisation of the MKCs is important in achieving and maintaining the AKCs, it is, therefore, necessary to involve process capability data within the design process. (See Section 4.12).

3. Access to a process capability database during the design process will allow designers to use realistic and achievable tolerances, (See Section 3.4), ensuring that the manufacturing capability matches the design intent.

4. The present system of blanket tolerancing of parts by category can make manufacturing unnecessarily expensive, often results in unrealistic demands on manufacturing. (Section 3.4). It is unsuitable for the realisation of JAM. The alternative approach is for the designers to initially concentrate on, and calculate the tolerances, that are necessary to ensure the delivery of the PKCs. It may then be possible to relax the tolerances on less important features.

5.6 Conceptual Design

The conceptual design phase is where the design team generates broad solutions to the problem. This is sometimes claimed to be the most important stage of the design process as decisions made here can have exponential consequences in the later stages of product design.

The conceptual design phase can be split into two distinct areas, (Ref. 87);

- Concept of ideas
- Concept of form.

5.6.1 The Concept of Ideas

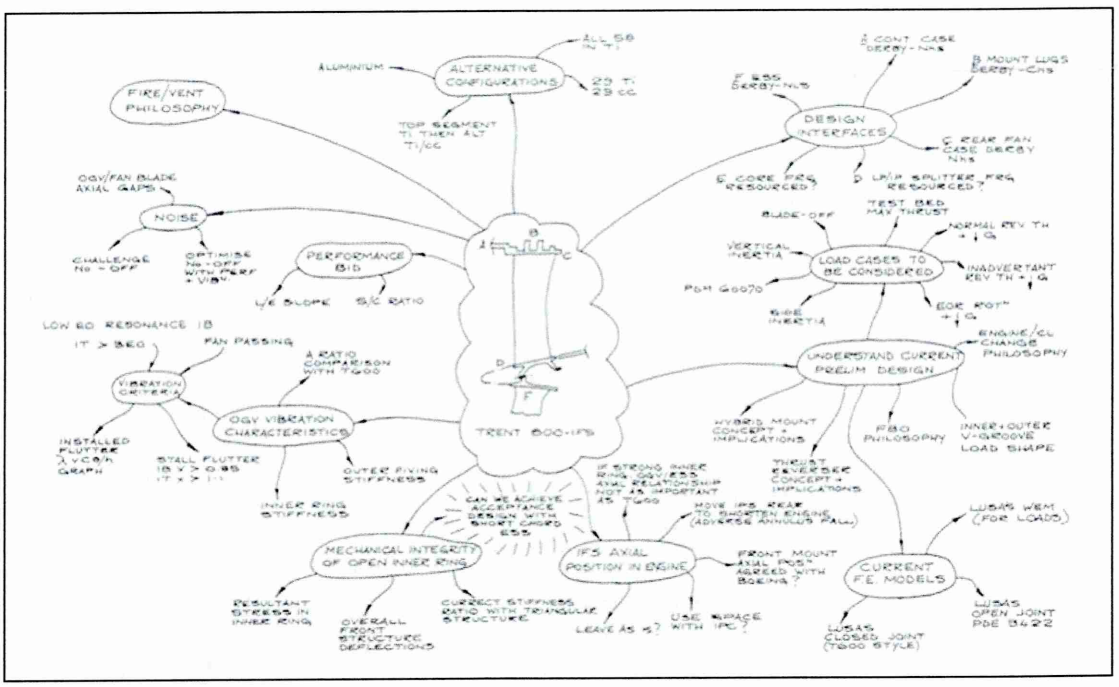
The concept of ideas stage involves generating alternative solutions to the problem. The process requires background knowledge, understanding, perception, and awareness, with gifted designers being able to make imaginative leaps to produce totally original concepts. For an 'Assembly Centric' design, this becomes a two tier process with alternative assembly concepts being generated for each of the design concepts.

5.6.2 Team Working and Brain Storming

IPD 'Team Working', (See Section 3.4), is proven to be effective; with analysis of the alternative concepts by team members of different disciplines, producing new ideas and refining and improving existing concepts. (Ref. 88).

5.6.2.1 Mindmapping

Mindmapping was developed by Tony Buzan in the 1970s, (Ref. 89), as a process to rapidly externalise the ideas generated in the brain.



A Mindmap Produced by Rolls Royce Engineers for the Trent 800 Series Engine *Fig. 83*

There are five stages to mindmapping;

1) Using a large sheet of paper, write a brief description of the topic to be addressed in the centre, and draw a circle around it. (*Figure 83,* Ref. 90).
2) Around the topic write down the sub-topics to be investigated. Circle these and draw lines to connect them to the centre topic.
3) Take each of the sub-topics in turn and identify the issues that relate to it, representing them on the map by words or pictographs. Keep going until the map stops growing.
4) Organise the map by looking for logical links and connect them by lines.
5) Redraw the map in a more logical format and prepare a written report with a sub-heading for each of the sub-topics.

5.6.2.2 The Concept of Form

The concept of form stage is concerned with the form and visual appearance of a design proposal. Computer Aided Conceptual Design, (CACD), software exists to help the designer in creating the shape and form of a product although the functionality of a product can influence the shape of design, such as the aerodynamics of an aircraft or car.

CACD software has been under development for a number of years, (Ref. 91), and commercial packages are available. (Ref. 92). During the intelligence gathering for this research, there was no evidence that CACD was being used for the Airbus UK wing design program. This is probably because each new wing is effectively a smaller or larger version of the previous wing to be designed, and any changes are most likely to be in the details of the structure and the parts. A totally new design would require re-certification by the Civil Aviation Authority, (CAA); involve extensive mechanical testing and cost millions of pounds.

The continuing development of CACD should be closely followed as it has the potential of becoming a useful design tool.

5.7 Selection of Best Concept

The output from the conceptual design stage is a number of alternative solutions. These are compared and evaluated with the best one or two being selected for further development.

There are a number of tools that can be used to help the process, (Ref. 93);

- Feasibility judgement
- Technology readiness assessment
- Go/No-Go screening
- Decision matrix

5.7.1 Feasibility Judgement

The IPD, (See Section 3.4), answers questions such as;

1) 'Will it work?'
2) 'Can it be built?'
3) 'Is it worth considering?'
4) 'Is it affordable?'

The answers are based on the intuition of the experienced designers, engineers, and cost analysts that make up the IPD team. (See Section 5.13 - Risk Analysis).

5.7.2 Technology Readiness Assessment

This assessment is particularly relevant to very competitive industries, such as aerospace, that embrace high technology to gain a competitive advantage. The

technique evaluates the technologies that are needed to manufacture the product by seeking answers to the following questions;

1) Is the new technology mature?
Establish if other companies are using the proposed technology and find out their experiences.
2) Can the product be manufactured with known processes?
Establishes a 'fall-back' solution if the new technology fails to meet expectations.
3) Is the technology able to reliably deliver the PKCs? (See Section 5.5).
4) Is the technology controllable throughout the product's life cycle?
This question addresses the product's manufacture, service, and retirement. It also raises other interesting questions such as, 'Can the by-products be safely disposed of?', 'How will this product be retired?', 'Will it degrade safely?' This is particularly relevant to carbon/epoxy composite products that have no intrinsic value as scrap and are not easily recyclable. (Ref. 94).

5.7.3 Go/No-Go Screening

The list of the customer requirements, (See Section 5.4), is transformed into questions addressed to each concept, in turn. The questions have to be answerable as either yes or maybe (Go), or no (No-Go). 'No-go' responses result in rejection; 'go' responses mean the concept meets the customer criteria, and 'maybe' responses indicate the need for more conceptual development.

5.7.4 Decision Matrix

The decision matrix, (*Figure 84*), also known as 'Pugh's Method', (Ref. 95), is an iterative evaluation method that tests the completeness and understanding of requirements, and rapidly identifies the strongest alternatives. The method is most effective if each member of the team performs it independently and the individual results are then compared. The results of the comparison lead to a repetition of the technique with the iteration continuing until the team is satisfied with the results.
There are four basic steps, (Ref. 96), for evaluation using a decision matrix;

1) Select criteria
Based on the customer requirements. (See Sections 5.4 and 5.5)

2) Select concepts
(See Section 5.6.1)

Criteria \ Concept	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Ease of achieving 105 – 125 DbA		S	–		+	–	+	+	–	–	–	–	S	+
Ease of achieving 2000 – 5000 Hz		S	S	N	+	S	S	+	S	–	–	–	S	+
Resistance to corrosion, erosion and water		–	–	O	S	–	–	S	–	+	–	–	–	S
Resistance to vibration, shock and acceleration	D	S	–	T	S	–	S	–	–	S	–	–	–	–
Resistance to temperature	A	S	–		S	–	–	–	S	S	–	–	S	S
Response time	T	S	–		+	–	–	–	–	S	–	–	–	–
Complexity: number of stages	U	–	+	E	S	+	+	–	–	–	+	+	–	–
Power consumption	M	–	–	V	+	–	–	+	–	–	–	–	S	+
Ease of maintenance		S	+	A	+	+	+	–	–	S	+	+	S	–
Weight		–	–	L	+	–	–	–	S	–	–	–	–	+
Size		–	–	U	S	–	–	–	–	–	–	–	–	–
Number of parts		S	S	A	+	S	S	–	–	+	–	–	S	–
Life in service		S	–	T	+	–	S	–	–	–	–	–	–	–
Manufacturing cost		–	S	E	–	+	+	–	–	S	–	–	–	–
Ease of installation		S	S	D	S	S	+	–	S	–	–	–	S	–
Shelf life		S	S		S	S		–	S	S	S	S	S	S
Σ+		0	2		8	3	5	3	0	2	2	2	0	4
Σ–		6	9		1	9	7	12	11	8	13	13	8	9
ΣS		10	5		7	4	4	1	5	6	1	1	8	3

A Decision Matrix *Fig. 84*

3) Generate scores

Scoring is a comparison between the selected concepts and a datum design, which can be either an existing design, or the IPD teams' intuitively favourite concept. For each criterion the concepts are judged to be, 'better than', (+), 'same as', (S), or 'worse than', (-). (A computerised spread sheet uses a, +1, 0, -1, scoring system). A variation on the scoring system is to 'weight' each criterion and multiply the score by the weight.

4) Compute totals

The total score for each concept is the difference between the plus scores and the minus scores.

Repeat the analysis using the highest scoring concept as the new datum, and continue the iteration until a clear 'best concept' emerges.

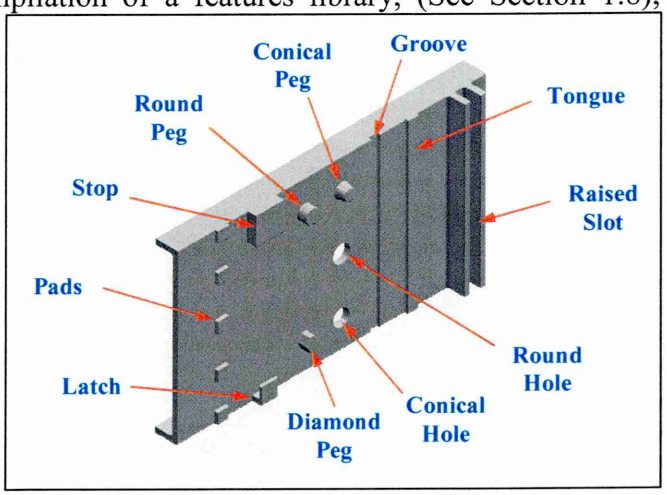
It is argued that to achieve a JAM design the concept selection techniques described in Section 5.7 must also include 'assembly concept' analysis.

5.8 Structurally Integrated Tooling

As the need for hard tooling is reduced, it's several roles, (See Section 3.5.7), must be embedded in the design of the individual parts and in the capabilities of the manufacturing, and assembly processes. (Ref. 5).

This can be achieved by manufacturing parts to drawing, and by incorporating location, holding, and reference features in the detail design of parts.

The JAM project included the compilation of a features library, (See Section 1.8), together with the outlining of a framework for feature selection. (Ref. 97).



A Selection of Machined Features *Fig. 85*

Features are selected to fulfil specific tooling functions;

1. Adjustment of detail parts. For selection when the manufacturing processes are predicted as being unable to deliver the AKCs.
2. Temporary support of detail parts before fitting the permanent fasteners.
3. Temporary location and fastening.
4. Full kinematic restraint, allowing fastener hole drilling with the parts in-situ.

At present, the library is a 'stand alone' system, with the features, (*Figure 85*), being selected by the designer and approved by the stress engineers for each specific application. (See Section 4.5 – Finite Element Modelling and Analysis).

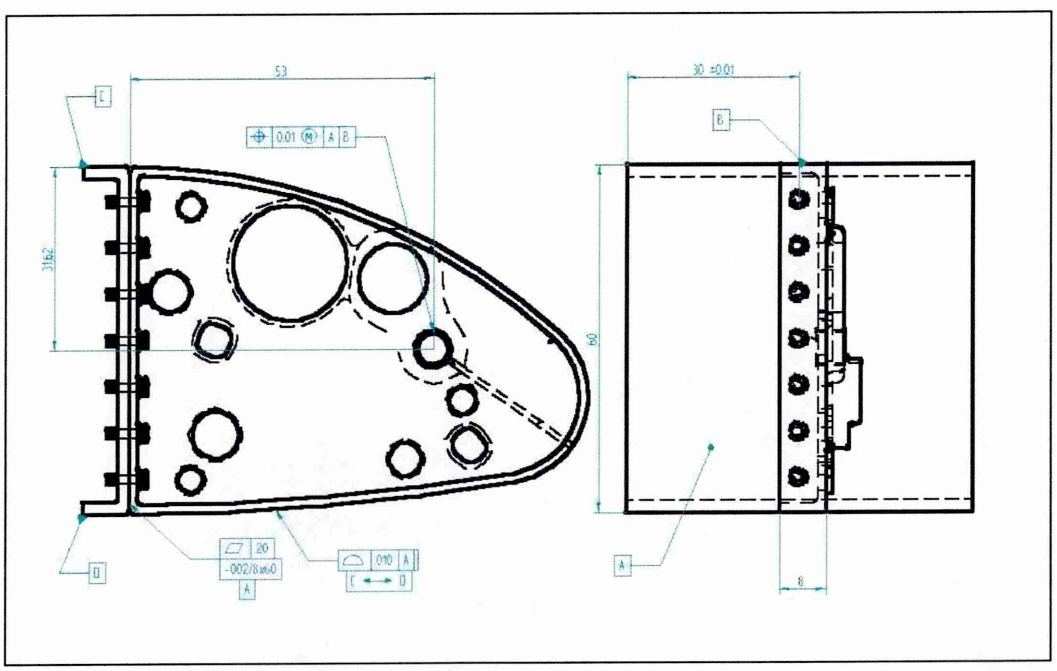
As the IPD team has a conceptual design that includes knowledge of the sub-structure down to part-level, selection of the location features is possible at this stage, ahead of the detailed part-design.

For JAM assembly centric design;

At this very early stage in the design process, the IPD team should concentrate on the part-interfaces, and imagine the completed assembly with the location features in bold and the detail parts in ghosted outline.

5.9 Geometric Dimensioning and Tolerancing

The development of 'Geometric Dimensioning and Tolerancing', (GD&T), is accredited to Stanley Parker in the 1940s in Scotland and has developed into a detailed set of standards issued by both ANSI, (Ref. 98), and ISO, (Ref. 99). Somewhat belatedly, it is now rapidly gaining acceptance in general industry because, unlike traditional tolerancing schemes, it conveys unambiguous information to define the designer's intent. It is a system that replaces words with symbols. (Ref. 100).



AKCs captured by Geometric Dimensioning and Tolerancing *Fig. 86*

GD&T clarifies the dimensioning of parts in relation to their assumed geometry, function and relationship to other parts; it is ideal for JAM, in capturing and describing a product's AKCs. (*Figure 86*). (See Section 5.9).

SYMBOL	DESCRIPTION	TYPE
—	Straightness	
▱	Flatness	FORM
○	Circularity	
⌭	Cylindricity	
⌒	Profile of a Line	PROFILE
⌓	Profile of a Surface	
∠	Angularity	
⊥	Perpendicularity	ORIENTATION
//	Parallelism	
⌖	True Position	
◎	Concentricity	LOCATION
≡	Symmetry	
↗	Runout	RUNOUT
⌰	Total Runout	

Types of GD&T Geometric Tolerances *Table 3*

5.9.1 Geometric Tolerances. (*Table 3*)

- The five types of geometric tolerances are form, profile, orientation, location, and runout.
- The four characteristics of 'Form' are straightness, flatness, circularity, and cylindricity.
- The two characteristics of 'Profile' are profile of a line and profile of a surface.
- The three characteristics of 'Location' are true position, concentricity, and symmetry.
- The two characteristics of 'Runout' are circular and total.

5.9.2 Modifier. (*Table 4*)

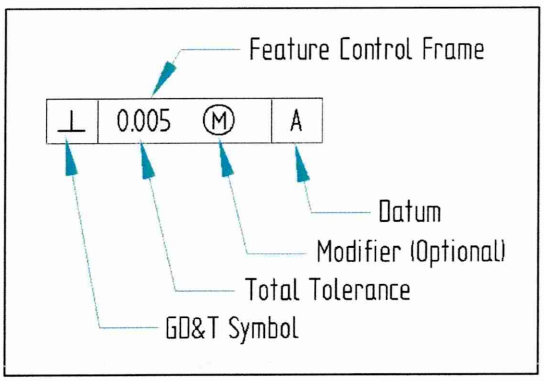
Symbol	Description
Ⓜ	Maximum Material Condition
Ⓛ	Least Material Condition
Ⓢ	Regardless of Size
Ⓟ	Projected Tolerance Zone

GD&T Modifiers *Table 4*

- 'Modifiers' are used to clarify the status of the material when a tolerance is applied.

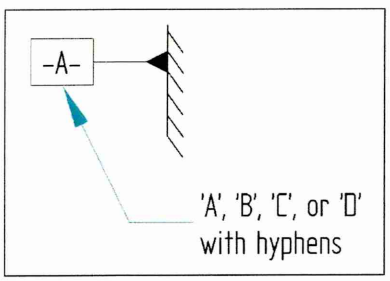
- There are four types of modifiers:
  1) Maximum material condition
  2) Least material condition
  3) Regardless of feature size
  4) Projected tolerance zone.

5.9.3 Feature Control Frame. (*Figure 87*)



Feature Control Symbols *Fig. 87*

- A 'Feature Control Frame' is drawn as a rectangle long enough to include Geometric Dimensioning and tolerancing Symbol, a total tolerance value, and a datum letter.
- 'Feature Control Frames' are attached to edges and surfaces by extension lines and to features by a leader.



Datum Symbol *Fig. 88*

5.9.4 Datums. (*Figure 88*)

- 'Datums' are edges, surfaces, or features that are considered accurate for locating other features or surfaces.
- 'Datums are labelled with a rectangle that contains a letter preceeded by a hyphen and followed by a hyphen..

The datum features in a callout create the origin of a part coordinate system for a feature, called the Datum Reference Frame (DRF). Measurements of features related to the same DRF share the same origin point. The number in the callout indicates the size

of the functional envelope. If the part feature violates the envelope it will not fulfil the design intent.

GD&T is now used by both Airbus and BAE Systems for all new designs.

5.9.5 Analysis

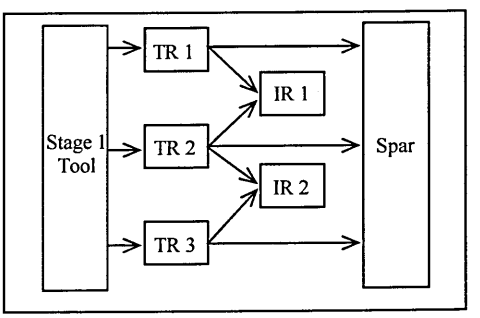
Although Geometric Dimensioning and Tolerancing conveys unambiguous information to define the designer's intent, it can also be used to convey Six Sigma manufacturing capability. (See Section 4.12). This will then enable assembly analysis to be performed with data referring to the control limits of a process instead of to the designer's specified limits. (See Section 3.4).

Datum transposition poses a serious problem for the aerospace industry. The designers and tooling engineers work from an aircraft datum point centred in space, under the fuselage and between the two wings, *(Figure 234)*. The drawings passed to the manufacturing engineers are, for practical purposes, dimensioned to a local drawing datum, (*Figure 243*). A CNC programmer will create a more convenient machining datum, often in sacrificial material, (*Figure 31*), and a sub-assembly may be assembled to a different datum from that used when it is built into a main assembly, (Section 3.3.6). Each transposition represents a possible source of error, however, an assessment can be made of each datum error and those values can be included as Transfer Errors in the analyses of the Featurised Datum Flow Chains, (Section 5.11).

5.10 Datum Flow Chains

Datum flow chains, (DFCs), are a recent development in conceptualising the design of complex assemblies, (Ref. 101).

A datum flow chain, (DFC), is a graphical representation showing the links between parts and represents the underlying structure of dimensional references. By differentiating between links that establish and transfer dimensional location between parts (mates) and those that just provide strength or support (contacts), it is possible to represent graphically the dimensional transfers for given assemblies.



DFC Diagram *Fig. 89*

Not all links affect the delivery of the PKCs and by flowing the PKCs down through the engineering specifications, (See Section 5.5); it is possible to identify local assembly and part datums and the links that affect their delivery. Hence a DFC can control the delivery of PKCs in an assembly process by controlling the order of establishment of the mates.

Importantly, datum flow chains show tooling functions, (*Figure 89*), unlike traditional product decompositions.

5.10.11 Analysis

DFCs identify the links that establish a PKC and unlike conventional product decomposition diagrams include the tooling. This will enable tooling errors to be included in the error analysis.

5.11 Featurised Datum Flow Chains

The work on datum flow chains has been extended by the team at the MIT to incorporate the actual features, (*Figure 90*), that participate in the assembly of the product, (Ref. 102). Due to the imperfect nature of these features, the dimensional transfer between parts will be subject to errors equalling the algebraic sum of the manufacturing imperfections. By adding compounded process capability tolerances to the features in the chain, (See Section 4.12.4), simple root-sum-square, (RSS), calculations can then be used to predict the error in an assembly.

PART	FEATURE	CALLOUT	LINK	Tx	Ty	Tz
Tool	Loc1 Pin A	SPF .010	Tool 1.1	0.010		
	Loc1 Hol B	POS .005	Tool 1.2		0.005	0.005
	Loc1 Slot C	POS .005	Tool 1.3			
	Loc2 Pin A	SPF .010	Tool 2.1	0.010		
	Loc2 Hol B	POS .005	Tool 2.2		0.005	0.005
	Loc2 Slot C	POS .005	Tool 2.3			
BH1	BH1 Pin A	FLT .005	BH1 0.1	0.005		
	BH1 Hol B	PER .005	BH1 0.2		0.005	0.005
	BH1 Hol C	POS .005	BH1 0.3			
	BH1 Sur 1ML	SPF .020	BH1 1.1		0.020	0.020
BH2	BH2 Pin A	FLT .005	BH2 0.1	0.005		
	BH2 Hol B	PER .005	BH2 0.2		0.005	0.005
	BH2 Hol C	POS .005	BH2 0.3			
	BH2 Sur 1ML	SPF .020	BH2 1.1		0.020	0.020

A Feature Error Table *Table 5*

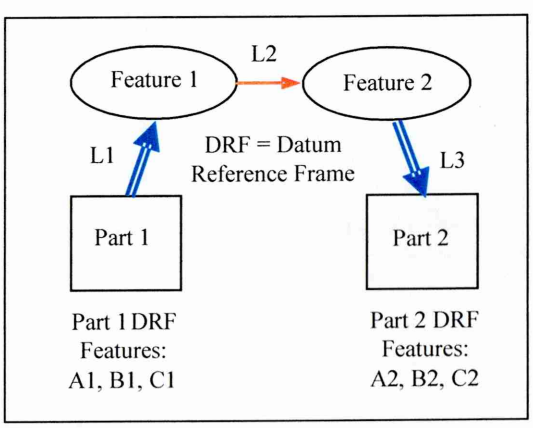
5.11.1 Featurised Datum Flow Chain Analysis

Schwemmin, (Ref. 102), describes five steps in the analysis of featurised datum flow chains;

Step 1 Define KCs, parts, tooling concepts and preliminary mate relationships.

'Mates' are defined as feature-to-feature connections that constrain a part from moving or rotating, and are distinct from 'Contacts' that are touching but not positioning features.

Step 2 Draw the FDFC labelling each link for later reference in tables and calculations. The FDFC is a directed cyclic graph that shows the 'mate' relationships.



FDFC Diagram *Fig. 90*

Step 3 Tabulate the Datum Reference Frame, (DRF), and Feature GD&T Callouts in the Chain. (*Table 5*).

Step 4 Resolve Each Callout into X, Y, and Z Directions. (Also, *Table 5*).

Step 5 Trace and Sum the Errors for Each Key Characteristic.
The final calculation is an RSS combination of all the terms that lie on the chain of delivery for the KC. The result is a prediction of the positional variation in the KC.

Schwemmin's, (Ref. 102), work is primarily directed at tracing assembly problems with existing structures, but as it is based on constraint theory, (See Section 4.3 - Kinematic Analysis and Minimal Restraint), its potential as a tool for comparing and assessing JAM assembly centric designs is apparent.

5.11.2 Analysis

1. The analysis of the Featurised Datum Flow Chains provides an estimate of the ability of a specific assembly concept to satisfy the KC requirement.

2. Counting the degrees of freedom entering a part box gives an indication of whether the part is over, under, or correctly restrained using minimal kinematic restraint. (See Section 4.3 - Kinematic Analysis and Minimal Restraint).

5.12 Error Budgeting

For an assembly of parts, an error is defined as any variation from the idealised system. Essentially these variations from perfection will be captured by the application of tolerances, (See Section 5.9), to ensure that the completed assembly delivers the PKCs. (See Section 5.5). These variations are caused by a number of factors, but include manufacturing capabilities, (dimensional and geometric), and environmental variations, (temperature and humidity). (See Section 4.12.4 and Section 4.1).

Error Budgeting is used in machine tool design as an analytical tool to predict the total error of the machine system at the design stage, (Ref. 53). The starting point is a target error for the total machine which is then distributed through an error budget to set the individual sub-systems errors. The error budget is next used as a trade-off tool between the various sub-systems of the machine to achieve a balance between the target and the degree difficulty in achieving it. (Ref. 103).

An adaptation by the Cranfield JAM researchers, (See Section 1.8), of the MIT work on Featurised Datum Flow Chains, (See Section 5.11), has resulted in the development of a three dimensional Error Budgeting system for comparing the potential, and efficiency, of KC deliveries between alternative assembly concepts. (Ref. 104).

5.12.1 Error Budgeting Analysis

The summation of the Six Sigma errors in the links for each PKC, (See Section 4.12 – Statistical Process Control), reveals their impact on the quality of the assembly and the realisation of that PKC. These errors arise because of manufacturing inaccuracy and

variation. Since it is highly improbable that all of the errors will be at their maximum values simultaneously, (Worst Case Stack Calculations), it is statistically reasonable to express the error totals as Root-Sum-of-Squares, (RSS), additions, (Ref. 105). This assumes that the processes are under statistical control. (See Section 4.12).

Using the nomenclature in *Table 6*;
With reference to Odi, (Ref. 104), the transfer error equation, E_t, is given by;

Equation 1 $$E_t = \sqrt{\varepsilon_f^2 + \varepsilon_p^2 + e_o^2 + e_l^2}$$

And the mate error equation, E_m, is given by:

Equation 2 $$E_m = \sqrt{e_d^2 + e_f^2 + e_p^2 + e_r^2}$$

And, for N number of features the combined error, e_N, is given by:

Equation 3 $$e_N = \sqrt{\sum_{i=1}^{N} \left(e_{feature}\right)_i^2}$$

And, the total error for an assembly is given by:

Equation 4 $$E_A = \sqrt{\sum (E_t)_{Li}^2 + \sum (E_m)_{Lj}^2}$$

Where i, j are DFC links

Three different types of 'Target Errors' are defined as being useful in error budgeting;

1) Ultimate Target Error
This is the total error of the FDFC delivering a specific PKC. The value must not exceed the tolerance given to the PKC, or the PKC requirements will not be met.

2) Relative Target Error

	⟹	⟶
	Transfer Error	**Mate Error**
Datum Feature	ε_f = *form tolerance* ε_p = *profile tolerance*	
Ordinary Feature	e_o = *orientation tolerance* e_l = *location tolerance*	e_d = *dimensional tolerance* e_p = *profile tolerance* e_r = *runout tolerance*

Feature Error Nomenclature *Table 6*

This is the total mate error of an assembly concept and is used for comparing the JAM efficiency of alternative assembly concepts.

3) Reference Target Error

This is the total system error of an existing structure and is compared to the reference target errors of re-engineered versions of the same design to establish their comparative JAM efficiencies.

(See Chapter 7 for practical demonstrations of Error Budgeting Analysis).

5.12.2 Analysis

Consideration of Error Budgeting suggests the following:

1. Error Budgeting is a powerful tool that can be used for comparing and assessing alternative assembly concepts.

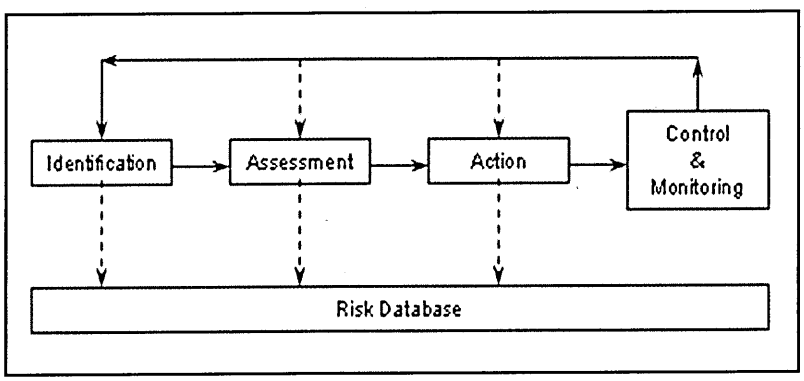
2. When re-engineering existing designs, and when the process capabilities are unknown, alternative assembly concepts can be compared using the tolerances stated on the engineering drawings.

3. In that case, of course, there can be no guarantee that the KC requirements will be satisfied and Six Sigma calculations cannot be used as the shape of the distribution between the limits is unknown. (See Section 4.12).

5.13 Risk Analysis

A risk is defined as an uncertainty, which if it occurs, will have an impact on the product's cost, delivery, and quality. (Ref. 106).

Risk Analysis is best convened as an IPD team exercise. (See Section 3.4). Two or more of the best design concepts are analysed by the IPD team seeking to identify the



Risk Management Process *Fig. 91*

uncertainties associated with the specific concepts. The IPD team will also assess the likely impact of any risk and prepare mitigation plans. (*Figure 91*).

A risk can be weighted by assessing the probability of it happening and the financial impact if it does and using the Risk Exposure value, (*Figure 92*), along with the Costings Analysis, (See Section 4.4 – Assembly Analysis), as deciding factors in the concept selection process.

Impact	**Probability**
£100, £1000, £100,000	1 in 10 Chance 1 in 100 Chance 1 in 1000 Chance

Risk Exposure = Impact × Probability

Risk Quantification *Fig. 92*

Risk Quantification must be a factor in any concept selection process.

5.14 Guidelines for a JAM Solution

The following guidelines for a JAM solution have been deduced from analysis of Chapter 4 and the previous sections in Chapter 5;

1. Remember that the goal is a cost-effective design and assembly plan
2. Always work as a multi-disciplinary team
   - Use Brainstorming and Mindmapping to generate ideas
3. Start the process by listening to the needs of the customer
   - Voice of the Customer
4. Analyse the customer's problem
   - Produce a detailed Product Design Specification
5. Use the PDS to identify the Product Key Characteristics
   - Use Brainstorming and Mindmapping
6. Produce a number of conceptual designs
   - Individually at first then meet as a team to discuss
   - Use Brainstorming and Mindmapping to generate ideas
7. Refer to enabling technologies database
   - Look for technologies to reduce the number of parts
8. Minimise the number of parts
   - Part integration
   - Off-line joining technologies
9. Select best schemes
   - Feasibility judgement
   - Technology readiness assessment
   - Go/No Go screening
   - Decision matrix
10. Generate outline assembly concept plans

- Individually at first then meet as a team to discuss
- Use Brainstorming and Mindmapping to develop ideas
- Minimise the number of parts
- Use gravity, do not fight it
- Design out dedicated hard tooling
- Refer to enabling technologies database for ideas
- Design for part-to-part assembly
- Design in reference features
- Ergonomic design – think of the assembly technicians

11. Select best two or three assembly concepts
    - Team work
    - Consider the practicality of each concept
    - Consider the manufacturing requirements
    - Compare outline costings
    - Compare risk analyses
12. Select assembly features
    - Determine kinematic constraint requirement
    - Refer to features library
    - Size using FE expert system
    - Identify manufacturing processes
    - Use processes capability database to determine manufacturing tolerances
13. Identify enabling technologies
    - To aid assembly
14. Analyse assembly concepts
    - Draw featurised datum flow chains
    - Check kinematic constraint requirements
15. Analyse delivery of PKCs
    - Use process capability data
16. Design in hard-tooling if necessary – and only if necessary!
    - To ensure delivery of PKCs
    - Consider gaugeless tooling an alternative
    - Consider robotic manipulators
    - Consider reconfigurable tooling
17. Re-analyse assembly concepts
18. Compare alternative assembly concepts
    - Error budgets
    - Costings analysis
    - Risk analysis
19. Select best assembly concept
20. Develop design concept as a solid model
    - Use virtual engineering toolset
21. Fine tune the design and assembly tolerances
    - Team work
    - Use 3D tolerance analysis software

6.0 A DESIGN METHODOLOGY FOR JAM

In this Chapter the guidelines, (Section 5.14), are logically arranged and merged with the basic design algorithm, (See Section 5.1), to create a holistic design Methodology for JAM. Two slightly different forms of the JAM design algorithm are described; one for the creation of new conceptual designs, (Section 6.1), and the other for the re-engineering of existing designs. (Section 6.2).

JAM is defined as a design, manufacturing and assembly philosophy to help reduce the need for dedicated hard tooling, (Section 1.5). In Section 5.0 it is argued that to achieve an effective JAM design DFA must be applied at the conceptual design stage and ahead of the detail part geometry and that this then implies the need for a new or modified design algorithm.

6.1 The JAM Design Algorithm

The algorithm consists of two parts: a Nominal Design Phase, (*Figure 93*), and a Variation Design Phase. *(Figure 95)*.

6.1.1 The Nominal Design Phase

(With reference to *Figure 93*).

6.1.1.1 Customer Requirements

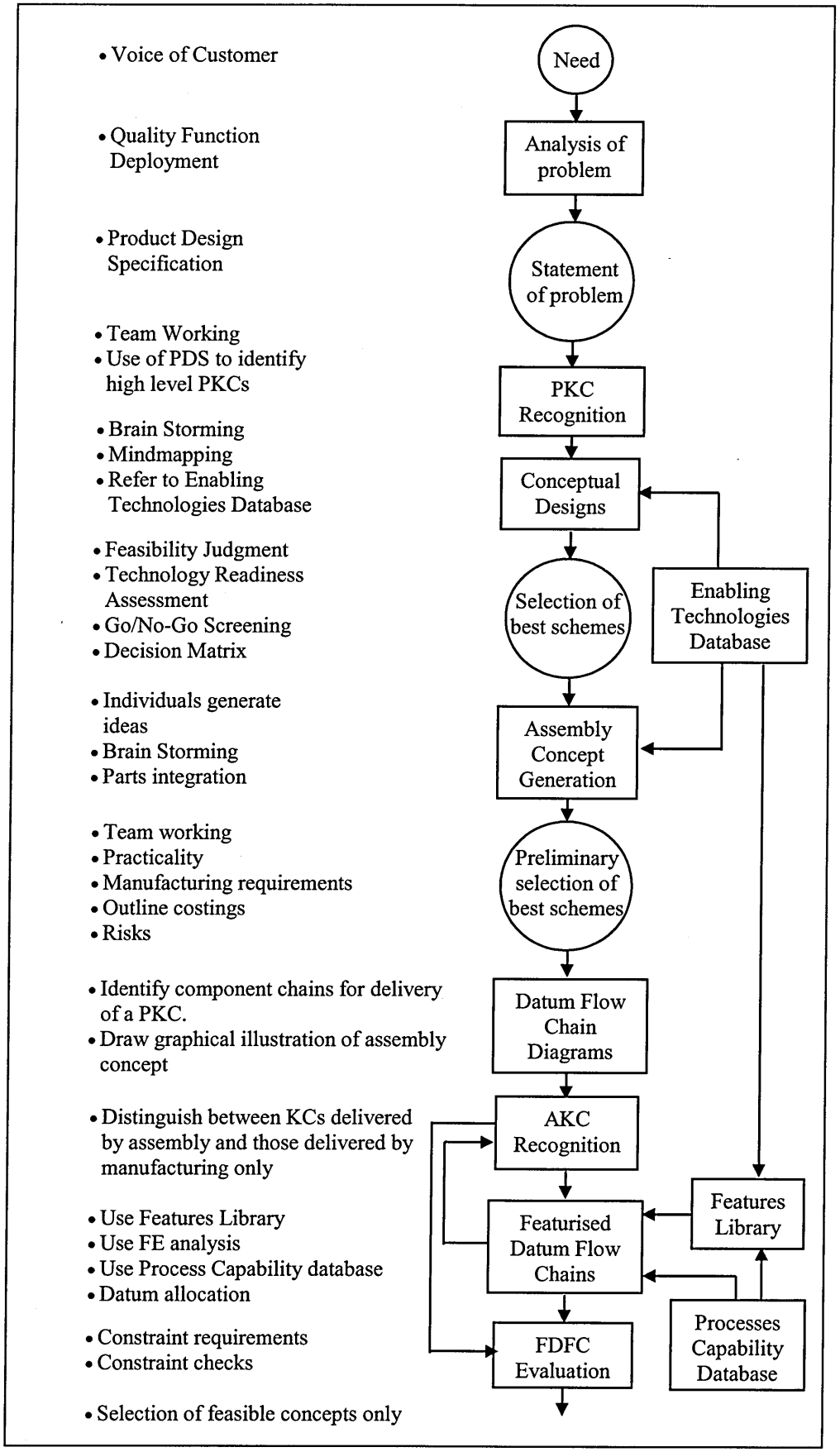
In Section 5.3 it is argued that a JAM design methodology must begin in the same way as the traditional design process by determining the needs of the customer, and that this is achievable through using a combination of VOC, PDS and QFD. (See Section 5.4).

6.1.1.2 High Level Key Characteristics Recognition

With the Product Design Specification agreed and ratified, the IPD team Brain Storms to identify the high level PKCs, (See Sections 3.4, 5.5, and 5.6.2). The high level PKCs are permanent for a given PDS, and, for an aerospace structure, will include definitions of aerodynamic form profile, and primary and secondary surface finishes. The aerodynamic requirements are convertible to GD&T profile tolerances, (Section 5.5, Section 5.9), and it is these tolerance definitions that establish the final assembly tolerances.

6.1.1.3 Conceptual Designs

For an aerospace structure, the concept of form, (See Section 5.6.2.2), is determined by the aerodynamic requirements defined in the PDS. Therefore, this stage of the JAM design algorithm involves the IPD team using a combination of Brain Storming and Mind Mapping to develop alternative solutions for the design of the underlying structure. The conceptual drawings can be hand sketches and need show only sufficient detail to demonstrate how the design will ensure the delivery of the high level PKCs. This is because the assembly concept analysis involves only the part mating features and any more detailing of parts is unnecessary and wasteful of time if that concept is not chosen for further development.



JAM Design Algorithm - Nominal Design Phase *Fig. 93*

However, the algorithm is generic and is equally applicable to other branches of engineering design where the use of CACD may be appropriate, (Section 5.6.2.2).

At this point the team should reference the Enabling Technologies Database as this will assist lateral thinking and originality, and may result in imaginative and inspirational concepts.

6.1.1.4 Selection of Best Concept

The output from the conceptual design stage is a number of broadly defined alternative solutions that the IPD team has to collectively compare and evaluate, and select the best one or two for further development. (See Section 5.7).
Evaluation tools include:

- Feasibility Judgement, (Section 5.7.1).
- Technology Readiness Assessment, (Section 5.7.2).
- Go/No-Go Screening, (Section 5.7.3).
- Decision Matrix, (Section 5.7.4).

To prevent undue influencing by stronger personalities the IPD team members should independently determine their preferred concepts before meeting as a team and making the final, collective, decision.

6.1.1.5 Assembly Concept Generation

The members of the IPD team should again first work independently with each member producing an assembly concept for each of the chosen design concepts.

Particular consideration should be given to;

- Parts integration, (Section 4.7)
- Reducing the overall parts count through novel joining techniques, (Section 4.9)
- Reducing the need for type specific hard tooling through the use of flexible tooling systems and robotics, (Section 4.8, Section 4.11,)
- The use of in-process metrology systems and photogrammetry to control and monitor the build. (Section 4.10).

At this stage, no ideas are to be rejected on the grounds of practicality or expense.

6.1.1.6 Preliminary Selection of Best Assembly Concepts

Meeting as a team the IPD further explore and develop the assembly concepts. The final decision being made on a simplified analysis of practicality, manufacturing requirements, outline costings, and risks.

6.1.1.7 Datum Flow Chain Diagrams

Having determined the PKCs, (See Section 6.1.1.2), the DFCs can be drawn for each of the chosen assembly concepts producing graphical representations of the links between the parts, including tooling, that affect the delivery of a PKC. (Section 5.10).

6.1.1.8 AKC Recognition

The links in the DFCs identify the AKCs that are needed to control the delivery of the PKCs. Some of the AKCs are delivered directly by the manufacturing process

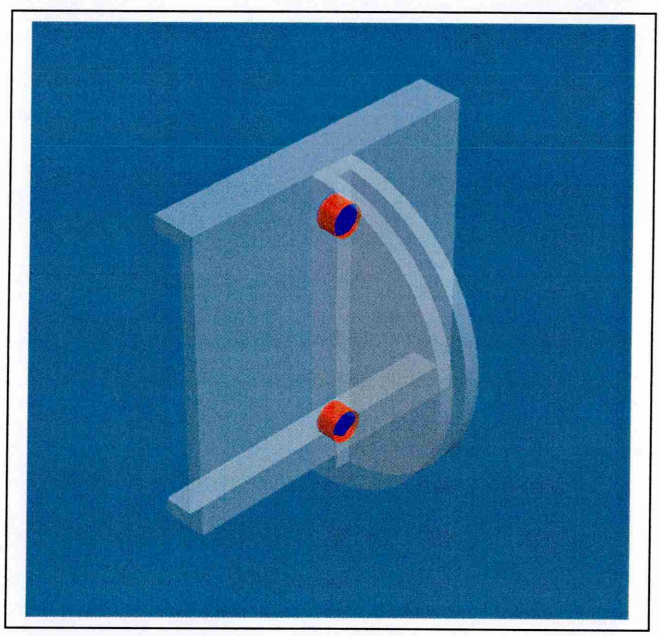
capabilities, (See Section 4.12), and the others will be delivered by the assembly strategy. These AKCs are associated with a given assembly strategy and therefore they are assembly plan dependent. They cannot be deduced by inspecting the PDS, (Section 5.4.2). AKCs are changeable and will be different if the assembly strategy is changed. This fact gives rise to the first of the feedback loops in the design algorithm, (*Figure 93*).

6.1.1.9 Featurised Datum Flow Chains

Preliminary determination of the AKCs permits populating the DFC diagrams with integrated assembly features to create FDFCs, (Section 5.8). The feedback arrow, (*Figure 93*), indicates the need to re-confirm the AKCs, (Section 6.1.1.8), and to identify the 'Mate' relationships, (Section 5.8.1). The feed-forward arrow, (*Figure 93*), indicates that once these are confirmed it is possible to move on to the next stage and begin evaluating the FDFCs.

6.1.1.10 Featurised Datum Flow Chains Evaluation

Confirmation is obtained that the kinematic restraint requirements are satisfied from counting the degrees of freedom that enter a box, (Section 5.11.2). Any assembly concepts that do not satisfy the criteria are modified or discarded. (Section 4.3).



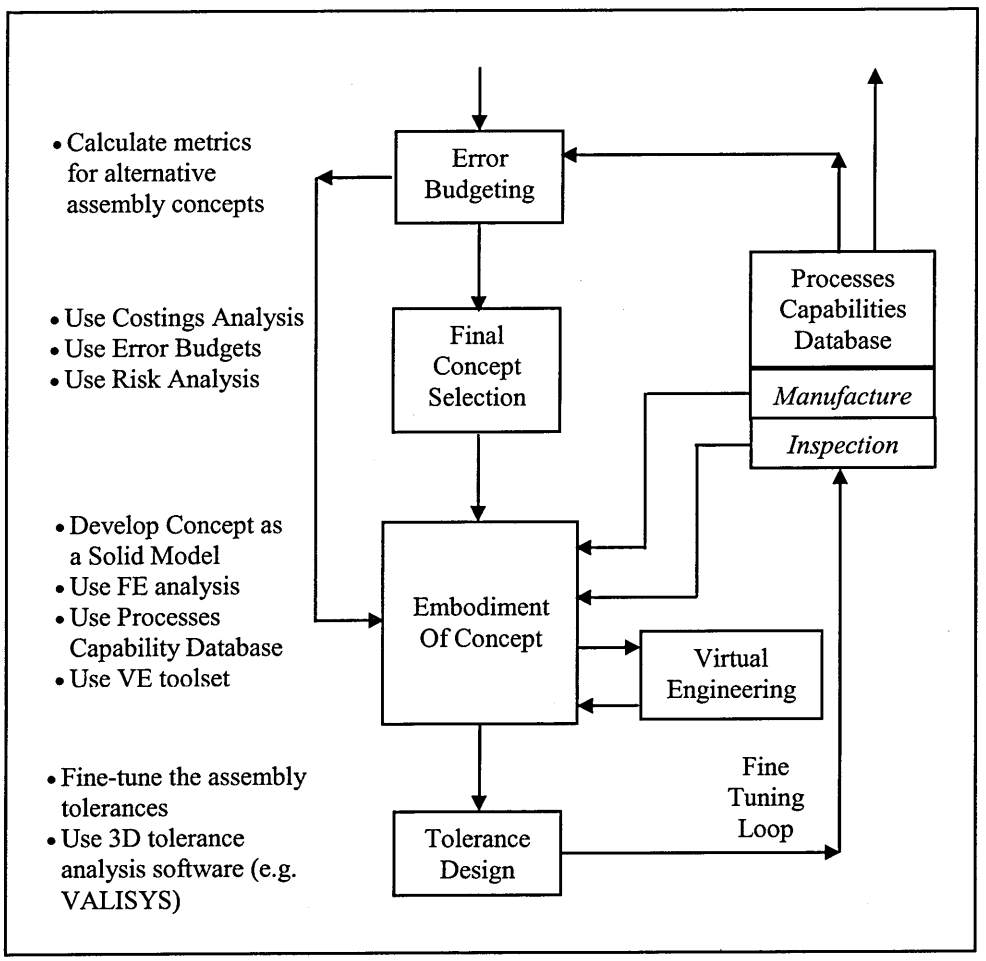
Conceptualisation of Assembly Concept *Fig. 94*

At this stage, conceptualisation is simplified if the assembly concepts are imagined with the part-interfaces or 'mate' features in bold and the detail parts in ghosted outline. (*Figure 94*).

Referencing the Processes Capability Database will provide values for the six sigma mate errors associated with the different features and required for the later Error Budgeting evaluation. (Section 6.1.2.1).

6.1.2 The Variation Design Phase

The Variation Design Phase, (*Figure 95*), is an iterative process which initially identifies the assembly concept most likely to achieve the design intention at an acceptable cost and risk, followed by 'fine-tuning' of the assembly feature tolerances to ensure a robust assembly strategy by tightening tolerances where necessary and opening tolerances where possible.



JAM Design Algorithm – Variation Design Phase *Fig. 95*

6.1.2.1 Error Budgeting

Error Budgeting is used to compare the alternative assembly concepts, (Section 5.12), and to assess the degree of difficulty that each concept will have in satisfying the PKCs.

The starting point of the Error Budgeting Process for new designs is the Ultimate Target Error, (UTE), (Ref. 6). The UTE is the maximum allowable volumetric error associated with each high level PKC, (Section 5.5). Therefore the summation of the total Transfer and Mate errors of the links that deliver a given PKC must be equal to or less than the UTE for that PKC. Error values for the links are established by referring to the six-sigma processes capability data and converting these into GD&T engineering tolerances, (Section 4.12.4).

When the links are to be established using in-process metrology then the Six Sigma measuring and alignment errors are included in the error summations. (Section 4.12.4).

6.1.2.2 Final Concept Selection

The error budgeting is used to compare the alternative assembly concepts and to identify which ones are capable of satisfying the PKC requirements. Final concept selection follows a technology assessment, plus risk and costings analyses of the top contenders. (Section 5.13 and Section 4.4).

6.1.2.3 Embodiment of Concept

The embodiment of the concept involves solid modelling the end-product together with the major assembly tooling. (Section 6.1.1.3), (Section 4.2), (Section 4.3). Full use is made of the Virtual Engineering suite of programmes, (Section 4.2.1), enabling computer assisted interference analysis, (Section 4.2.2), assembly analysis, (Section 4.4), FE analysis, (Section 4.1), (Section 4.5), ergonomic analysis, (Section 4.4), and the production of engineering drawings and CNC part-programs, (Section 4.6).

The conceptual embodiment can form the kernel of a full Workplace Model, providing an invaluable off-line training tool and line-tuning facility. (Section 4.4).

6.1.2.4 Tolerance Design

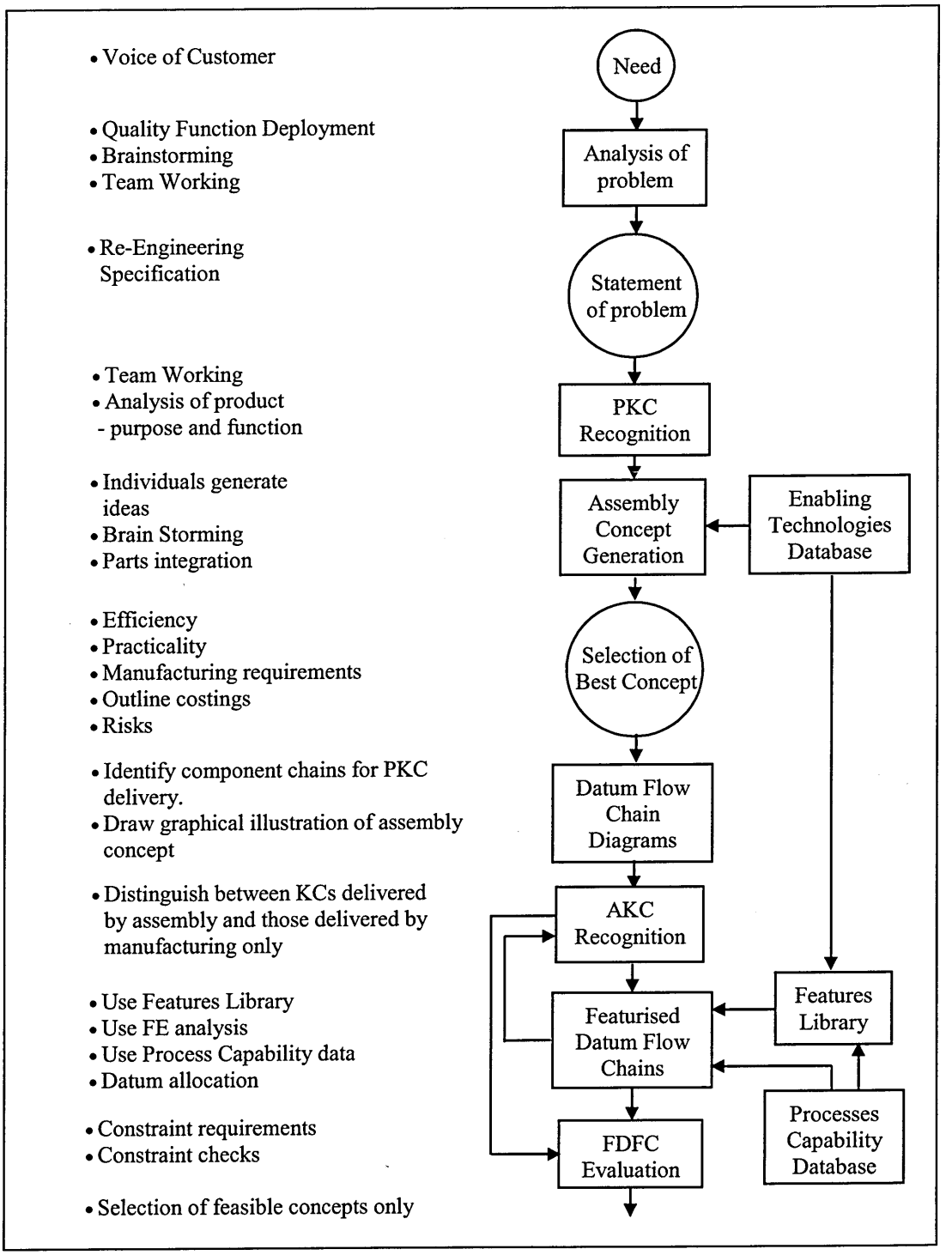
Using commercial analysis software such as VALISYS/Assembly, (Ref. 107), the assembly process can now be evaluated from a tolerance management point of view. The analysis will indicate any datum features or tolerances that need to be revisited and fine-tuned to ensure consistently successful assembly with guaranteed delivery of the PKCs. (Section 4.4)

6.2 The JAM Re-Engineering Design Algorithm

The JAM Project defined re-engineering as the detail re-designing of an existing product to improve its assemblability and/or reduce cost.

Re-engineering is not a major product re-design and this is reflected in the re-engineering algorithm.

The algorithm consists of two parts: a Nominal Design Phase, (*Figure 96*), and a Variation Design Phase. *(Figure 97)*.



JAM Re-Engineering Design Algorithm - Nominal Design Phase *Fig. 96*

6.2.1 The Nominal Design Phase
(With reference to *Figure 96*).

6.2.1.1 Customer Requirements
The first step in re-engineering design is to determine the customers' requirements. These are most likely to be expressed in simple terms; stating a need to be more competitive, reduce assembly time, a wish to take advantage of modern technology, a reduction in labour costs, the use of unskilled labour. (VOC – Section 5.4.1).

6.2.1.2 Analysis of Problem
The IPD team work together in analysing the Customer Requirements and interpreting them as production characteristics expressed in explicit engineering terminology, leading to the development of a re-engineering specification. (Section 5.4.1).

6.2.1.3 Statement of Problem
The specification comprehensively and formally lists the objectives and restraints that apply to the product re-engineering. (Section 5.4.2). It can form a legal contract between customer and supplier.

6.2.1.4 PKC Recognition
Identify high-level PKCs, (Section 5.5), in IPD team brainstorming sessions through the analysis and comparison of;
1) Customers' opinion – Listen to the customers' opinion of the product's function and purpose.
2) Existing tooling – Analyse existing assembly tooling and establish which product features are used to control the assembly.
3) Product function – The IPD team must further investigate the product's function and establish any relationships to fitted sub-assemblies or to a main assembly.

6.2.1.5 Assembly Concept Generation
Conventional product decomposition will show the relationship between parts and help to identify families of parts that can be integrated into a monolithic component.
The IPD team members should then work independently and, with reference to the re-engineering specification, the PKCs, and the Enabling Technologies Database, each aiming to produce two alternative concepts designed to establish the PKCs on assembly. Input from the Enabling Technologies Database will encourage lateral thinking and may result in imaginative leaps in assembly concepts.

6.2.1.6 Selection of Best Concept
The members of the IPD next meet as a team and present their conceptual ideas for team evaluation, analysis and development. The best two concepts are selected for further development; based on the criteria of practicality, efficiency, manufacturing requirements, outline costings and risk assessment,

6.2.1.7 Datum Flow Chains
For the two selected concepts the IPD team can now draw the DFCs which are the graphical representations of the mate relationships between assembled parts, fixtures, and other tooling. (Section 5.10).

6.2.1.8 AKC Recognition

Use the DFC diagrams to identify the AKCs for each concept and to determine which, if any, of the AKCs are delivered directly by the manufacturing processes. (Section 5.5).

6.2.1.9 Featurised Datum Flow Chains

The DFCs are now populated with features selected from the Features Library. The features have the role of traditional hard tooling and can be selected to hold parts, locate parts, guide cutting tools, and be reference features. (Section 5.8). The assembly features are the actual mates between parts, and it is the summation of the dimensional and geometric errors of these mates that add up to the total error of an assembly.

A realistic estimation of the feature errors can be obtained by referring to the Six Sigma data listed in the processes capability database.

If a database does not exist, then published tables of generalised processes capabilities can be referenced. (Section 4.12.4 and Section 7.3). This will allow a comparison to be made of different concepts, but will not establish whether the PKCs can be satisfied.

The feedback arrow, (*Figure 96*), indicates the need to confirm that the mate relationships are satisfied and that the AKCs will be under control. The feed-forward arrow indicates that once these are confirmed the FDFCs can be evaluated.

6.2.1.10 FDFC Evaluation

Count the number of links entering each box and confirm that all links are kinematically restrained. A concept identified with over-restrained or under-restrained links needs further development before continuing on to the Variation Design Phase.

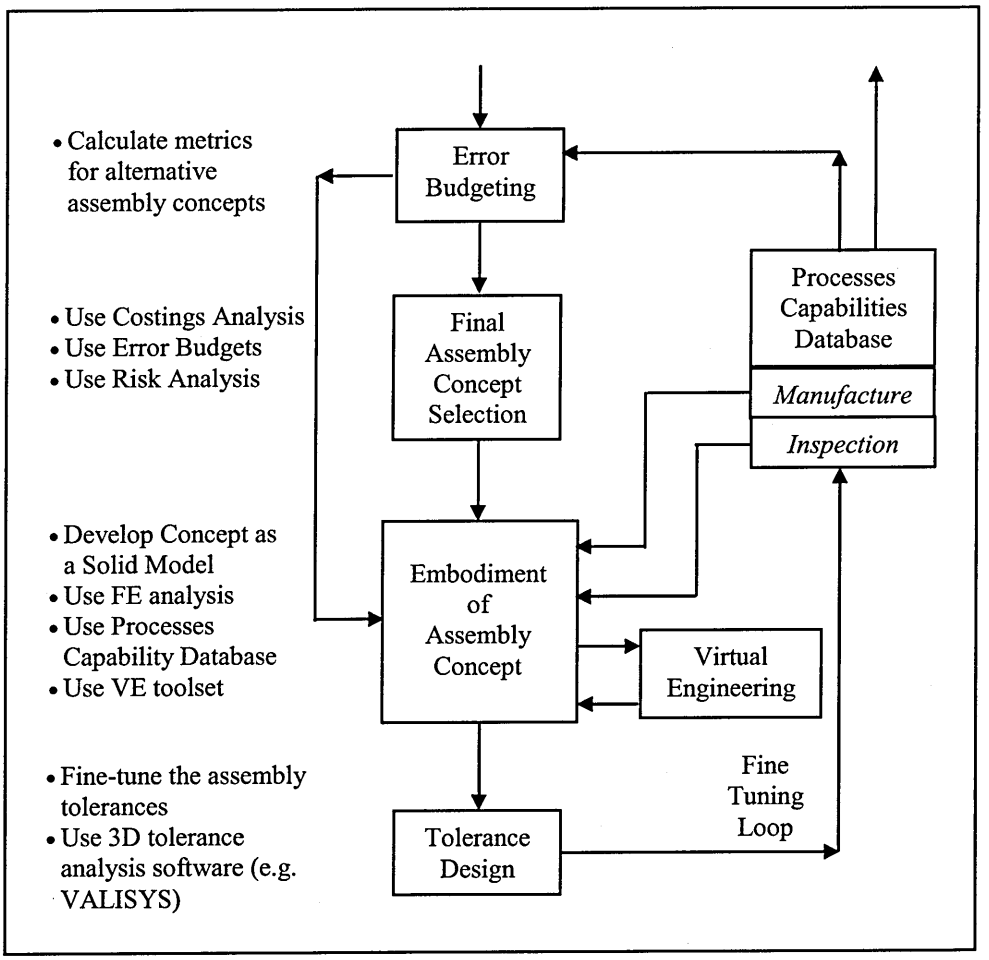
6.2.2 The Variation Design Phase

(With reference to *Figure 97*).

The Variation Design Phase is iterative where first, the efficiencies of the alternative assembly concepts are established and compared, secondly, the best assembly concept is identified, and thirdly, the tolerances are fine-tuned to ensure a robust assembly strategy.

6.2.2.1 Error Budgeting

When re-engineering an old and well established product a lot of the original 'Concept of Form', (Section 5.6, and Section 6.1.1.2), design data will have been lost, but the desired quality of the end-product will have been embedded into the dedicated tooling, (Section 1.2). Therefore, the tooling drawings will provide sufficient dimensional and tolerancing information and will be more reliable than the part drawings which may have been subject to blanket tolerancing, (Section 3.4), and may not be adhered to in practice, (Section 3.5.4). Similarly, when the processes capabilities are unknown the alternative assembly concepts can be compared using the tolerances stated on the engineering or tooling drawings, (Section 5.11.1). This will not establish that the PKCs can be satisfied, because Six-Sigma processes capabilities data is not being used, but it does allow a valid comparison between new assembly concepts and the existing process.



JAM Re-Engineering Design Algorithm – Variation Design Phase *Fig. 97*

6.2.2.2 Final Assembly Concept Selection

Final selection is based on analysis of expected savings, implementation risks, and by comparing the Reference Target Errors, (Ref.TE), values of the new assembly concepts with that of the existing method, (Section 5.12.1).

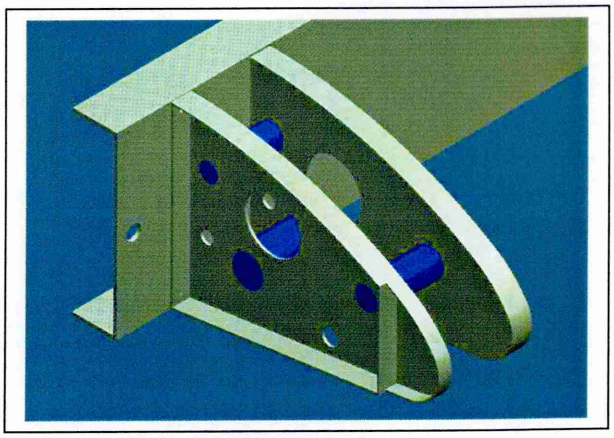
6.2.2.3 Embodiment of Concept

The embodiment of the selected assembly concept involves solid modelling the mating features and links, together with any necessary assembly hard tooling. Ideally, the product already exists as a solid model, in which case it is easy to incorporate the detail design changes. If the product does not already exist as a solid model then a minimal model can be created having just sufficient detail to allow three-dimensional tolerance analysis of the links that establish the PKCs, (*Figure 98*). It should, however, be born in mind that a minimal solid model will not identify other part-dimensions that may need to be modified.

6.2.2.4 Tolerance Design

Use commercial analysis software such as VALISYS/Assembly, (Section 6.1.2.4), to fine tune the assembly and ensure a robust assembly strategy.

Figure 98 is a minimal solid model created for VALISYS analysis of an assembly concept. The degree of minimalism can be assessed by comparing and contrasting with the full solid model *Figure 185.*



Minimal Solid Model *Fig. 98*

7.0 RESULTS - TESTING AND EVALUATION

The JAM design methodology was tested and evaluated by applying it to two 'Case Study' design exercises;

Case Study 1.	Re-engineering the Airbus A320 fixed leading edge
Case Study 2.	Designing a new Airbus A320 fixed leading edge

The design exercises were also useful in helping to identify the necessary links for creating an integrated JAM Methodology, supported by a computer-based design tool. (Chapter 10 – Recommendations for Further Work).

7.1 Case Study 1 – Re-Engineering the Airbus A320 Fixed Leading Edge

The A320 fixed leading edge structure and the present methods of manufacture and assembly are described in Chapter 3.

7.1.1 The Customer Requirements

Airbus UK requested a re-engineering of the fixed leading edge as part of a major project to re-engineer the A320 wing with the purpose of reducing costs, (Section 3.1). Additionally, the use of modern technology is seen as being essential for the company to project the correct image of being progressive and forward thinking in a very competitive market sector.

Along with the request, Airbus UK laid down three specific ground rules;

1. Minimal quantity of 'Product specific tooling'.
2. No re-design that would require re-certification of the structure.
3. No increase in overall weight of the structure.

7.1.2 Analysis of Problem

The fixed leading edge is classed as secondary structure, (Section 3.1.1), but the sub-assembly includes the front spar of the main wing-box, which is quite clearly primary structure, (*Figure 29*). It was agreed with the Airbus designers that to avoid the risk of having to re-certify the structure, the front spar should not be subject to any design modifications that could be construed as stress-raisers. Finite Element modelling had shown that this includes the addition to the spar of most forms of integrated tooling assembly features, (Section 5.8, *Figure 85*), (Ref. 108). This does not mean that integrated tooling can never be used, but that its use for the assembly of stress-critical structure needs very careful consideration. (Ref. 109).

Analysis of the current manufacturing and assembly processes, (Sections 3.2 and 3.3), indicated opportunities to reduce tooling requirements and save weight through part-integration and innovative assembly concepts utilising technological advances made during the twenty plus years since the A320 wing first entered production. It was expected that cost-savings would follow as a result of simplified assembly, but it was

accepted that this could not be quantified until after the final concept selection and completion of the cost model.

7.1.3 Statement of Problem

1. The Airbus A320 fixed leading edge is to be re-engineered as part of a major re-engineering of the wing.
2. The purpose is to reduce the build cost, improve competitiveness, and to enhance the Airbus reputation of being a technologically advanced and forward thinking company.
3. This is to be achieved by following the 'JAM Re-Engineering Design Algorithm'.
4. The three ground rules, (Section 7.1.1), must be adhered to.

7.1.4 PKC Recognition

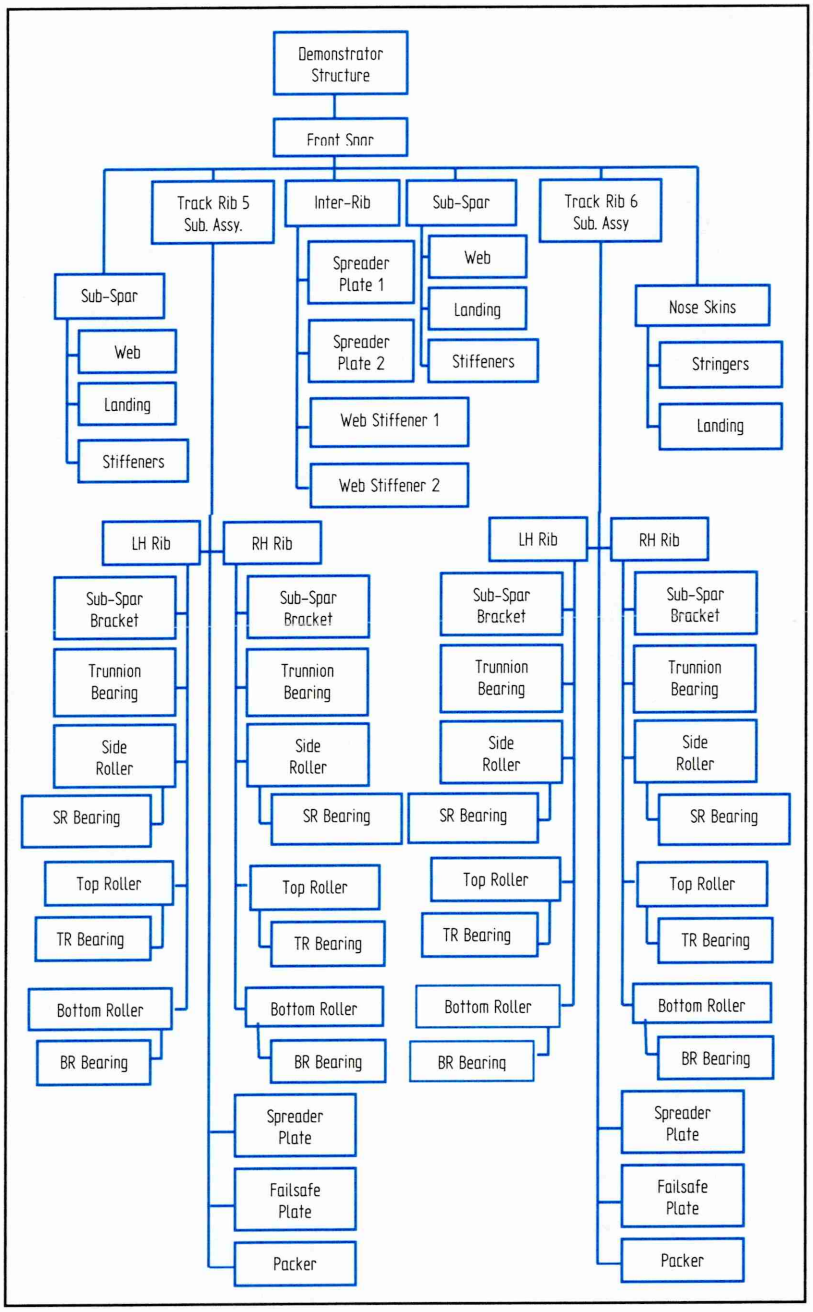
As it proved impossible to assemble all of the necessary people in the same place at the same time, individual interviews were arranged with the assembly cell managers, Airbus designers, and tooling engineers. (Appendix B). As a result, it was determined that the main function of the fixed leading edge is to house the slat tracks and the slat operating mechanisms in an aerodynamic covering, and that therefore the higher level PKCs are;

PKC#1. Slat track geometry
(Described as being very critical with respect to wing lift coefficient, C_L).
PKC#2. Aerodynamic profile
(If it is of poor quality, then the slow speed, high lift performance of the wing will not be achieved).
PKC#3. Appearance
Very important to the customer

The existing concept was virtually disassembled and the resulting Product Decomposition Diagram, (*Figure 99*), used as an aid in the production of the PKC Flow-Down Diagrams, (*Figures 100, 101, 102*), which then facilitated the identification of the lower level PKCs. The lower level PKCs must be achieved for there to be certainty of successfully delivering the higher level PKCs.

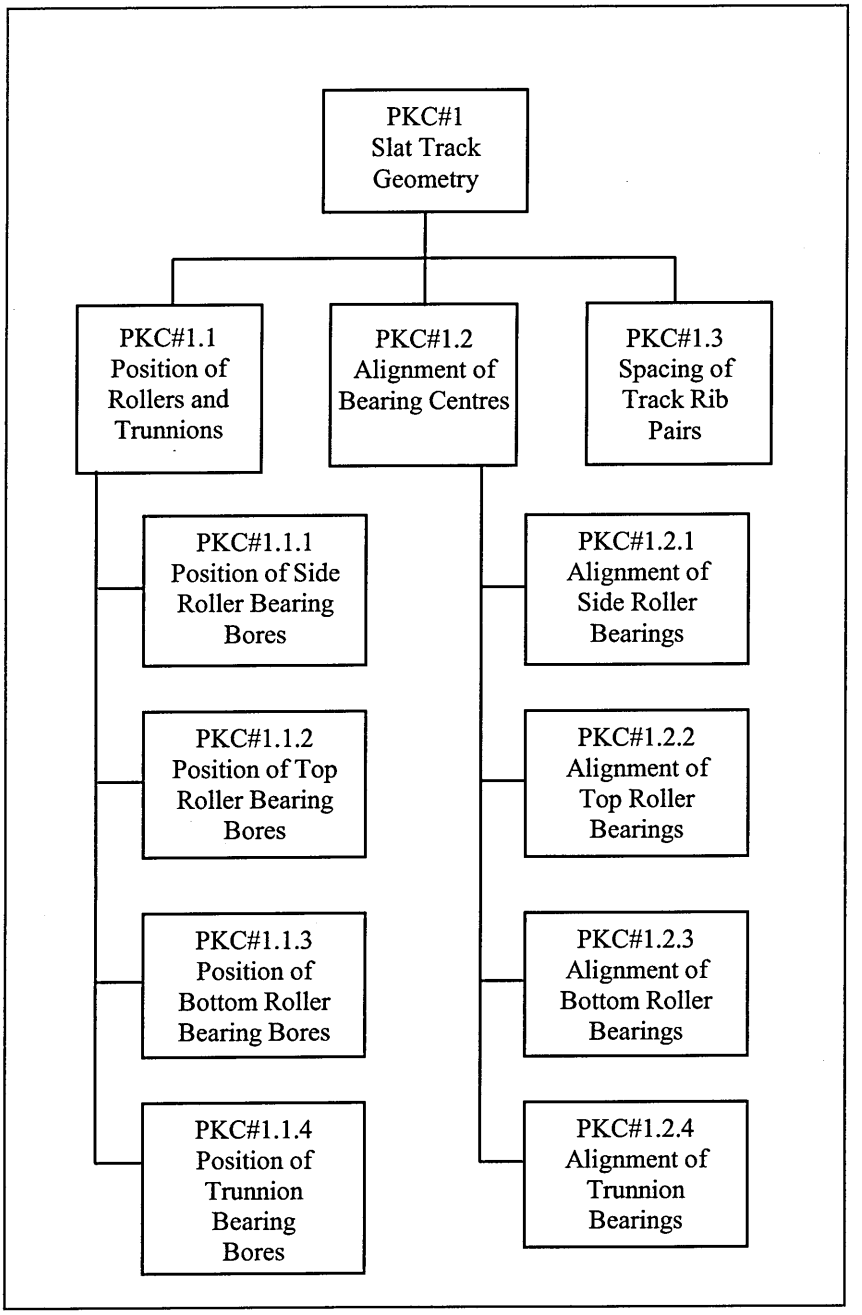
From the PKC Flow-Down Diagrams it is determined that the following lower Product Key Characteristics must be controlled;

PKC#1. The slat track geometry. This flows down to controlling the position of the trunnion and guide roller bearing bores during manufacturing, and to controlling the alignment of the trunnion bearings and the positioning of the track-rib pairs during assembly, (*Figure 100*). Correct alignment of the trunnion bearings ensures the correct alignment of the hinge line, which is important to ensure smooth operation of the slats in-service, and is considered more important than the straightness of the front spar which is allowed to meander off-line by as much as ±1 mm. (Section 3.3.1).



Product Decomposition *Fig. 99*

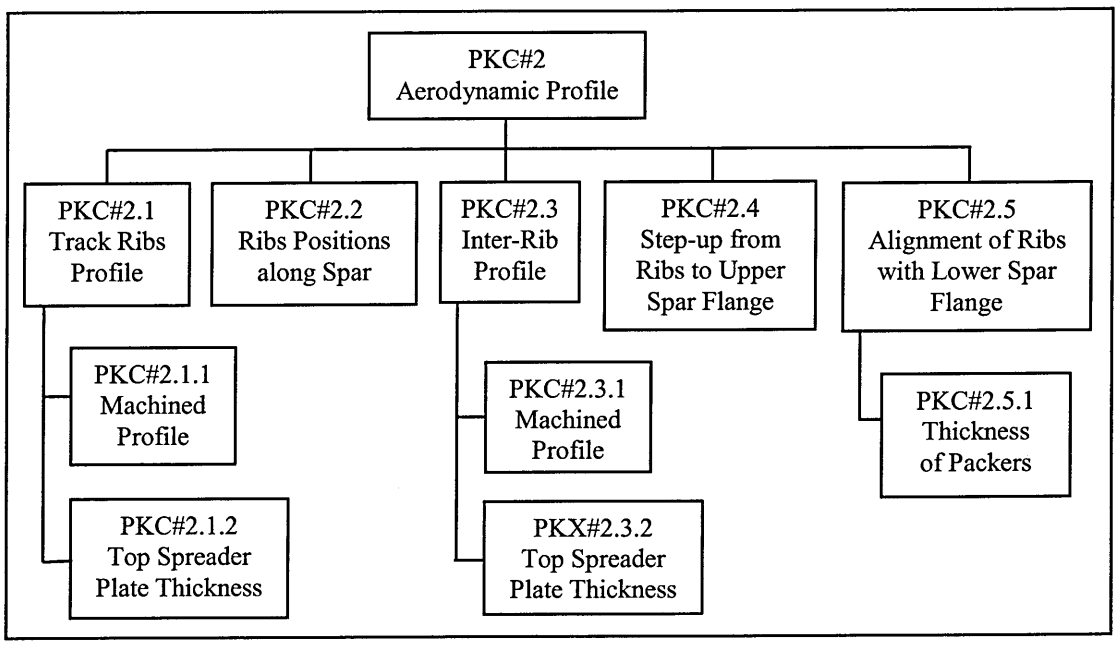
PKC#2. The aerodynamic profile. This flows down to controlling the step up from the top of the ribs to the upper spar flange, (Section 3.1.2), the rib positions and alignment along the spar, and the alignment between the lower aerodynamic surface of the ribs and the lower spar flange during assembly, (Section 3.3.3 and Section 3.1.2), and the profile dimensional tolerance of the nose ribs during manufacturing. (*Figure 101*).



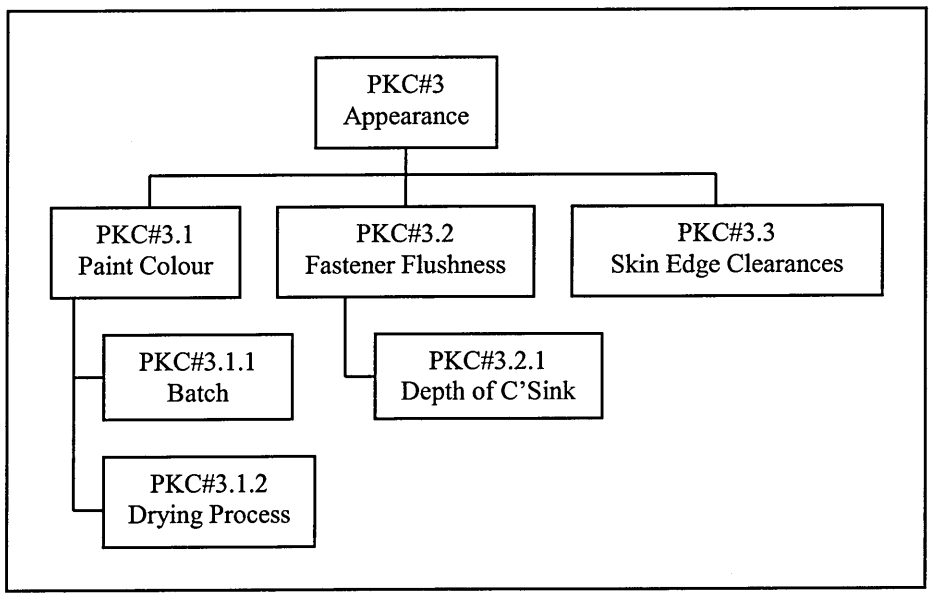
PKC#1 Flow-Down *Fig. 100*

PKC#3. Appearance.

A number of factors are involved in this, including paint shading that can be affected by the type of drying process. However the PKC#3 that must be achieved during part-manufacture and assembly are the edge clearances between the sheet metal D-Nose skin sections, (Section 3.3.2), (*Figure 102*), that are parallel and of the correct width.



PKC#2 Flow-Down *Fig. 101*



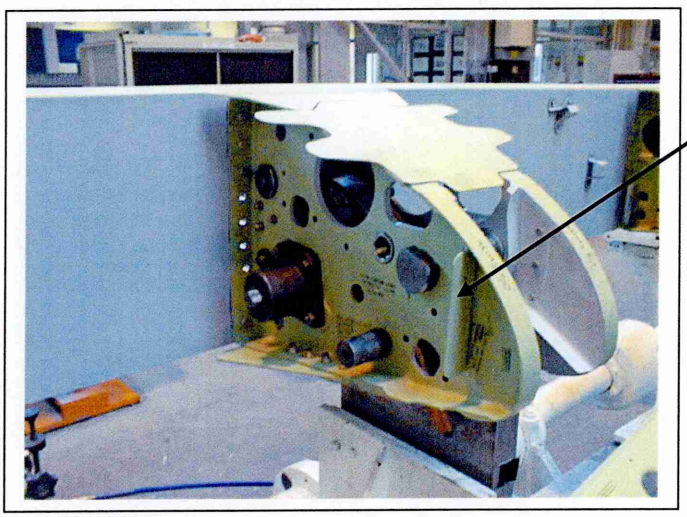
PKC#3 Flow-Down *Fig. 102*

7.1.5 Parts Integration

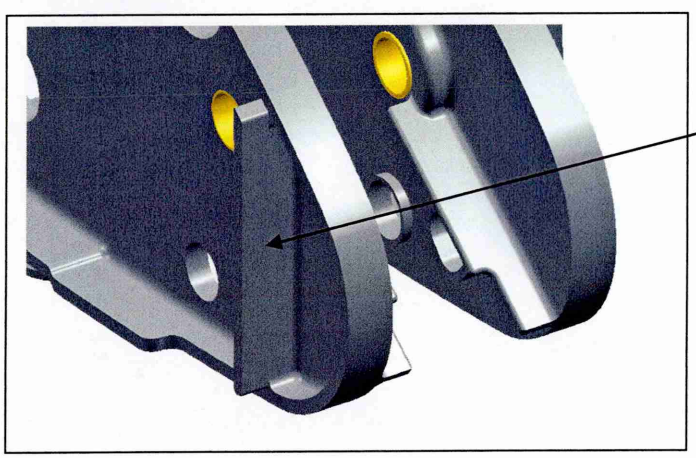
Parts integration was investigated next.

Part integration and, therefore part reduction leads to simplification of the assembly process and to reductions in the number of manufacturing and assembly tools.

After reference to the Enabling Technologies Database, five possibilities were identified;



Sub-Spar Brackets *Fig. 103*



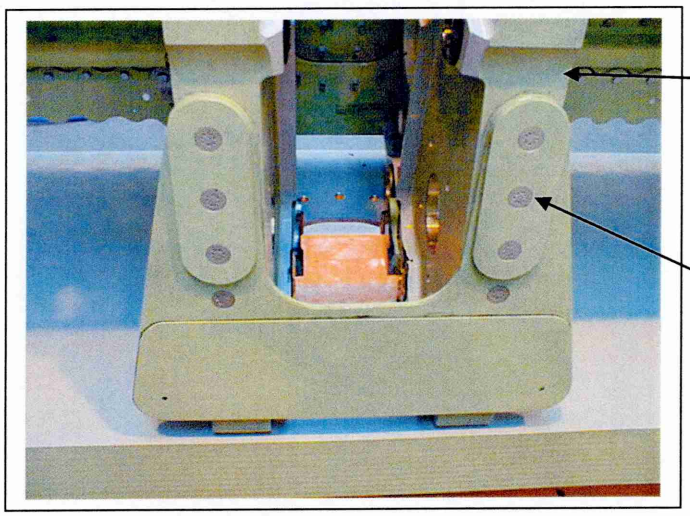
Integrated Sub-Spar Brackets *Fig. 104*

1) Integration of the Sub-Spar Brackets with the Track Ribs.

The existing track-rib blank has sufficient thickness to accommodate this modification which will result in savings in assembly time, cost, weight, and at least one assembly tool per nose rib. (*Figures 103 and 104*).

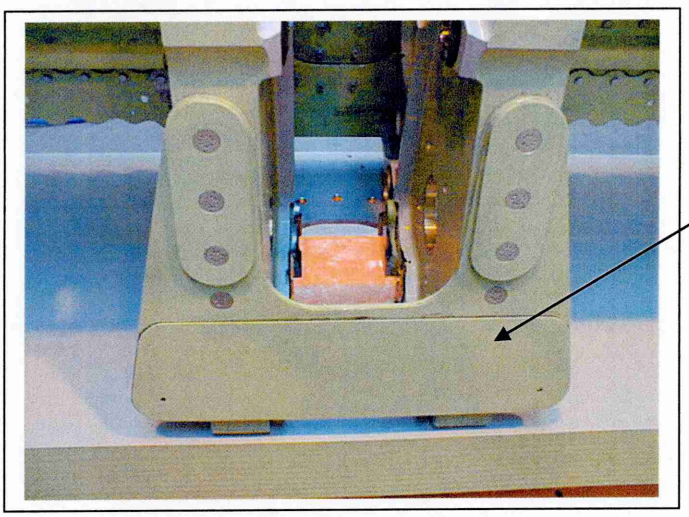
2) Eradication of the Double Packers.

The external sub-contractor assembles the track-rib pairs using one thick and one thin packer, (*Figure 105*). It is thought that the original purpose of the packers is to absorb manufacturing and assembly variations but as the same two thicknesses of packers are always used, (Section 3.2.3), and as the assembly cell leaders did not report any problems in this area, it is reasonable to assume that the existing track-ribs manufacturing and assembly processes are adequate and repeatable.



Riveted Packers *Fig. 105*

The packers can, therefore, be designed out by either integrating their thickness into a CNC machined spreader plate, (*Figure 107*), or alternatively by reducing the depth of relief in the ribs. There will be resultant savings in assembly time, weight, cost, and tooling.



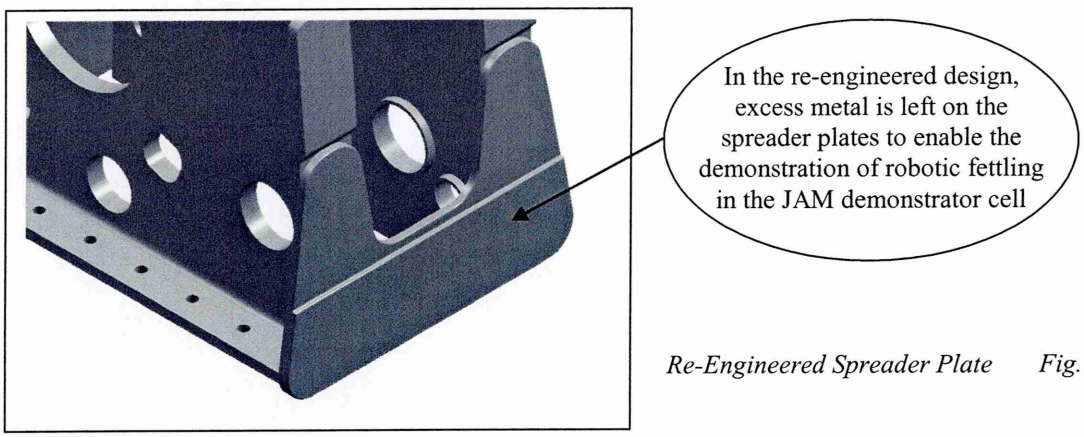
Adhesively Bonded Packer *Fig. 106*

3) Eradication of the Bonded Packers.

The thicknesses of the adhesively bonded packers are determined by inspection after final assembly of the leading edge. Their purpose is to absorb machining and assembly inaccuracies, (Section 3.3.3). It should be possible to eradicate them by;

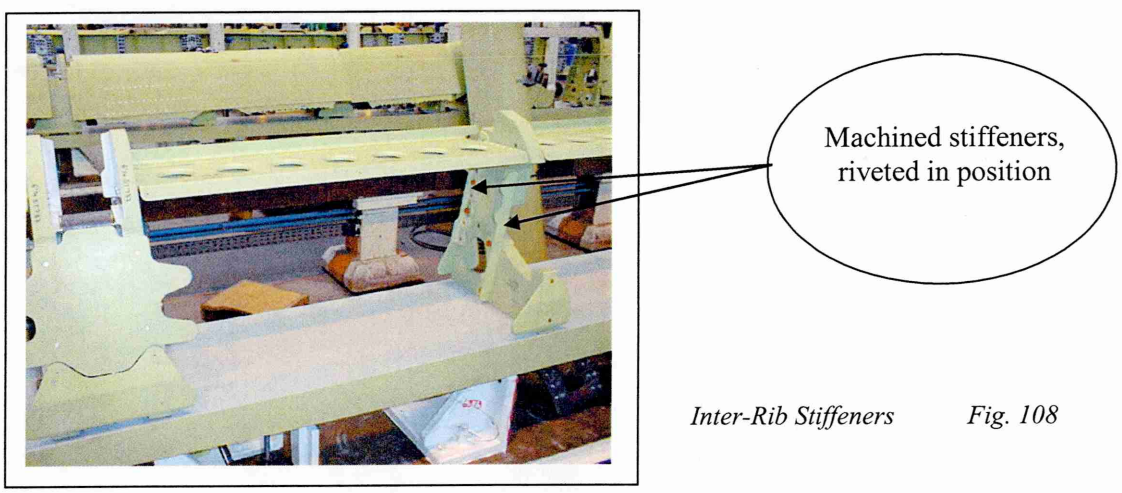
1. By manufacturing ribs to the correct size.
2. By manufacturing spars to the correct size.
3. By ensuring that the spars and ribs are correctly located with reference to each other, (Section 3.5.6).
4. By drilling rib-to-spar fixing holes in the correct positions.

Eradication of the packers will produce savings of assembly time and cost. (*Figure 107*).



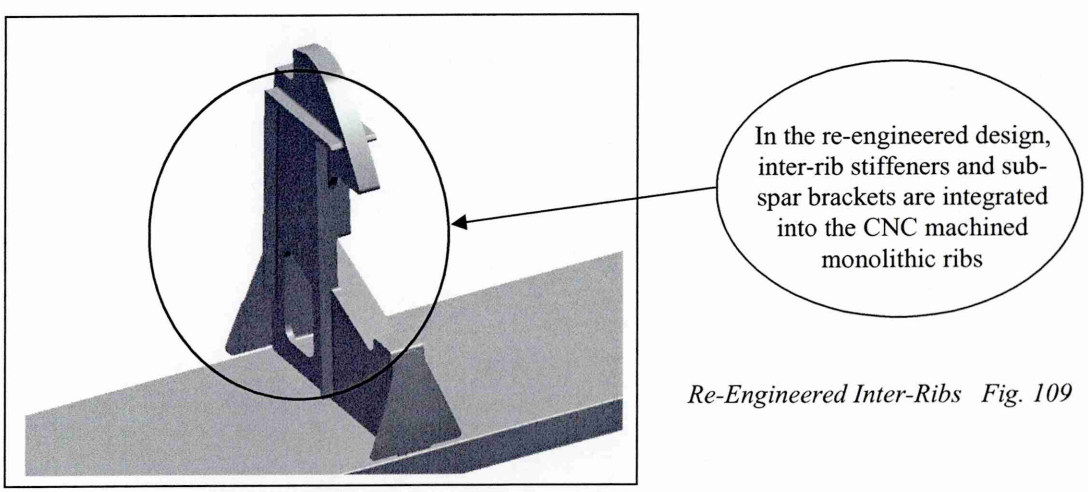
Re-Engineered Spreader Plate *Fig. 107*

4) Integration of the Stiffeners and Sub-Spar Brackets with the Inter-Ribs.



Inter-Rib Stiffeners *Fig. 108*

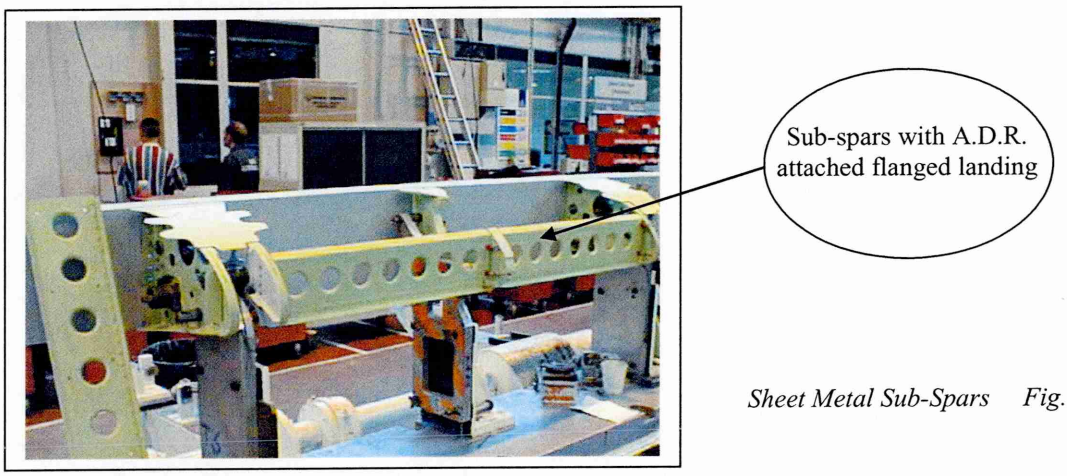
In the re-engineered design, the riveted inter-rib stiffeners, (*Figure 108*), together with the sub-spar brackets, are integrated into a CNC machined monolithic inter-rib. (*Figure 109*).



Re-Engineered Inter-Ribs *Fig. 109*

This will result in savings in assembly time, structural weight, cost, and hard tooling, but a much thicker material blank will be necessary and most of this will end up as swarf. It is, therefore, necessary to ensure that the cost model is able to make a realistic comparison with the existing method.

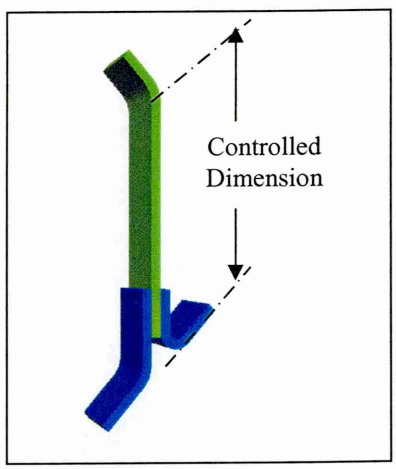
5) Extruded Sub-spars



Sheet Metal Sub-Spars *Fig. 110*

The existing design has press-formed sheet metal sub-spars with flanged landings attached using a manually operated Auto-Drill Riveter, (Section 3.2.6), (*Figure 110*).

This is a conventional aerospace design technique that avoids the need to manufacture sheet metal components to exacting tolerances. The controlled dimension shown in *Figure 111* is achieved by clamping the three component parts in an assembly tool and pilot drilling the fastener holes.

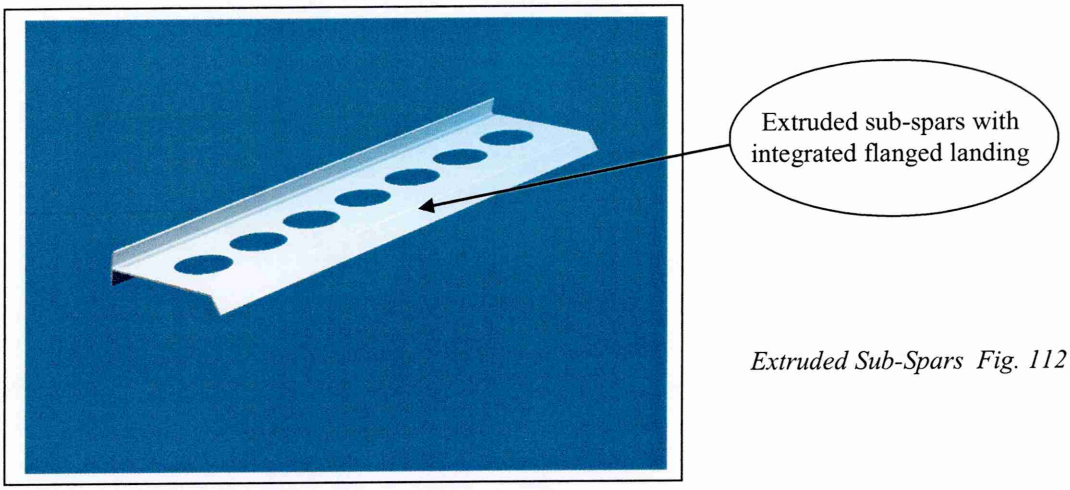


Controlled Dimension *Fig. 111*

The re-engineered design solves this problem with the proposed use of extruded sections, (*Figure 112*).

The sub-spars are classed as secondary structure spacing the nose ribs apart and supporting the nose skins. In practice they also protect the primary structure of the front spar from bird strike damage during take-off and landing. Because of this, it was with some reticence that the designers agreed in principle to the use of extruded sections and that agreement is subject to obtaining acceptable results from a programme of mechanical testing.

The extrusion dies are surprisingly cheap and the extrusions are cheap, but the mills have requirements for a minimum order quantity. This factor could produce problems with bonded storage space and it will be a move away from the economies of JIT.



Extruded Sub-Spars Fig. 112

7.1.6 Alternative Assembly Concepts

Each team member was asked to work independently in developing ideas and to then bring one or two outline assembly concepts to an IPD team, 'Assembly Concept Meeting'. The team eventually ended up discussing and further developing a total of seven alternative assembly concepts;

1. Building from the skin inwards – envelope tooling,
2. Building directly onto the spar,
3. Building on the track-rib hinge line,
4. Using the bleed air duct as 'flyaway tooling',
5. Using re-configurable modular tooling,
6. Building with modular sub-assemblies,
7. Building directly onto the wing-box.

Concept 1 Building From the Skin Inwards – Envelope Tooling,

Envelope tooling involves building aerostructure from the skins inwards. The method was developed by Fairey Aviation in the late 1940s and early 1950s in an attempt to achieve the surface quality required for high-speed flight, (Refs. 110 and 111).

This method of assembly ensures that the structure is built to the 'form profile' – as intended by the aerodynamicist.

Build Cycle:

The fixed leading edge is built vertically upwards from the skins.

Pogo Sticks ⇒ Skin ⇒ Stringers ⇒ Track Ribs ⇒ Inter-Ribs ⇒ Sub-Spars ⇒ (Spar ⇒ Tool)



Pogo Stick Fixturing Fig. 113

Build Sequence:

- The skins are held in position by a matrix of re-configurable, CNC programmable 'Pogo Sticks', (Ref. 57 and Section 4.8), (*Figure 113*), mounted in front of a travelling CNC drill/milling head. The Pogo Sticks are fitted with vacuum cup end-effectors. Photogrammetry, (Section 4.10.2), or alternatively, touch probes are used to establish the precise position and alignment of the skins causing a three-dimensional co-ordinate shift of the machining software. Minor profile errors in the skins are also measured and corrected at this stage by automatic adjustments of the Pogo Sticks.
- The skins are fixtured as a single entity. A machine mounted routing cutter is used to machine the slots dividing the skin into shorter lengths to cope with wing flexure. Any skin profiling is also done at this stage.
- De-burr the machined edges, then load airbrush from tool carousel and spray chromate primer on bare edges.
- Drill location holes for stringers.
- Position stringers on skins using pre-drilled location holes and temporarily fasten using Cleco pins.
- Fasten stringers to skins using a machine mounted ADR head, (Auto Drill Riveter), retrieved from the tool change carousel. Access for the anvil is facilitated by the ability of the individual Pogo sticks to retract, as necessary, under CNC control.
- Measure and check skin positions and profiles, and correct as necessary through minor adjustments of the Pogo Sticks.
- Drill location holes for ribs.
- Manually offer up ribs and temporarily fasten using Cleco pins in the pre-drilled location holes.
- Measure and check rib positions and alignment, and correct as necessary.
- Fasten ribs to skins using a machine mounted ADR head, (Auto Drill Riveter), retrieved from the tool change carousel.
- Manually offer-up sub-spars and temporarily fasten using Cleco pins in pre-drilled location holes.
- Fasten sub-spars to skins using a machine mounted ADR head, (Auto Drill Riveter), retrieved from the tool change carousel.
- Locate spar using pre-drilled holes and temporary fasteners.
- Drill remaining holes, de-burr, and permanently fasten spar to ribs.

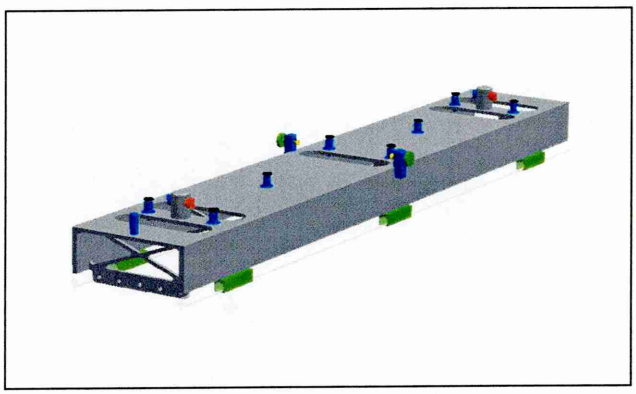
The spar must be fitted with a temporary backing structure to prevent flexure and twisting. The backing structure will be equipped with lifting eyes for suspension from a gantry.

Concept 2 Building Directly Onto the Spar

The spar is a monolithic CNC machined component. It must be made to sufficient accuracy to be the base component of the fixed leading edge build process. King holes, pilot holes, and assembly features will be machined in at the CNC stage.

The machined spar is very flexible and can also warp following machining and shot peening. To overcome these problems it is envisaged that a simple support, 'Build Tool', will be needed to provide a base structure. The 'Build Tool' is the only hard

tooling needed and will have cut-outs to allow through drilling and ease of assembly. *(Figure 114).*



Build Tool for Concept 2 Fig. 114

(See Appendix E for a full description of the Build-Tool)

Build Cycle:
The fixed leading edge will be built vertically upwards from the spar, allowing gravity to be an aid rather than a hindrance.

Build Tool ⇒ Spar ⇒ Track Ribs ⇒ Inter-Ribs ⇒ Sub-Spars ⇒ Skins

Build Sequence:

- Following normal CNC machining and shot peening, the spar is transferred to the assembly cell and located on the build tool.
- The spar is horizontal and the build is vertically upwards.
- Track ribs are located at the pre-drilled holes, or location features, and temporarily fastened to allow slat-track hinge line alignment checks before final fixing.
- Permanently fasten track ribs.
- Inter-ribs are located at the pre-drilled holes, or location features, and temporarily fastened to allow alignment checks before final fixing.
- Permanently fasten inter-ribs.
- Sub-spars are located to the pre-fitted and pre-drilled brackets and temporarily fastened using Cleco pins in the pre-drilled location holes.
- Drill out rivet holes to full size, de-burr, and permanently fasten sub-spars in position.
- Skins are located using Cleco pins in the pre-drilled location holes. Pull down using strap clamps off the spar support fixture.
- Drill rivet holes out to full size, de-burr and permanently attach skins.

Concept 3 Building On the Track-Rib Hinge Line

Like the current method of assembly, this concept uses the slat-track hinge-line to control the build process.

The track-rib pairs are manufactured and assembled as at present. However, the dummy rollers used to assemble the track-rib pairs are re-designed to allow the fitting of hollow spacer-bars to set the precise distance between each track-rib pair. Locking of the bars to the dummy rollers is achieved through bayonet connectors that are pneumatically or hydraulically powered-on to pull tight and lock, and powered-off to release and retract

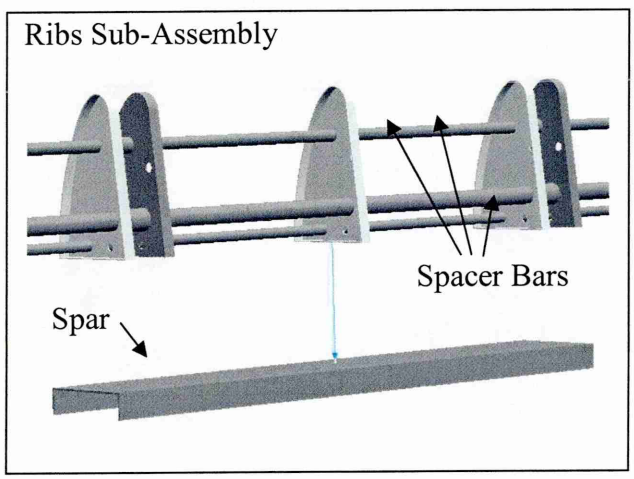
into the spacer-bar to facilitate removal. The dummy rollers carry the female fitting and the spacer-bars carry the retractable male fitting. Minor design modifications to the inter-ribs would allow them to be included in the sub-assembly.

The spacer-bars are type specific, but the bayonet end fittings may be common to a range of similar sub-assemblies.

As before the spar is fitted with a lightweight stiffening/tooling structure. The tooling structure can be fitted with hand screws to enable minor adjustment of the spar to the upper aerodynamic surface of the track ribs.

Build Cycle:
The fixed leading edge will be built vertically upwards and downwards from the slat-track hinge line.

(Spacer Bars ⇒ Track Ribs ⇒ Inter-Ribs) ⇒ (Spar ⇒ Tool) ⇒ Sub-Spars ⇒ Skins



Concept 3 Fig. 115

Build Sequence:

- After the normal manufacturing processes, the spar is transferred to the leading edge assembly cell and fitted to the build tool.
- The spar is horizontal and the build is vertical.
- Assemble the track ribs and the modified inter-ribs to the spacer-bars.
- Lower the ribs sub-assembly to the spar. *(Figure 115).*
- Locate to King Holes and adjust to correctly align with spar.
- Clamp and drill off pilot holes from pilot holes in ribs.
- Remove rib sub-assembly.
- Drill out full size and de-burr location holes.
- Refit and permanently fasten ribs.
- Sub-spars are located to the pre-fitted and pre-drilled brackets and temporarily fastened using Cleco pins in the pre-drilled location holes.
- Drill out rivet holes to full size, de-burr, and permanently fasten sub-spars in position.
- Skins are located using Cleco pins in the pre-drilled location holes. Pull down using strap clamps off the spar support fixture.
- Drill rivet holes out to full size, de-burr and permanently attach skins.

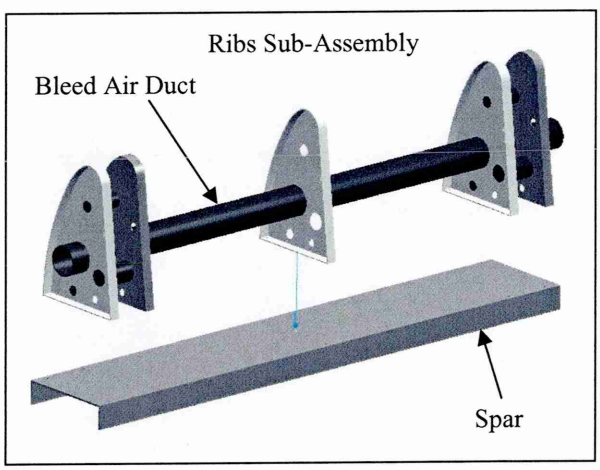
Concept 4 Using the Bleed Air Duct as 'Flyaway Tooling'

This concept requires that the bleed air duct be redesigned to run the length of the fixed leading edge and have sufficient stiffness and quality to be the main tooling feature. The following build cycle assumes a carbon fibre pultruded tube with stepped changes of diameter to provide locations for the track rib pairs. The diameter of the tube reduces from the wing root to the tip.

As before the spar is fitted with a lightweight stiffening/tooling structure.

Build Cycle:
The fixed leading edge will be built vertically downwards and upwards from the bleed air duct.

(Track Ribs + Inter-Ribs ⇒ Bleed Air Duct) ⇒ (Spar ⇒ Tool) ⇒ Sub-Spars ⇒ Skins



Concept 4 *Fig. 116*

Build Sequence:

- Assemble the track rib pairs and the inter-ribs to the bleed air duct.
- Following CNC machining and shot peening, refit the spar to the tooling structure and transfer to the leading edge assembly cell.
- The spar is horizontal and the build is vertically upwards.
- Lower the bleed air duct/ribs sub-assembly onto the spar. *(Figure 116).*
- Track ribs and inter-ribs are located at the pre-drilled holes, or location features, and temporarily fastened to allow alignment checks before final fixing.
- Permanently fasten all ribs.
- Sub-spars are located to the pre-fitted and pre-drilled brackets and temporarily fastened using Cleco pins in the pre-drilled location holes.
- Drill out rivet holes to full size, de-burr, and permanently fasten sub-spars in position.
- Skins are located using Cleco pins in the pre-drilled location holes. Pull down using strap clamps off the spar support fixture.
- Drill rivet holes out to full size, de-burr and permanently attach skins.

Concept 5 Using Re-Configurable Modular Tooling

The assembly cell for Concept 5 is constructed using off-the-shelf, extruded aluminium, modular tooling elements, (*Figure 117*).

This concept is particularly suited to one-off designs and limited production runs. It is a variation on Concept 2, 'Building on the Spar'.

High precision is not built into the cell. Instead, the part locations are fitted with knuckle joints. These are manually adjusted during each build cycle to ensure compliance with the design drawings. Laser trackers provide in-process measurements.



Re-Configurable Modular Tooling *Fig. 117*

Build Cycle:
The fixed leading edge is built vertically upwards from the spar.

(Spar ⇒ Tool) ⇒ Track Rib/Inter-Rib ⇒ Sub-Spars ⇒ Skins

Build Sequence:

- After normal CNC machining and shot peening, the spar is refitted to the tooling fixture and transferred to the leading edge assembly cell.
- The spar is horizontal and the build is vertically upwards.
- Starting outboard, individual track rib pairs and inter-ribs are located to the reconfigurable tooling elements and positioned to comply with the in-process measurements by minor adjustments of the knuckle joints.
- Spot drill position of fixing holes and remove the track-rib pair, or inter-rib.
- Drill and de-burr location holes.
- Permanently fasten.
- Repeat for all the ribs, sequentially working towards the wing root.
- Sub-spars are located to the pre-fitted and pre-drilled brackets and temporarily fastened using Cleco pins in the pre-drilled location holes.
- Drill out rivet holes to full size, de-burr, and permanently fasten sub-spars in position.

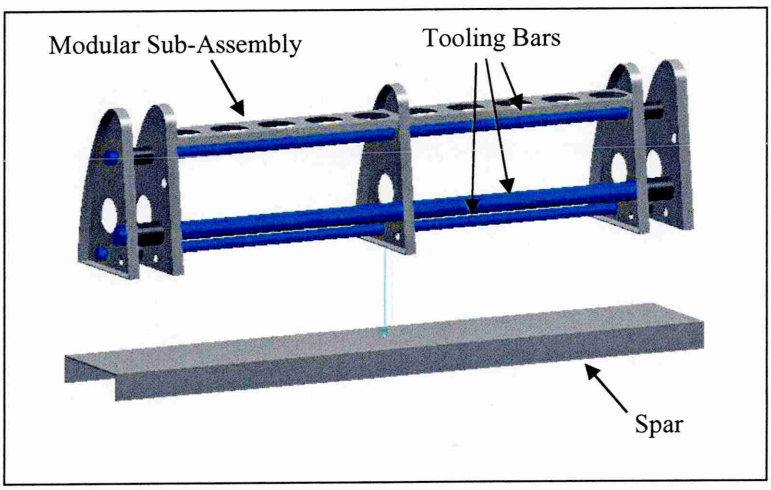
- Skins are located using Cleco pins in the pre-drilled location holes. Pull down using strap clamps off the spar support fixture.
- Drill rivet holes out to full size, de-burr and permanently attach skins.

Concept 6 Building from Modular Sub-Assemblies

This concept involves building the fixed leading edge as a series of modular sub-assemblies. Each sub-assembly would consist of two track rib pairs, an inter-rib and two sub-spars, correctly aligned and spaced by tooling bars. (*Figure 118*).

Build Cycle:
This build cycle is based on Concept 3, 'Building on the track rib hinge line'.

$$(\text{Spacer Bars} \Rightarrow \text{Track Ribs} \Rightarrow \text{Inter-Ribs} \Rightarrow \text{Sub-Spars})^{n}$$
$$\Rightarrow (\text{Spar} \Rightarrow \text{Tool}) \Rightarrow \text{Sub-Spars} \Rightarrow \text{Skins}$$



Concept 6 *Fig. 118*

Build Sequence:

- After the normal manufacturing processes, the spar is transferred to the leading edge assembly cell and fitted to the build tool. The spar is horizontal and the build is vertically upwards.
- Using the spacer-bars build the modular sub-assemblies. These would consist of two track rib pairs an inter-rib and two sub spars.
- Working from the outboard end, lower the first modular sub-assembly to the spar.
- Adjust spar as necessary in the Y-axis and spot drill position of fixing holes.
- Remove modular sub-assembly.
- Drill and de-burr location holes.
- Refit and permanently fasten modular sub-assembly.
- Repeat for the other modular sub-assemblies.
- Fit the in-fill inter-ribs.
- Fit the remaining sub-spars to the pre-fitted and pre-drilled brackets and temporarily fastened using Cleco pins in the pre-drilled location holes.
- Drill out rivet holes to full size, de-burr, and permanently fasten sub-spars in position.

- Skins are located using Cleco pins in the pre-drilled location holes. Pull down using strap clamps off the spar support fixture.
- Drill rivet holes out to full size, de-burr and permanently attach skins.

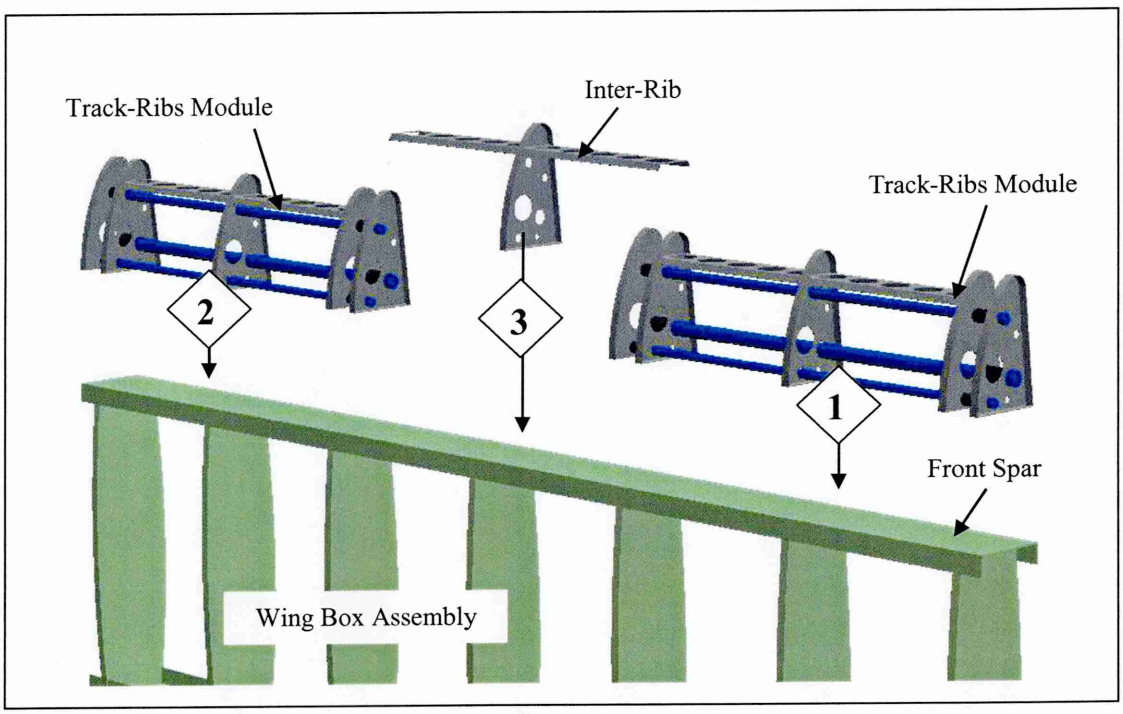
Concept 7 Building Directly Onto the Wing Box

This concept assumes that the spar is built into the wing box primary structure, (*Figure 119*), and is no longer included in the fixed leading edge secondary structure. This is probably most likely if the wing box is a composite structure and the, more commonly damaged, fixed leading edge is of light alloy construction.

Alternatives Schemes for Building on the Wing Box

Envelope assembly as in Concept 1
Build on the spar as in Concept 2
Build on the track rib hinge line as in Concept 3
Build on the bleed air duct as in Concept 4
Build from modular sub-assemblies as in Concept 6

The last three are the more practical.



Concept 7 *Fig. 119*

The front spar is built into the wing box. To ensure that the key characteristics are achieved, it may be necessary to use liquid shim at the spar/rib interface and to have a fettling allowance on the lower aerodynamic surfaces of the nose ribs.

Build Sequence:

This build cycle is based on Concept 6, 'Building from Modular Sub-Assemblies'.

(Spacer Bars ⇒ Track Ribs ⇒ Inter-Ribs⇒ Sub-Spars)^n
⇒ (Inter-Ribs ⇒ Sub-Spars)^n ⇒ Wing Box ⇒ Skins

Build Process:

- The wing-box is vertical and the build is vertically upwards. (*Figure 119*).
- Build the track-ribs modular sub-assemblies as for Concept 6. (*Figure 118*).
- Build the inter-rib modular sub-assemblies as for Concept 6.
- Working from the outboard end, lower the first tracks-rib module onto the spar.
- Drill fastener holes through, then remove the modular sub-assembly and de-burr.
- Use liquid shim as necessary at the ribs/spar interface.
- Refit and permanently fasten the first tracks-rib module onto the spar.
- Repeat for the second tracks-rib module.
- Fit the in-between inter-rib module.
- Repeat for the remaining modular sub-assemblies.
- Fettle to produce a smooth transition between the lower aerodynamic surfaces of the nose-ribs and the spar.
- Nose skins are initially located using Cleco pins in the pre-drilled King Holes. Align with spar and pull down using strap clamps off the spar.
- Drill rivet holes out to full size, de-burr and permanently attach skins.

7.1.7 Selection of the Two Best Concepts

After developing outline assembly processes and considering build cycles for all seven alternative concepts, the two best concepts were then selected, based on the criteria of practicality, efficiency, manufacturing requirements, outline costings and risk assessment. (Section 6.2.1.6).

The evaluation of the criteria was aided by the knowledge acquired during the industrial based research programme, (Section 3), from researching the enabling technologies, (Section 4), and from the interviews with skilled and knowledgeable practitioners, (Appendix B).

For example, despite recognising that Concept 7, building the fixed leading edge directly onto the wing-box using modular sub-assemblies, (Concept 6), would eradicate the need for the major assembly tool described in Section 3.3.1, (*Figure 43*), it was known that this would be unacceptable to Airbus because of the extra time that the wing would be occupying a Stage 01 final assembly tool, (*Figures 51* and *52*), and the need for globalisation of manufacture as part of the overall sales package.

Concept 1, envelope assembly, was dismissed because the nose skins are only partially wrapped under the leading edge and would not provide sufficient support for the rest of the structure. Additionally, rough estimates of the cost of the re-configurable tooling cell indicated that with the uncertainty of success this would be too great a financial risk.

The use of light weight modular tooling, (Concept 5), is thought to be ideal for one-offs and limited production runs but there is no convincing proof of its durability over a long time period.

Concept 4 in which the bleed air duct is used as flyaway tooling is interesting but impractical for this re-engineering project. In reality the duct is not straight, having a number of cranks along its length, and it would require major design analysis to ensure that it has sufficient strength to be used in this manner.

It was envisaged that by building on the track rib hinge line, Concept 3, the delivery of the hinge line PKC, (Section 7.1.4), would be guaranteed, but the use of spacer-bars to lock and locate the track-rib pairs and the inter-ribs needs careful investigation to ensure that there is sufficient access for completing the assembly. It is also doubtful as to whether the complete sub-assembly would have sufficient longitudinal and axial stiffness to prevent sagging and twisting. However, there is a fall-back option of using several smaller sub-assemblies, such as is shown in *Figure 119*, to mitigate this risk of failure. Therefore Concept 3 was selected as the first of the two JAM assembly concepts for comparison and evaluation.

Building on the spar, Concept 2, was the second concept to be selected, although it was realised that without the existing assembly tooling, (Section 1.2 and Section 3.5.7), it would be important to establish and then control the manufacture of key part-features. With this proviso, Concept 2, appeared very practicable, required even less hard tooling than Concept 3, and had a lower, perceived, risk of failure.

7.1.8 Selection of the Best Concept

The aim of the selection process is to identify an assembly process that uses less tooling than the existing process whilst also being able to produce structure of equivalent or greater quality. This is achieved by creating and comparing the error budgets, (*Tables 10 and 11*), of the two selected concepts with that of the existing concept. (*Table 9*).

For the existing process the required quality is resident in the tooling and is not represented by the sum of the individual parts. Therefore the error budget for the existing process, selectively, uses a combination of tooling tolerances, assembly tolerances, and part-manufacturing tolerances. The error budgets for the alternative concepts utilise generalised manufacturing tolerances obtained from published papers and tables. (See Section 7.3), (Refs. 42, 112, 113, 114, 115 and 116). Using this data the error budgets will not establish that the assembly processes can achieve the PKCs but they do enable realistic comparisons to be made between alternative assembly schemes.

7.1.8.1 FDFC Evaluation

Evaluation of the Featurised Datum Flow Chains, (Section 5.11), provides an estimate of the ability of a specific assembly concept to satisfy the KC requirements, (Section 5.11.2). Additionally, counting the degrees of freedom entering a box gives an indication as to whether the part is over, under, or correctly restrained, (Section 5.11.2).

Using a simplification of Randolph Odi's method, (Section 5.12 and Ref. 104), the FDFC links establishing PKC#1 are next evaluated to provide comparative error budgeting metrics, (*Table 12*).

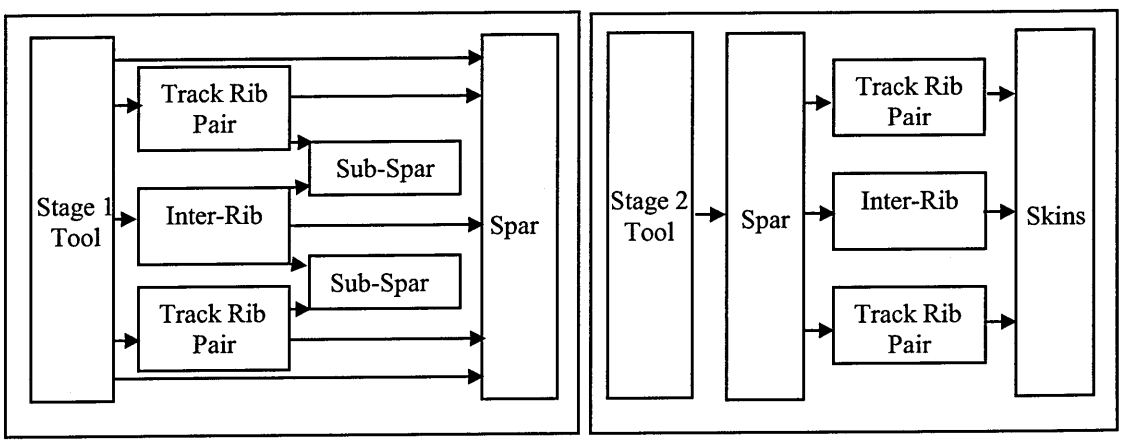
7.1.8.1.1 Current Method of Assembly

Build Cycle

(Build Tool ⇒ Spar) ⇒ (Build Tool ⇒ Track Ribs) ⇒ (Build Tool ⇒ Inter-Ribs) ⇒ Sub-Spars ⇒ Skins

Datum Flow Chains *(Figure 120)*

See Section 5.10 for an explanation of DFCs and Section 3.3 for a description of the current assembly process.



a) Stage 1 *b) Stage 2*

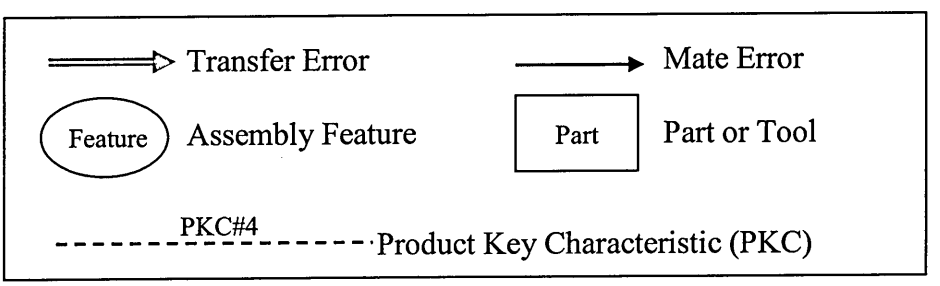
DFC Diagrams for the Current Method of Assembly *Fig. 120*

Featurised Datum Flow Chains

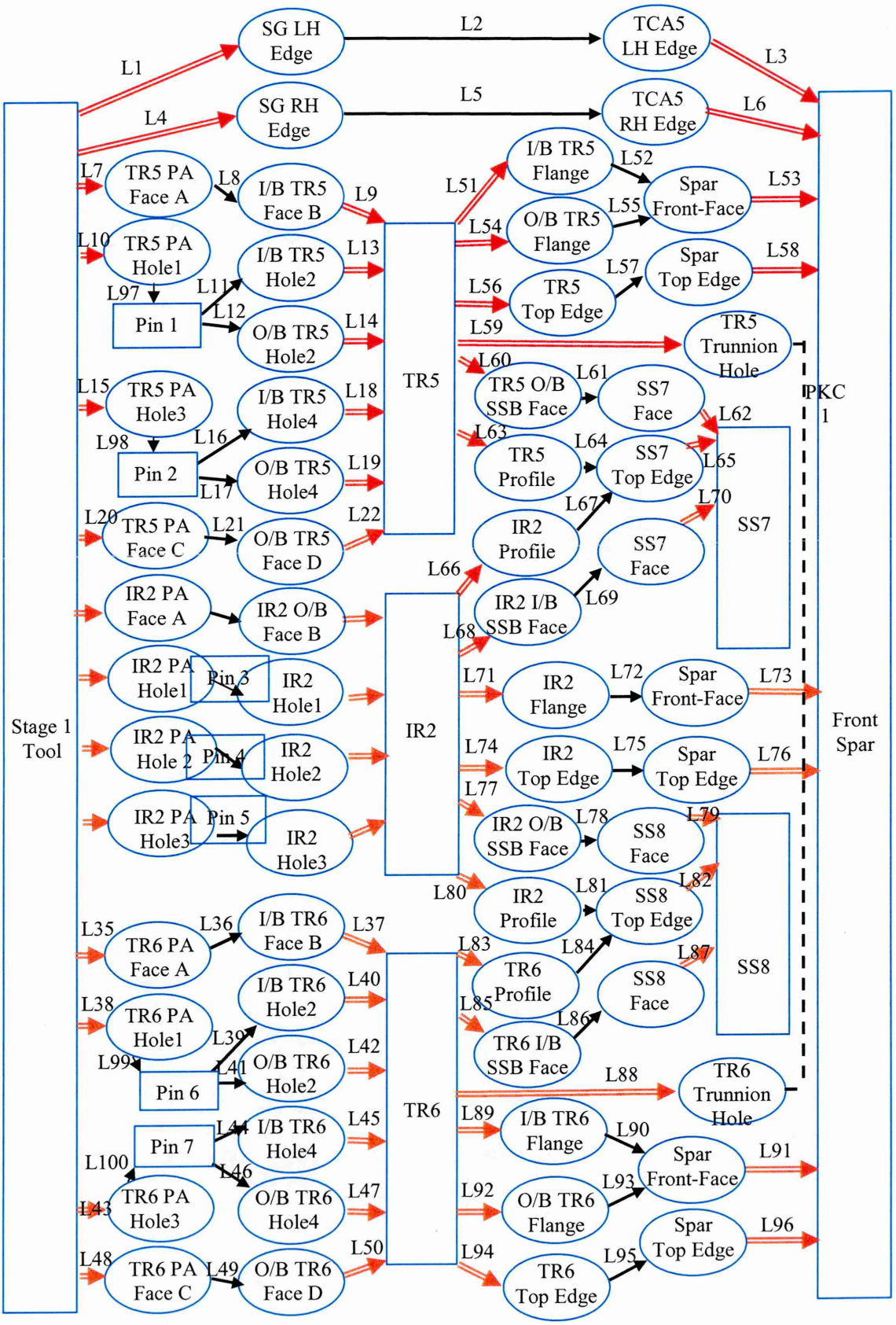
TR	Track Rib	SG	Setting Gauge	I/B	Inboard
IR	Inter-Rib	PA	Pick-up Arm	TCA	Track Can Aperture
SS	Sub-Spar	LH	Left hand	SSB	Sub-Spar Bracket
SK	Nose Skin	RH	Right Hand	O/B	Outboard

Abbreviations Used in the FDFC Diagrams *Table 7*

See Section 5.11 for an explanation of FDFCs



Conventions Used in the FDFC Diagrams *Table 8*



Assembly Stage 1 FDFC Diagram for the Current Method of Assembly *Fig. 121*

Feature Error Table – Current Method of Assembly

PKC#1. Slat track geometry

PART	FEATURE	CALLOUT	LINK	Tx	Ty	Tz
Location of Track Rib Pair 5						
Tool pick-up arm 1	Face A	POS	L7	0.160		
Track Rib 5	Face B	FLT	L8	0.050		
Tool pick-up arm 1	Hole 1	MMC	L10		0.025	0.025
Pin 1	Shank	LMC	L97		0.025	0.025
Track Rib 5	Inboard Hole 2	MMC	L11		0.025	0.025
Track Rib 5	Outboard Hole 2	MMC	L12		0.025	0.025
Tool pick-up arm 1	Hole 3	MMC	L15		0.025	0.025
Pin 2	Shank	LMC	L98		0.025	0.025
Track Rib 5	Inboard Hole 4	MMC	L16		0.025	0.025
Track Rib 5	Outboard Hole 4	MMC	L17		0.025	0.025
Tool pick-up arm 1	Face C	POS	L20	0.160		
Track Rib 5	Face D	FLT	L21	0.050		
Location of Track Rib Pair 6						
Tool pick-up arm 2	Face A	POS	L35	0.160		
Track Rib 6	Face B	FLT	L36	0.050		
Tool pick-up arm 2	Hole 1	MMC	L38		0.025	0.025
Pin 6	Shank	LMC	L99		0.025	0.025
Track Rib 6	Inboard Hole 2	MMC	L39		0.025	0.025
Track Rib 6	Outboard Hole 2	MMC	L41		0.025	0.025
Tool pick-up arm 2	Hole 3	MMC	L43		0.025	0.025
Pin 7	Shank	LMC	L100		0.025	0.025
Track Rib 6	Inboard Hole 4	MMC	L44		0.025	0.025
Track Rib 6	Outboard Hole 4	MMC	L46		0.025	0.025
Tool pick-up arm 2	Face C	POS	L48	0.160		
Track Rib 5	Face D	PAR	L49	0.050		
			Sum of the Squares	0.112	0.01	0.01
			RSS Target Error for PKC#1	0.363		

Feature Error Table for PKC#1 Current Method of Assembly *Table 9*

The main KC for this assembly is PKC#1, the slat track geometry, and the Reference Target Error of this assembly is used as a means of comparing the JAM efficiencies of the different assembly concepts. (See Section 5.12.1).



Aircraft Datum Reference Frame *Fig. 122*

By flowing PKC#1 down through the Product Decomposition diagram, (*Figure 99*), it can be seen that the KC is established by the correct positioning of the top, bottom, side and trunnion roller bearings relative to the aircraft datum, (Section 3.4). The FDFC has been drawn for PKC#1, (*Figure 121*), and the dimensional transfers between parts identified and entered into the Feature Error Table, (*Table 9*). Care was taken to resolve the traditional tolerancing scheme used on the original Airbus parts and

assembly drawings into the correct axes and to determine the GD&T feature callouts as the designers' original intent. The origin of the axes system and the origin of the datum reference frame of the aircraft are coincidental. (*Figure 122*). Transfer Error Links L9, 13, 14, 18, 19, 22, 59 and 88 are ignored in this instance because they are directly delivered by the CNC manufacturing process and will, therefore, be the same for each of the re-engineering concepts.

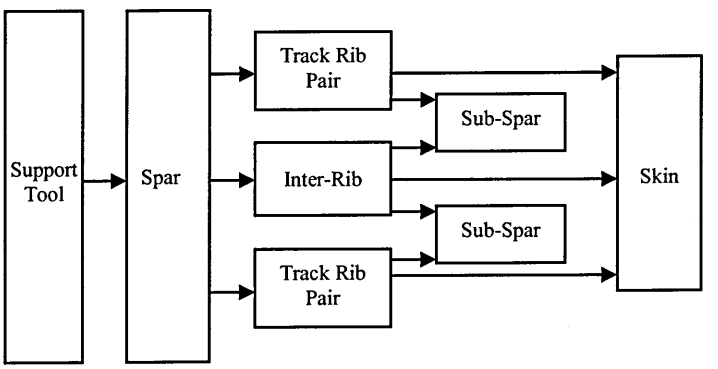
7.1.8.1.2 Building Directly onto the Spar, (Concept 2)

Build Cycle

Build Tool ⇒ Spar ⇒ Track Ribs ⇒ Inter-Ribs ⇒ Sub-Spars ⇒ Skins

Datum Flow Chain

The DFC Diagram for Concept 2 is shown in *Figure 123*



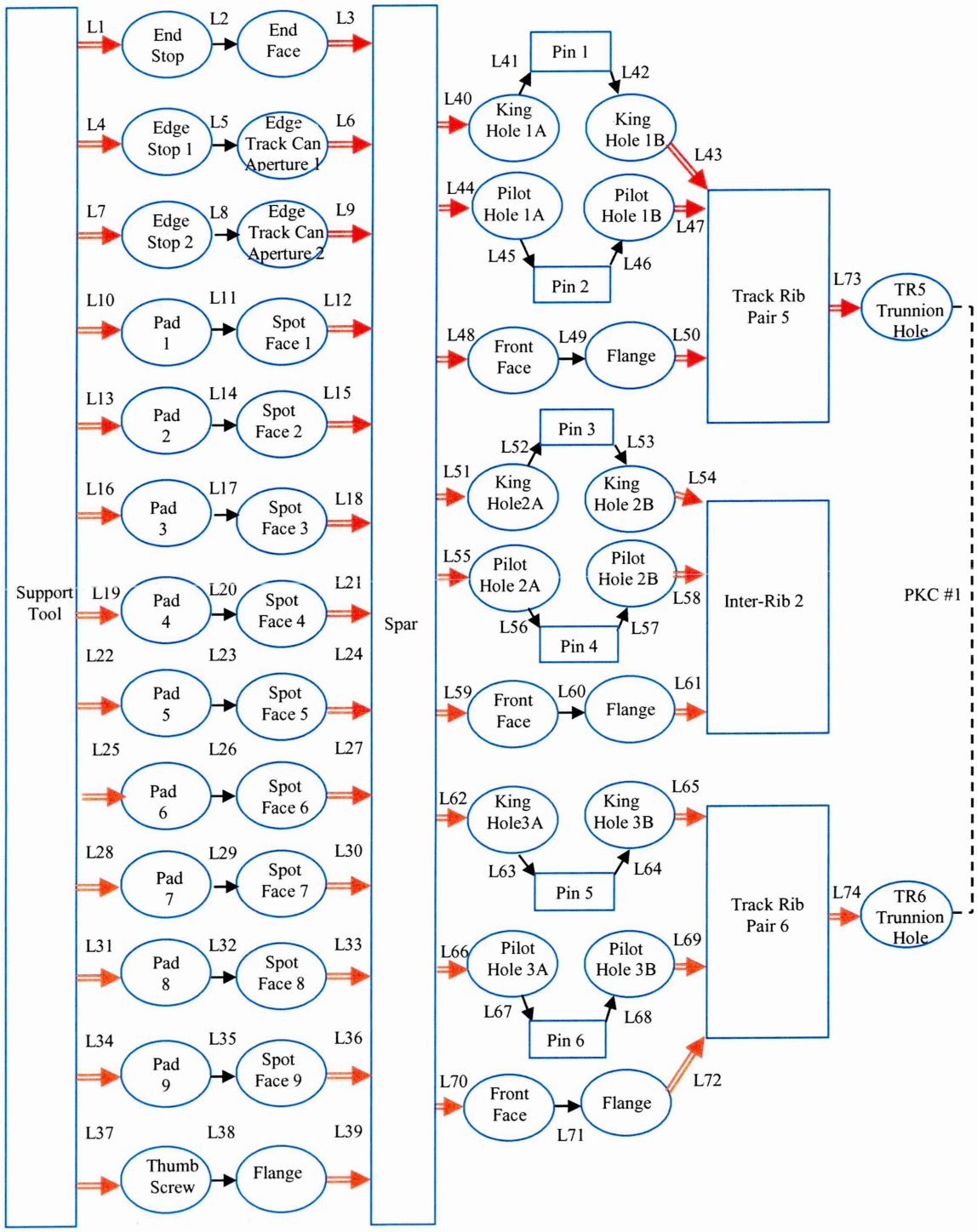
DFC Diagram for Concept 2 *Fig. 123*

Featurised Datum Flow Chain

The Featurised Datum Flow Chain for Concept 2 is shown in *Figure 124*

Comments on the FDFC Analysis

1. For Concept 2, the main assembly reference plane is the front face of the spar. This is established through spot faces on the rear face of the spar locating onto manually set and grouted support pads on the support tool. The resulting error chain is included in the FDFC analysis but with the nine pads and the nine spot-faces being treated as single planar entities both having flatness tolerances of 0.0127mm. (Ref. 42).
2. Links L37, L38 and L39 are not included in the analysis as they are manually established through the use of thumbscrews and a sighting telescope.
3. Errors for the King holes and pilot holes are calculated from the Least Material Condition (LMC) and included in the Position error value. ((H7)+0.015+ (POS)0.1)) = 0.115mm.
4. Oversized Pilot holes 1A and 1B, and Pin 2 are included in the Feature Error Table for completeness, but are not included in the calculation as they are a clearance fit to allow for corrective adjustment on assembly.



FDFC Diagram for Concept 2 *Fig. 124*

Feature Error Table – Concept2

PKC#1. Slat track geometry

PART	FEATURE	CALL OUT	LINK	Tx	Ty	Tz
Spar Location						
Tool	Edge Stop 1	POS	L4		0.005	0.010
Spar	Edge Track Can Aperture 1	POS	L5		0.005	0.040
Tool	Edge Stop 2	POS	L7		0.005	0.010
Spar	Edge Track Can Aperture 2	POS	L8		0.005	0.040
Tool	Pads	FLT	L10		0.010	
Spar	Spot Faces	FLT	L11		0.010	
Track Rib 5 Location						
Spar	King Hole 1A	POS	L40	0.10		0.10
Pin 1	Diameter	LMC	L41	0.014		0.014
Track Rib 5	King Hole 1B	POS	L42	0.10		0.10
Spar	Pilot Hole 1A		L44	---------		
Pin 2	Diameter	LMC	L45	---------		
Track Rib 5	Pilot Hole 1B	LMC	L46	---------		
Spar	Front Face	PLL	L48		0.050	
Track Rib 5	Flange	POS	L49		0.050	
Track Rib 5	Trunnion Hole	Datum	L73		--------	--------
Track Rib 6 Location						
Spar	King Hole 3A	POS	L62	0.10		0.10
Pin 5	Diameter	LMC	L63	0.014		0.014
Track Rib 5	King Hole 3B	POS	L64	0.10		0.115
Spar	Pilot Hole 3A	POS	L66	---------		
Pin 6	Diameter	LMC	L67	---------		
Track Rib 5	Pilot Hole 1B	LMC	L68	---------		
Spar	Front Face	PLL	L70		0.050	
Track Rib 5	Flange	POS	L71		0.050	
Track Rib 5	Trunnion Hole	Datum	L74		--------	--------
			Sum of the Squares	0.04	0.01	0.047
			PKC#1 - Total Error for Concept 2	0.311		

Feature Error Table for PKC#1 Concept 2 *Table 10*

7.1.8.1.3 Building on the Track Rib Hinge Line, (Concept 3)

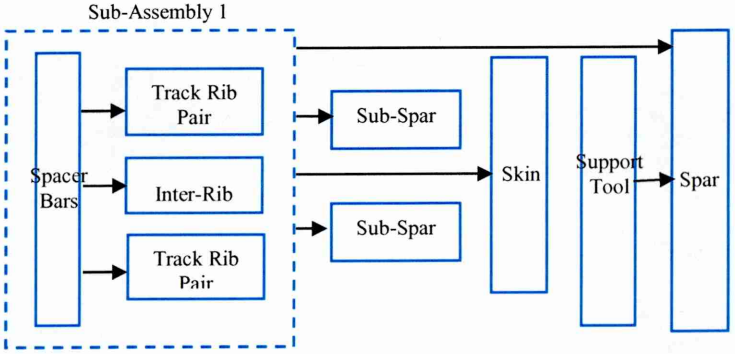
Build Cycle

(Spacer Bars ⇒ Track Ribs ⇒ Inter-Ribs) ⇒ (Spar ⇒ Tool) ⇒ Sub-Spars ⇒ Skins

Datum Flow Chain

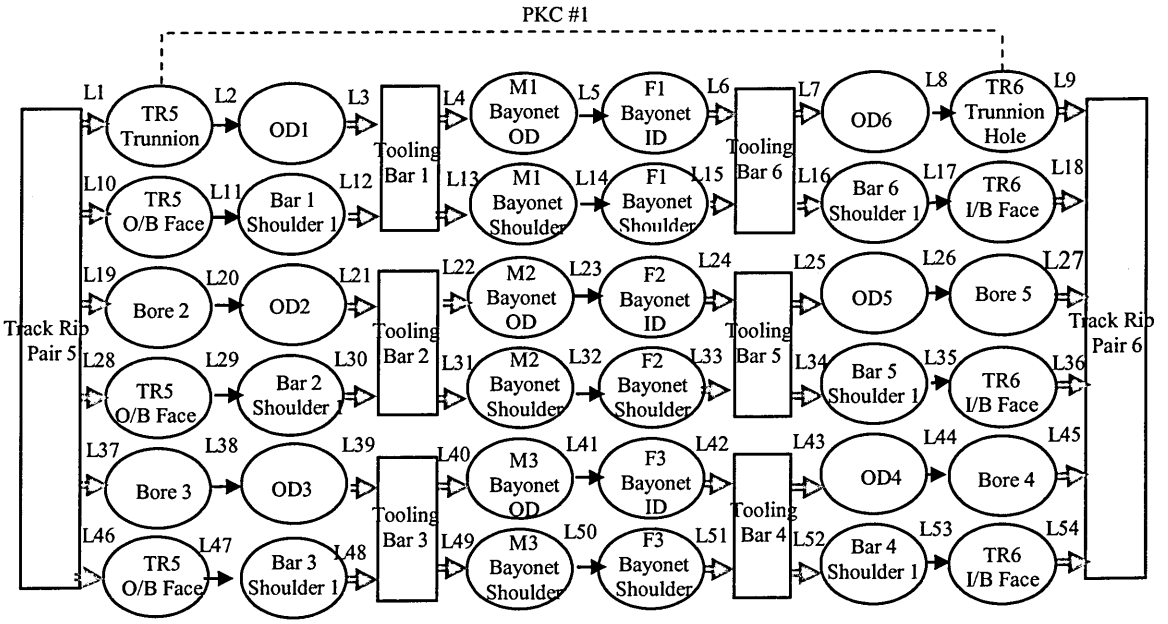
The DFC Diagram for Concept 3 is shown in *Figure 125.*

See Section 5.10 for an explanation of DFCs, and Section 7.1.6 for a description of Concept 3.



DFC Diagram for Concept 3 *Fig. 125*

Featurised Datum Flow Chain for Concept 3



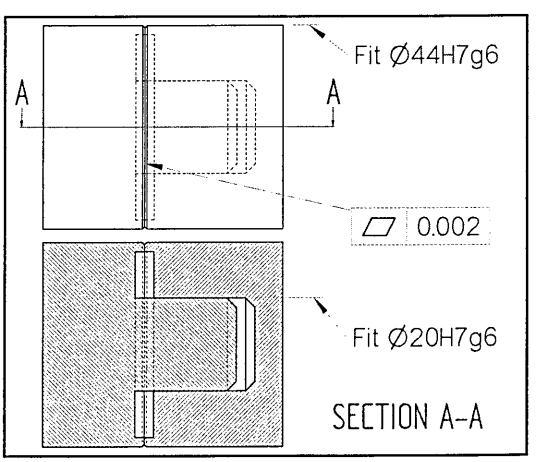
Sub-Assembly FDFC Diagram for Concept 3 *Fig. 126*

The Featurised Datum Flow Chain for Concept 3 is shown in *Figure 126.*

Comments on the FDFC Analysis

The spar, because it is a long flexible component, will need a support tool as for Concept 2, (*Figure 114*). However, the support tool and spar are not included in the FDFC analysis for Concept 3. This is because it is intended that the sub-assembly of the track-rib pairs and the tooling bars will be a rigid structure, and that the spar will be adjusted to align with the ribs, as in the current method of assembly. (See Section 3.3).

Each of the three tooling bars is split to enable the inclusion of the inter-rib in the assembly, but the inter-rib is not included in the analysis as it is sprung-loaded against collars on the bars and the rib thickness does not affect the overall length of the bars. The necessity of having to split the bars increases the number of assembly tools and interfaces, and therefore the number of 'Mate' and 'Transfer' errors. (See Section 5.11 and *Figure 127*).



Bayonet Error Assumptions *Fig. 127*

These are listed as 'Tooling Errors' in Feature Error Table for Concept 3, (*Table 11*).

Feature Error Table – Concept 3

PKC#1. Slat track geometry

PART	FEATURE	CALL OUT	LINK	Tx	Ty	Tz
Track Rib 5 Location						
Track Rib 5	Trunnion Hole ID	MMC	L2		0.025	0.025
Tooling Bar 1	OD1	LMC	L3		0.025	0.025
Track Rib 5	O/B Face	FLT	L11	0.002		
Tooling Bar 1	Shoulder 1	FLT	L12	0.002		
Track Rib 5	Bore 2	MMC	L20		0.025	0.025
Tooling Bar 2	OD2	LMC	L21		0.025	0.025
Track Rib 5	O/B Face	FLT	L29	0.002		
Tooling Bar 2	Shoulder 1	FLT	L30	0.002		
Track Rib 5	Bore 3	MMC	L38		0.025	0.025
Tooling Bar 3	OD3	LMC	L39		0.025	0.025
Track Rib 5	O/B Face	FLT	L47	0.002		
Tooling Bar 3	Shoulder 1	FLT	L48	0.002		
Tooling Errors						
Tooling Bar 1	M1 Bayonet OD	LMC	L6		0.020	0.020
Tooling Bar 6	F1 Bayonet ID	MMC	L5		0.020	0.020
Tooling Bar 1	M1 Bayonet Shoulder	POS/FLT	L13	0.10		
Tooling Bar 6	F1 Bayonet Shoulder	FLT	L15	0.10		
Tooling Bar 2	M2 Bayonet OD	LMC	L22		0.020	0.020
Tooling Bar 5	F2 Bayonet ID	MMC	L24		0.020	0.020
Tooling Bar 2	M2 Bayonet Shoulder	POS/FLT	L31	0.10		
Tooling Bar 5	F2 Bayonet Shoulder	FLT	L33	0.10		
Tooling Bar 3	M3 Bayonet OD	LMC	L40		0.020	0.020
Tooling Bar 4	F3 Bayonet ID	MMC	L42		0.020	0.020
Tooling Bar 3	M3 Bayonet Shoulder	POS/FLT	L49	0.10		
Tooling Bar 4	F3 Bayonet Shoulder	FLT	L51	0.10		
Track Rib 6 Location						
Track Rib 6	Trunnion Hole ID	LMC	L8		0.025	0.025
Tooling Bar 6	OD6	LMC	L8		0.025	0.025
Track Rib 6	I/B Face	FLT	L17	0.002		
Tooling Bar 6	Shoulder 1	FLT	L16	0.002		
Track Rib 6	Bore 5	MMC	L26		0.025	0.025
Tooling Bar 5	OD5	LMC	L25		0.025	0.025
Track Rib 6	I/B Face	FLT	L35	0.002		
Tooling Bar 5	Shoulder 1	FLT	L34	0.002		
Track Rib 6	Bore 4	MMC	L44		0.025	0.025
Tooling Bar 4	OD4	LMC	L43		0.025	0.025
Track Rib 6	I/B Face	FLT	L53	0.002		
Tooling Bar 4	Shoulder 1	FLT	L52	0.002		
			Sum of the Squares	0.06	0.01	0.01
			PKC#1 – Total Error for Concept 3	0.282		

Feature Error Table for PKC#1 Concept 3 *Table 11*

Concept	Metric PKC#1	Quality Comparison
Current Method of Assembly	0.363	100%
2 - Building Directly onto the Spar	0.311	117%
3 - Building on the Track-Rib Hinge Line	0.282	129%

Initial Error Budgets for PKC#1 *Table 12*

The error budget for the Current Method of Assembly is the target error and is compared to the error budgets for Concepts 2 and 3. The results indicate that Concept 2 has the potential to produce assemblies with a 17% quality advantage, and Concept 3 has the potential to produce assemblies with a 29% quality advantage, or reduction in the build error.

7.1.8.2 Final Decision Matrix

Concept / Criteria	2	3
Able to achieve PKC requirement?	Yes – but tolerances need tuning	Yes - Easily
Low risk?	Yes - Considered to be a very low risk approach	No - Problems expected with sub-assembly twisting and sagging
Good build-access?	Yes - Clear access to both sides of spar	No - Tooling bars restrict access to front of spar
Applicable to entire length of Leading Edge?	Yes	No – in reality the slat track hinge line is not a straight line
Are existing parts of adequate quality?	No – Some feature tolerances will need tightening up	Yes
Are existing assembly features sufficient?	No –Requires additional machining & resetting of parts.	Yes
Is concept suitable for automation?	Yes - Clear access to both sides of spar	No - Tooling bars restrict access to front of spar
Minimal tooling requirement?	Yes – Support tool only	No – Requires support tool and multiple tooling bars
Expected low cost compared to existing system?	Yes – initially, but additional recurring part manufacturing costs	Yes – but initially higher, non-recurring, tooling costs

Decision Matrix for Concepts 2 and 3 *Table 13*

The questions in the 'Final Decision Matrix', (*Table 13*), are posed in a way that allows Yes/No answers with qualifying statements. A 'Yes' answer is favourable to selection and a 'No' indicates that the Concept requires further development. The qualifying statements allow the IPD team members to discuss areas of uncertainty.

Concept	Responses	
	Yes	No
2	7	2
3	4	5

Concept Selection Scores *Table 14*

The Concept Selection Scores, (*Table 14*), indicate that, based on the chosen selection criteria, Concept 2 is the better choice for development.

7.1.9 Embodiment of the Best Concept

Solid models were developed and the assembly process for Concept 2 was developed in greater detail, (Appendix E), working on the basis of the JAM Guidelines given in Section 5.14.

VALISYS assembly analysis by BAE MA&A, Samlesbury confirmed that the proposed assembly concept, (*Figure 128*), is a viable alternative to the current assembly process. (Ref. 117).

7.1.9.1 Risk Analysis

ID No.	Risk Identification	Probability	Impact	Preventative Action	Control & Monitoring
1	Incorrect placement of fastener holes due to thermal growth of spar	1 in 10 Chance	£100,000 Scrap sub-assembly	Auto-drill heads to use king holes as local datums. Machine vision and RCC to locate holes.	Laser interferometry ref. to main ref. feature. (For confidence)
2	Poor quality parts	1 in 100 Chance	£1,000 Scrap part or rework by hand	Collect process capability data. Alt. 100% inspection of identified features	Statistical process control. Establish 6σ capability.
3	Poor quality holes drilled on assembly	1 in 100 Chance	£500 Rework by hand	Establish life of drill/reamer.	Visual inspection until confidence is established.

Risk Analysis *Table 15*

The registered risks were reappraised, (*Table 15*), in the knowledge of the detailed assembly plan, (Appendix E). This resulted in a change from position measurement relative to the spar datum hole, to using machine vision and a passive RCC device, (Remote Centre Compliance), (Ref. 118), to locate pre-machined king-holes in the spar, and to then establish these as local datum features for drilling the set patterns of fastener holes.

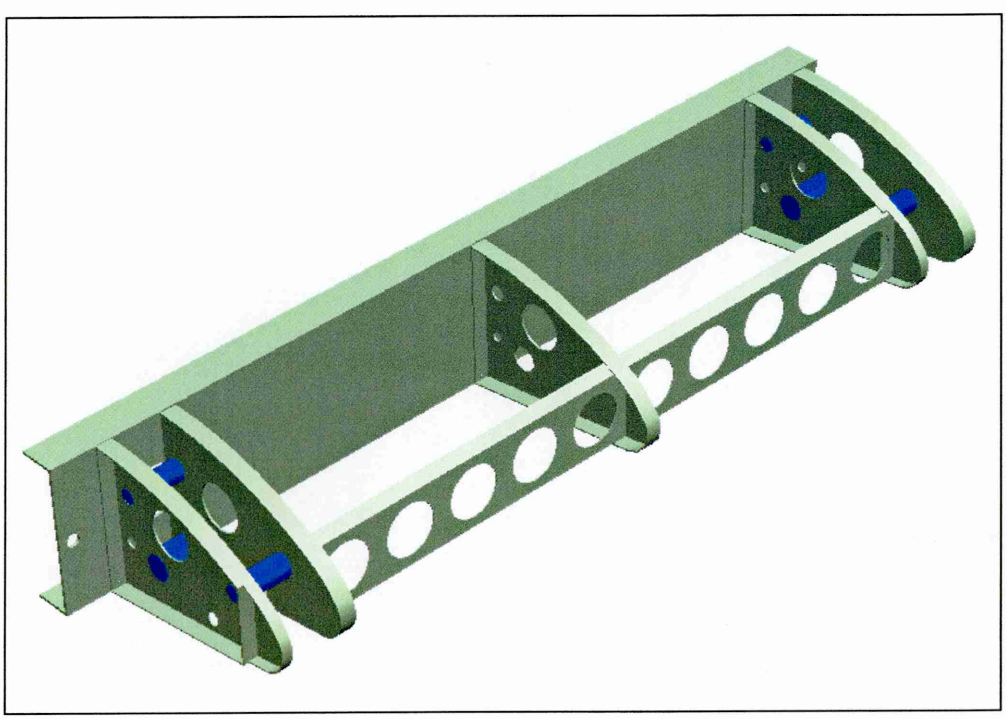
7.1.10 Costings Analysis

The cost model, (Ref. 119), evaluated those design and manufacturing costs directly affected by the introduction of jigless manufacture, including the two automated drilling and insertion heads, the new tooling and additional machining costs, but assumes that indirect support costs and overheads remain unchanged. The analysis of the proposed re-engineering design indicates a recurring cost saving of approximately 6% per aircraft set.

7.1.11 Presentations

The JAM design methodology together with the re-engineered A320 leading edge were presented at separate meetings to the University JAM teams and industrial collaborators, the A320 Single Aisle Programme, A320 Leading Edge Assembly Team, A380 Design Team, and EADS. The feedback was extremely positive from the managers and the assembly cell leaders but marginally less so from the designers who claimed to be already doing most of it intuitively, without the need for a formal JAM framework.

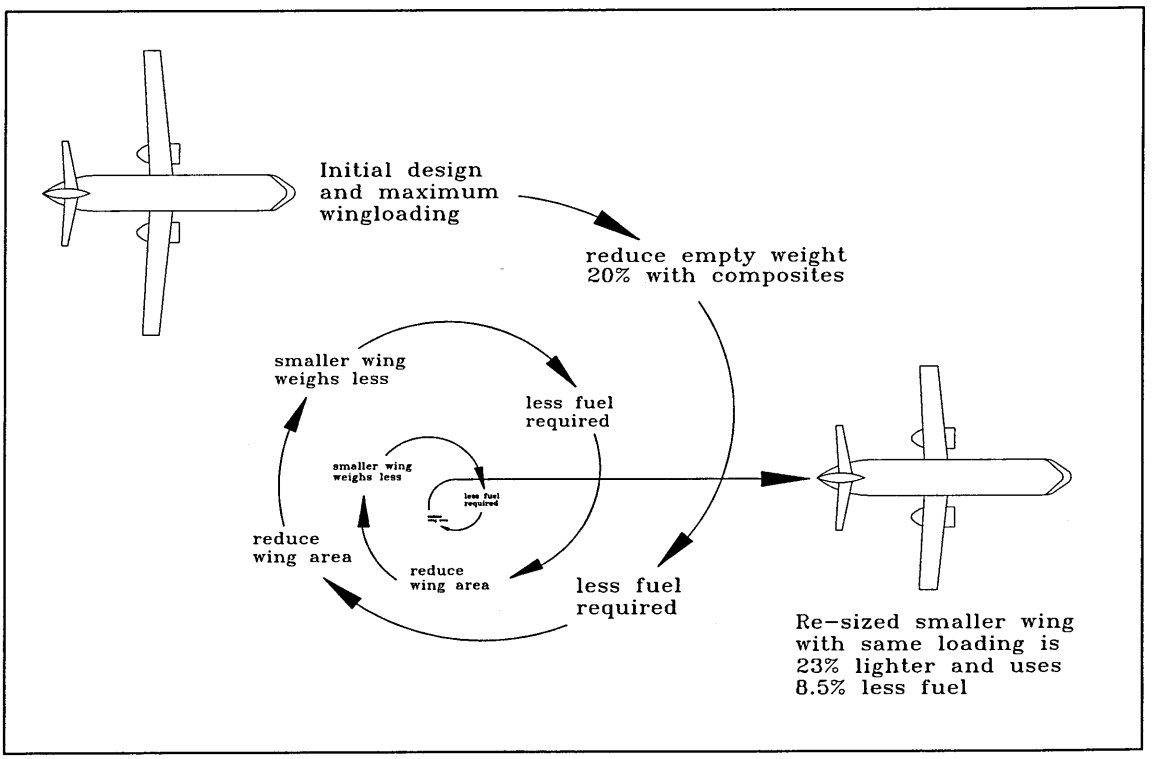
The presentational feedback is discussed in Chapter 8.



The VALISYS Assembly Model *Fig. 128*

7.2 Case Study 2 – Designing an Airbus A320, Composite, Fixed Leading Edge

The second Case Study tests the efficacy of the JAM algorithm in creating a new design for an advanced composite, Airbus A320, fixed leading edge. This is to be a direct replacement of the existing design, (*Figure 26*).



The Benign Spiral Effect of Weight Reduction for a Transatlantic Aircraft *Fig. 129*

The Airbus designers and engineers are continuously searching for ways to reduce both the weight and the cost of their structure. In theory the use of advanced composites allows the weight of an airframe to be reduced by up to 30% with the major weight savings coming from the vast reduction in the numbers of parts and fasteners. (Ref. 120). Consequently the latest generation of Airbus are flying with composite fin and rudder, ailerons, flaps, spoilers, engine cowls, pylon fairings, belly fairing, cabin floor, and undercarriage doors. Cost savings are possible through simplified assembly techniques compared to traditional metal airframe construction, (See Chapter 3), but these are often overshadowed by the higher part-manufacturing and raw material costs, and the use of composite is then justified by the reduced operating and life cycle costs. (*Figure 129*), (Ref. 121).

7.2.1 The Customer Requirements

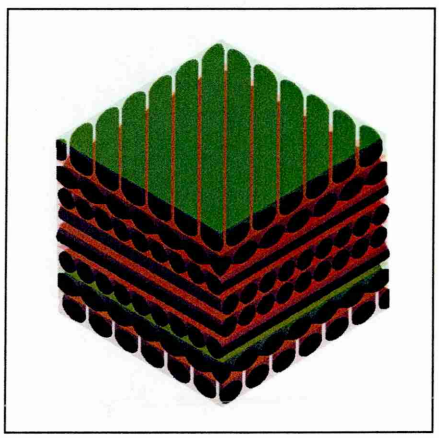
This is a research investigation to test the efficacy of the JAM algorithm in the creation of a new conceptual JAM design. The assumption is that Airbus has established an IPD team to design a JAM, advanced composite, fixed leading edge for an all new composite A320 wing.

Airbus UK laid down three specific requirements;

1. Minimal quantity of 'Product specific tooling'.
2. To be at least 20% lighter than the existing metal structure.
3. To be at least 20% cheaper than the existing metal structure.

7.2.2 Analysis of Problem

Composite parts are most commonly manufactured by laying sufficient ply of unidirectional carbon pre-impregnated sheet, 0.125mm thick, into a mould-tool. The plies are cut and laid with the carbon fibres orientated in different directions in accordance with the design intent, producing an anisotropic material having designed properties in specific directions, (*Figure 130*). The tool is then closed and loaded into an autoclave where it is subjected to high temperature and pressure that consolidate the composite and cure the resin. The end result is a permanently formed three-dimensional composite part having engineered properties in excess of the sum of the properties of the two parts.



Ply Stack of 0^0, 90^0 & $\pm 45^0$ Fibres *Fig. 130*

To achieve the maximum possible cost and weight savings, and to ensure the minimum of product specific tooling, the design, manufacture, and the assembly of a composite structure must all be considered concurrently and to ensure that the necessary part location and restraint features, (See Section 5.8), are incorporated into the mould-tools at the beginning of the design process, (See Section 5.4), and reproduced in the parts.

The mass of the structure can be determined once the design exists as a full solid model, (See Section 4.2), and the simultaneous development of a cost model will enable determination of costs and comparisons with the current metal design, (See Section 4.4).

7.2.3 Statement of Problem

1. A JAM design is to be developed for an advanced composite, fixed leading edge, compatible with an all new composite A320 wing.
2. There is to be a minimum quantity of 'Product specific tooling'.
3. The structure is to be least 20% lighter than the current metal structure.
4. The structure is to be least 20% cheaper than the current metal structure.
5. This is to be achieved by following the JAM Design Algorithm, (*Figures 93 and 95*).

7.2.4 PKC Recognition

The composite wing will have the same envelope profile and high-performance features, (See Section 3.1.1), as the current metal design and therefore the function of the fixed leading edge and the high level PKCs will be the same, (See Section 7.1.4).

The main function of the fixed leading edge is to house the slat tracks and the slat operating mechanisms in an aerodynamic covering, and therefore the higher level PKCs are;

PKC#1. Slat track geometry
(Described as being very critical with respect to wing lift coefficient, C_L).

PKC#2. Aerodynamic profile
(If it is of poor quality, then the slow speed, high lift performance of the wing will not be achieved).

PKC#3. Appearance
Very important to the customer

From the PKC Flow-Down Diagrams, (*Figures 100, 101, 102*), it is determined that the following lower Product Key Characteristics must be controlled;

PKC#1. The slat track geometry. This flows down to controlling the position of the pinion and guide roller bearing bores during manufacturing, and to controlling the alignment of the trunnion bearings and the positioning of the track-rib pairs during assembly, (*Figure 100*). Correct alignment of the trunnion bearings ensures the correct alignment of the hinge line, which is important to ensure smooth operation of the slats in-service, and is considered more important than the straightness of the front spar which is allowed to meander off-line by as much as ±1 mm. (Section 3.3.1).

PKC#2. The aerodynamic profile. This flows down to controlling the step up from the top of the ribs to the upper spar flange, (Section 3.1.2), the rib positions and alignment along the spar, and the alignment between the lower aerodynamic surface of the ribs and the lower spar flange during assembly, (Section 3.3.3 and Section 3.1.2), and the profile dimensional tolerance of the nose ribs during manufacturing. (*Figure 101*).

PKC#3. Appearance.
A number of factors are involved in this, including paint shading that can be affected by the type of drying process. However the PKC#3 that must be achieved during part-manufacture and assembly are the edge clearances between the composite D-Nose skin sections, (Section 3.3.2), (*Figure 102*). These must be parallel and of the correct width.

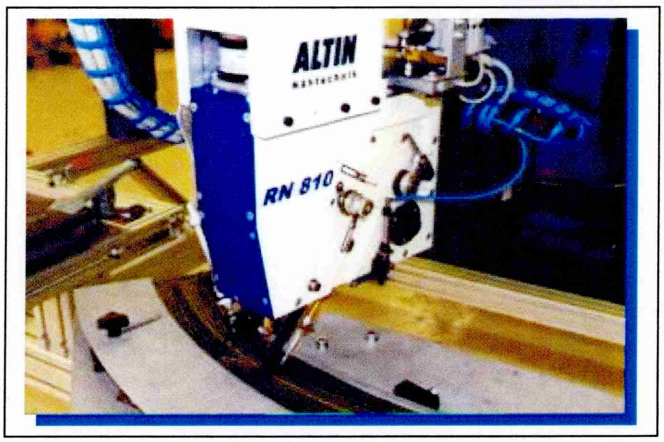
7.2.5 Conceptual Designs

Composite Concept 1 - Three-Dimensional Preform, (Monolithic Structure)
With reference to the database; the Enabling Technologies capable of manufacturing a three-dimensional preform, consisting of the spar and ribs, include;

1. Braiding,
2. Weaving,
3. Automated Fibre Placement by directed air jet,
4. Sewing together pre-cut parts, (*Figure 131*).

Manufacture:
The constructed preform is loaded into a closed mould tool for resin infusion, followed by consolidation and curing in an autoclave. PKC#1 is established on assembly, PKC#2 is established by the mould tool.

The cured part may need machining in dimensionally-critical areas.

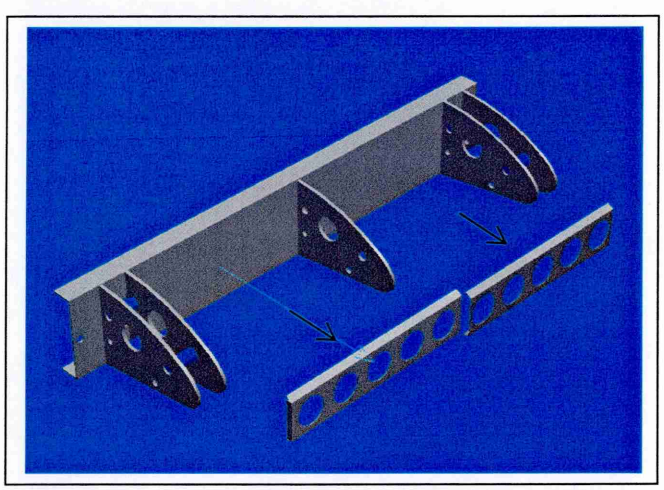


3D Sewing Head *Fig. 131*

Build Cycle:
The fixed leading edge is assembled with the preformed ribs pointing vertically upwards.

a) Flat Laminate ⇒ Form Tool ⇒ Autoclave ⇒ Skin
b) Preform ⇒ Mould Tool ⇒ Autoclave ⇒ Build Tool ⇒ Sub-Spars ⇒ Skin

Build Sequence:
- Manufacture preform, resin infuse and autoclave cure, (*Figure 132*).
- Locate the cured preform on a simple build tool and hold in position using vacuum clamps.
- Abrade or cryogenic shot blast bonding faces; and clean.
- Hard inserts in the form tool establish the bores for bearing inserts. (Establishes PKC#1).
- Position the sub-spars on location features formed from extensions of the upper sub-spar flanges and matched depressions in the ribs.
- Bond sub-spars in position and secure with G-cramps until the adhesive is cured.
- Oven cure adhesive.
- Abrade or cryogenic shot blast bonding faces; and clean.
- Locate nose skins, bond in position, and secure with strap-cramps until the adhesive is cured.
- Oven cure adhesive.



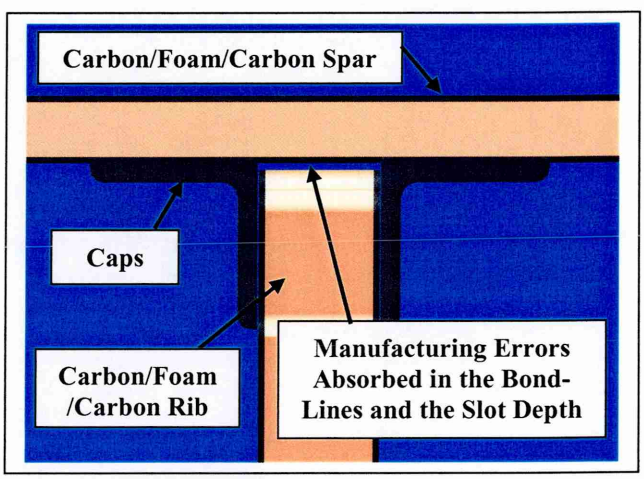
Composite Concept 1- Monolithic Assembly *Fig. 132*

Possible Variations:
- The preform can include the sub-spars at increased cost and complexity of the preform and the mould tool.

- Vacuum assisted resin transfer and SCRIM technologies are alternatives to resin infusion.
- Use of peel ply will avoid the need to abrade or cryogenic shot blast bonding faces.
- Fibre placement is an automated process that utilises a single tow air-jet to propel continuous fibre directly into a mould tool. (Ref. 122). The cured composite can be anisotropic, or isotropic with through-thickness fibres.
- In practice the CAA will probably require some permanent fasteners to strengthen a fully bonded structure.

Composite Concept 2 - Cost-Effective Parts Manufacture
This concept is based on the published reports and papers of the Airbus led AMCAPS projects. (Ref. 121, 123).

Manufacture:
For cheapness, and to need the minimum of form tooling, the parts are laminated in the flat as either sandwich panels that are cured and then machined to shape, or flat, B-staged laminated panels that are then vacuum-formed to shape before curing.



Use of Slots to Locate and Join Major Components *Fig. 133*

It is envisaged that the spar web and ribs would be machined from carbon faced sandwich panels and assembled together with deep slots formed by facing pairs of composite angle brackets. (See Section 2.1.1.5 and *Figure 11*).

A foaming adhesive having gap-filling properties will allow a relaxation of part-manufacturing tolerances. (*Figure 133*). (See Section 2.1.1.4 and *Figure 7*).

The use of slotted joints results in a structure that is largely self-tooling, (See Section 5.8), however, some assembly tooling will be necessary to align the bearing housings and establish PKC#1. PKC#2 and PKC#3 are established by the accuracy of the CNC machining and the accuracy of the assembly tooling.

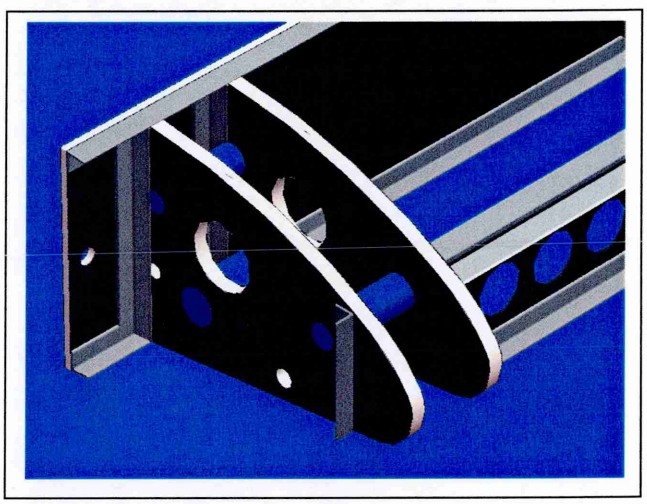
Build Cycle:
The fixed leading edge is assembled with the nose-ribs pointing vertically upwards.

a) Flat Laminates ⇒ Form Tools ⇒Autoclave = Brackets, Caps, Skin
b) Flat Laminates ⇒ Caul Plates ⇒ Autoclave ⇒ Sandwich Panels) ⇒ CNC Machine = Spar ⇒ Caps ⇒ Ribs ⇒ Brackets
c) Build Tool ⇒ Rib ⇒ Brackets ⇒ Oven = Inter-Rib
d) Build Tool ⇒ Bearings ⇒ Ribs ⇒ Brackets ⇒ Dummy Rollers ⇒ Oven = Track Ribs
e) Build Tool ⇒ Sub-Spar Webs ⇒ Caps ⇒ Oven = Sub-Spars

f) Build Tool ⇒ Spar ⇒ Caps ⇒ Track Ribs ⇒ Inter-Rib ⇒ Sub-Spars ⇒ Skin ⇒ Oven = Completed Assembly

Build Sequence:

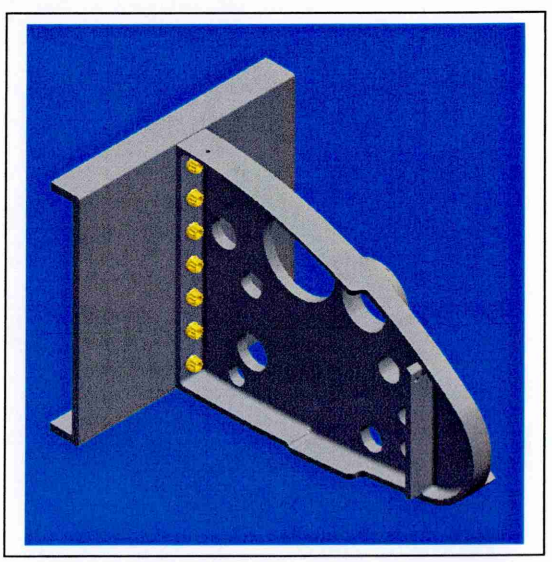
- Locate the cured sandwich structure spar web on a simple build tool and secure with vacuum clamps.
- Abrade or cryogenic shot blast bonding faces; and clean.
- Locate the cured brackets off the build tool and bond in position. (*Figure 134*).
- Oven cure adhesive.
- Abrade or cryogenic shot blast bonding faces; and clean.
- Locate the cured nose-ribs within the brackets and, locating off the build tool, bond in position.
- Oven cure adhesive.
- Check the alignment of the bearing housings using a laser and an optical target. (Establishes PKC#1).
- Abrade or cryogenic shot blast bonding faces; and clean.
- Bond sub-spars in position and hold with G-cramps until the adhesive is cured.
- Oven cure adhesive.
- Abrade or cryogenic shot blast bonding faces; and clean.
- Locate nose skins, bond in position, and secure with strap-cramps until the adhesive is cured.
- Oven cure adhesive.



Composite Concept 2 - Cost-Effective Parts Manufacture *Fig. 134*

Possible Variations:

- Co-curing cleats and spar web and cleats and nose ribs would simplify and speed-up assembly, but would require more complicated autoclave tools.
- Use of peel ply would avoid the need to abrade or cryogenic shot blast bonding faces.
- In practice the CAA will probably require the addition of some permanent fasteners to reinforce a fully bonded structure.



Composite Concept 3 - Black Metal Design *Fig. 135*

<u>Composite Concept 3</u> - Black Metal

Black metal is a derogatory term describing the design of a composite structure based on traditional metal technology, (*Figure 135*). Individual parts are manufactured

separately, located in assembly tooling, and drilled and fastened in a similar manner to metal structures. (See Section 3.3).

The structure will gain some advantages from the use of composite materials, but the full weight saving and assembly advantages of composite design will not be achieved.

Nevertheless, this approach is often taken because, as yet, there is no way of non-destructively establishing the integrity of a bonded joint. (Ref. 125).

Build Cycle:
The fixed leading edge is assembled with the nose-ribs pointing vertically upwards.

Form tools ⇒ Autoclave ⇒ Build Tool ⇒ Spar ⇒ (Cleats) ⇒ Ribs ⇒ (Cleats) ⇒ Sub-Spars ⇒ Skins

Build Sequence:
- Manufacture, cure, and machine as necessary, individual parts.
- Locate the cured spar on a simple build tool and secure with vacuum clamps.
- Locate the cured nose-ribs off the build tool, and drill fastener holes through.
- Remove, clean, and secure using permanent fasteners.
- Locate sub-spars in position and secure using G-cramps.
- Drill fastener holes through.
- Remove, clean, and secure using permanent fasteners.
- Locate nose skins and secure with strap-cramps.
- Drill fastener holes through.
- Remove, clean, and secure using permanent fasteners.

Possible Variations:
- Parts can be both bonded and mechanically fastened.
- Hand lay-up of parts will allow integration of the cleats but at an increased cost of lay-up, and increased complexity of the autoclave tooling.
- The use of 'Liquid Shim' on assembly will allow for a relaxation of some part-tolerances.

PKC#1 and PKC#2 are established through the accuracy of the CNC machining and of the assembly tooling. PKC#3 is established through the accuracy of the CNC machining of the skin profiles and the skill of the assembly technicians.

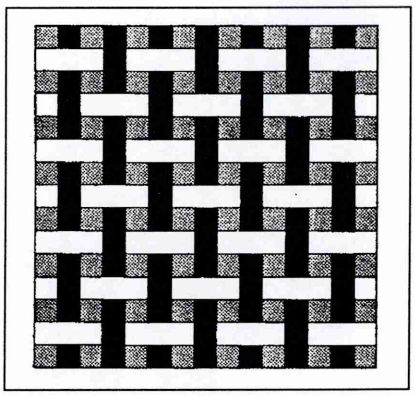
7.2.6 Selection of the Two Best Concepts

After developing outline assembly processes and considering part-manufacture and build cycles for the three alternative concepts, the two best concepts were selected for further consideration; based on the criteria of practicality, efficiency, manufacturing requirements, outline costings and risk assessment.

The evaluation of the criteria was aided by the knowledge acquired during the industrial based research programme, (Chapter 3), from researching the enabling technologies, (Chapter 4), and from interviewing skilled and knowledgeable practitioners, (Appendix B).

Composite Concept 1 Manufacturing and curing a three-dimensional preform, is a very attractive option as it allows the possibility of no final assembly and therefore no final assembly errors. Instead, any errors will be the result of either manufacturing or form-tool inaccuracies, and these can be controlled by the use of a high-precision machine tool. (Section 4.7).

Braided and woven preforms were rejected on the grounds of reduced mechanical properties resulting from crimping of the fibres, (*Figure 136*).



Plain Weave Cloth *Fig. 136*

Automated fibre placement by directed air jet was initially rejected because of the perceived difficulty in controlling the number of fibres in any given direction and therefore the known mechanical properties; and therefore, the repeatability of the mechanical properties, (Ref. 123). However, further consideration suggested that if the risk is acceptable, and the process can be made to work effectively, then it does offer an extremely cost-effective and very flexible manufacturing solution; and obviates the difficulty of handling a large flexible preform.



NASA Stitched Wing Preform *Fig. 137*

In discussions at Cranfield on the feasibility of the stitched preform, Ray Palmer, (ICAPS NASA stitched wing programme, (*Figure 137*)), (Appendix B), was of the opinion that the proposed solution and the resin infusion process were entirely feasible, although handling the finished preform and loading it into the mould tool would be problematical.

Composite Concept 2 Cost-Effective Parts Manufacture

The manufacture and assembly of parts using simple techniques has a very low risk factor and does not need any expensive matched autoclave tooling. On the negative side it has a higher part-count and will require simple assembly tooling to locate and hold parts during adhesive bonding. Additionally, designers will have to compromise on not being able to achieve the maximum possible weight savings. On the positive side, all parts can be rapidly laminated in the flat either by hand or an automated tape-laying machine. Sandwich panels are then cured and CNC profiled; whilst thin sections, such as skins and brackets, can be vacuum-formed over form tooling before autoclave curing.

Simple, but comparatively, labour intensive assembly.

Composite Concept 3 Black Metal

This is a low risk solution that simply replaces light alloy parts with composite parts. As the major cost and weight savings are to be achieved in reducing the number of mechanical fastenings and simplifying the final assembly; an un-optimised 'Black

Metal' design will not be competitive and will need both form tooling and assembly tooling, resulting in twice as much tooling as a conventional metal design.

Therefore, the 'Black Metal' concept was rejected, with 'Cost-Effective Parts Manufacture' and 'Automated Fibre Placement' being selected for further evaluation.

7.2.7 Selection of the Best Concept

The aim of the selection process is to identify the most cost-effective, manufacturing and assembly solution that will deliver the required quality based on delivery of the PKCs, whilst using the minimum of product specific tooling. For composite manufacture, tooling includes both form tools and assembly tools, (Section 7.2.2), with some aspect of the required final quality being resident in each tool, plus any machine tool used to machine a feature after curing. In the absence of any process capability data, (Section 4.12.4), the error budgets for the alternative concepts utilise generalised manufacturing tolerances obtained from published papers and tables. (Section 7.3), (Refs. 42, 112, 113, 114, 115, and 116). Using this data the error budgets will not establish that the manufacturing and assembly processes can deliver the PKCs, but they do enable realistic comparisons to be made between alternative assembly schemes.

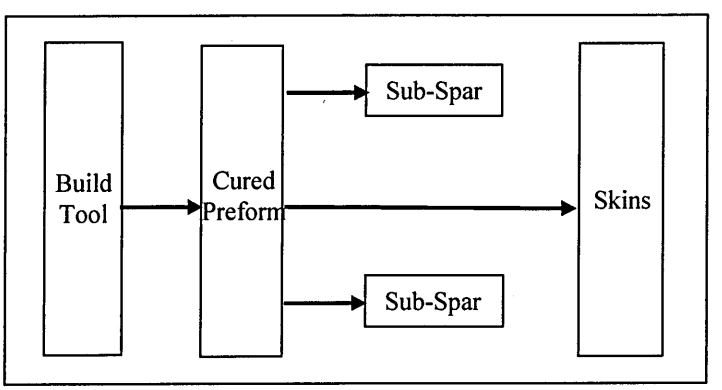
7.2.7.1 FDFC Evaluation

Evaluation of the Featurised Datum Flow Chains, (Section 5.11), provides an estimate of the ability of a specific manufacturing/assembly approach to satisfy the KC requirements, (Section 5.5). Additionally, counting the degrees of freedom entering a box gives an indication as to whether the part is over, under, or correctly restrained, (Section 5.11.2).

Using a simplification of Randolph Odi's method, (Section 5.12 and Ref. 104), the FDFC links establishing PKC#1 are evaluated to provide comparative error budgeting metrics, (*Table 12*).

7.2.7.1.1 Concept 1 - Three Dimensional Preform

(Automated Fibre Placement by Directed Air Jet)



DFC Diagram for Case Study 2, Concept 1 *Fig. 138*

Build Cycle
Build Tool ⇒ Preform ⇒ Sub-Spars ⇒ Skin

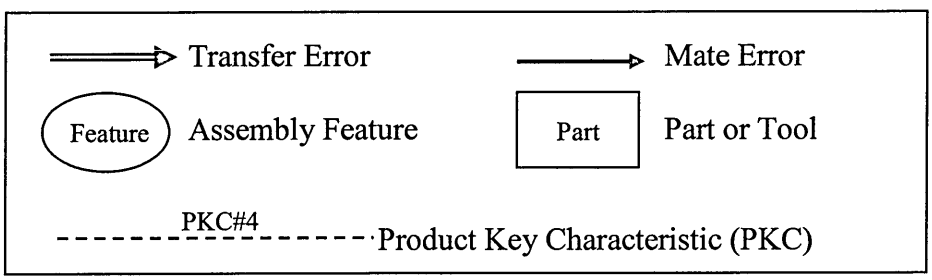
Datum Flow Chains *(Figure 138)*
See Section 5.10 for an explanation of DFCs and Section 7.2.5 for a description of the proposed manufacturing and assembly processes.

Featurised Datum Flow Chains

TR	Track Rib	SG	Setting Gauge	I/B	Inboard
IR	Inter-Rib	PA	Pick-up Arm	TCA	Track Can Aperture
SS	Sub-Spar	LH	Left hand	SSB	Sub-Spar Bracket
SK	Nose Skin	RH	Right Hand	O/B	Outboard

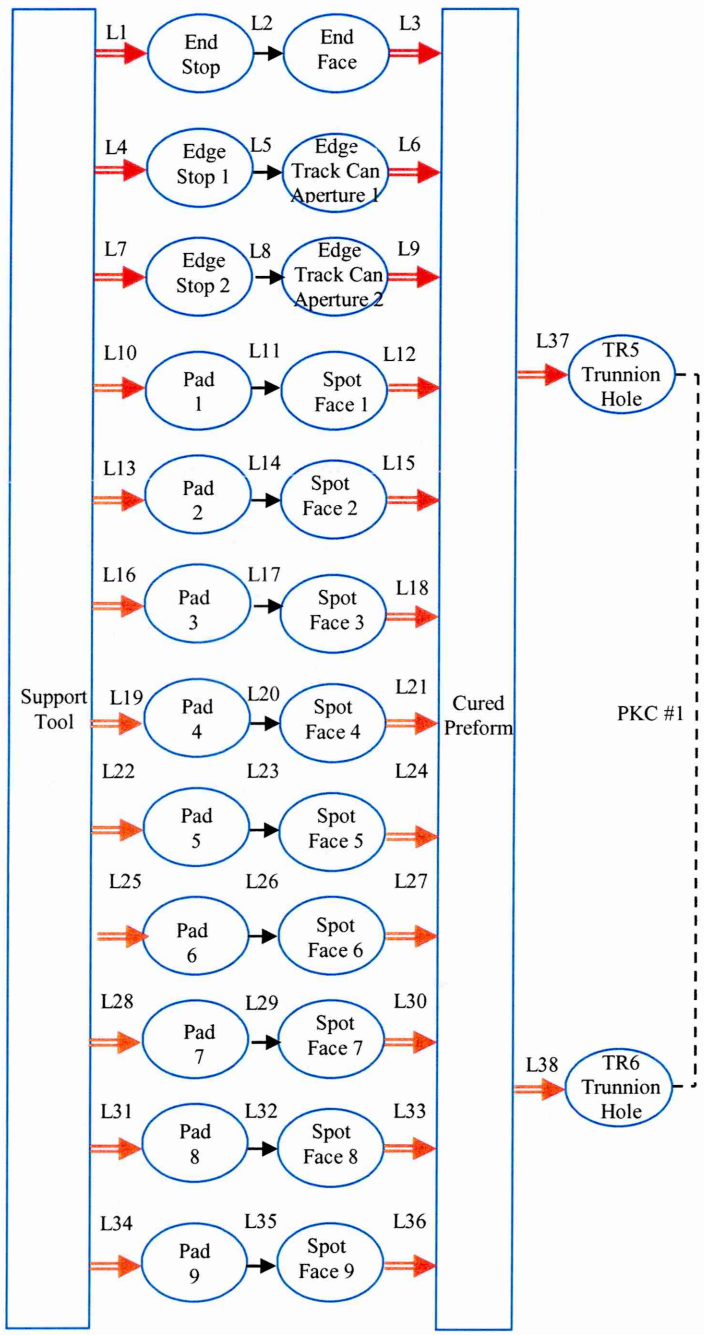
Abbreviations Used in the Case Study 2, FDFC Diagrams *Table 16*

See Section 5.11 for an explanation of FDFCs



Conventions Used in the Case Study2, FDFC Diagrams *Table 17*

Comments on the FDFC Analysis
For Case Study 2, Concept 1;
1. The assembly reference plane is formed by the nine spot faces.
2. The transfer error links, L13, L16, L19, L22, L25, L28, L31 and L34 are not included because their position relative to the build tool has no effect on establishing PKC#1.
3. The nine pads and the nine spot faces form a single, planar, entity with an error zone defined by a flatness tolerance.
4. Critical assembly features; including spot faces, track can aperture edges, and the trunnion holes; are established by 'hard inserts' in the form tool.
5. The transfer errors of the critical assembly features are calculated on the perceived positioning repeatability of the hard inserts.
6. Errors from the expansion differentials between hard inserts and carbon composites are considered negligible, as they are repeatable and can be allowed for in the design of the tooling.
7. The trunnion bearings will need to be adhesively bonded into the bearing holes in the track-rib pairs.
8. To ensure their correct positioning and alignment of the bearings it may be necessary to add pick-up arms to the build tool. If these prove necessary, there will be additional mate and transfer errors.
9. Lightweight tooling is acceptable as there are no in-process machining forces.



FDFC Diagram for Case Study2, Concept 1, PKC#1 *Fig. 139*

Feature Error Table – Case Study 2, Concept 1

PKC#1. Slat track geometry

PART	FEATURE	CALLOUT	LINK	Tx	Ty	Tz
Preform Location						
Tool	Edge Stop 1	POS	L4		0.005	0.010
Edge Stop 1	Nose	PFL	L5			x
Preform	Edge Track Can Aperture 1	POS	L6		0.005	0.040
Tool	Edge Stop 2	POS	L7		0.005	0.010
Edge Stop 2	Nose	PFL	L8			x
Preform	Edge Track Can Aperture 2	POS	L9		0.005	0.040
Tool	Pads	POS	L10		0.010	
Pads	Face	PFL	L11		x	
Preform	Spot Faces	POS	L12		0.010	
Trunnion Hole Locations						
Preform	TR5 Trunnion Hole	POS	L37	0.100	0.100	0.100
Preform	TR6 Trunnion Hole	POS	L38	0.100	0.100	0.100
			Sum of the Squares	0.02	0.02	0.023
			PKC#1 – RSS Error Metric for Case Study 2, Concept 1	0.251		
If Six Sigma process capability data is used: Then the predicted variations in the resolved Error Values are X0,141, Y0.141, Z0.141mm						

Feature Error Table for PKC#1 Case Study 2, Concept 2 *Table 18*

7.2.7.1.2 Concept 2 - Cost-Effective Parts Manufacture

Build Cycle

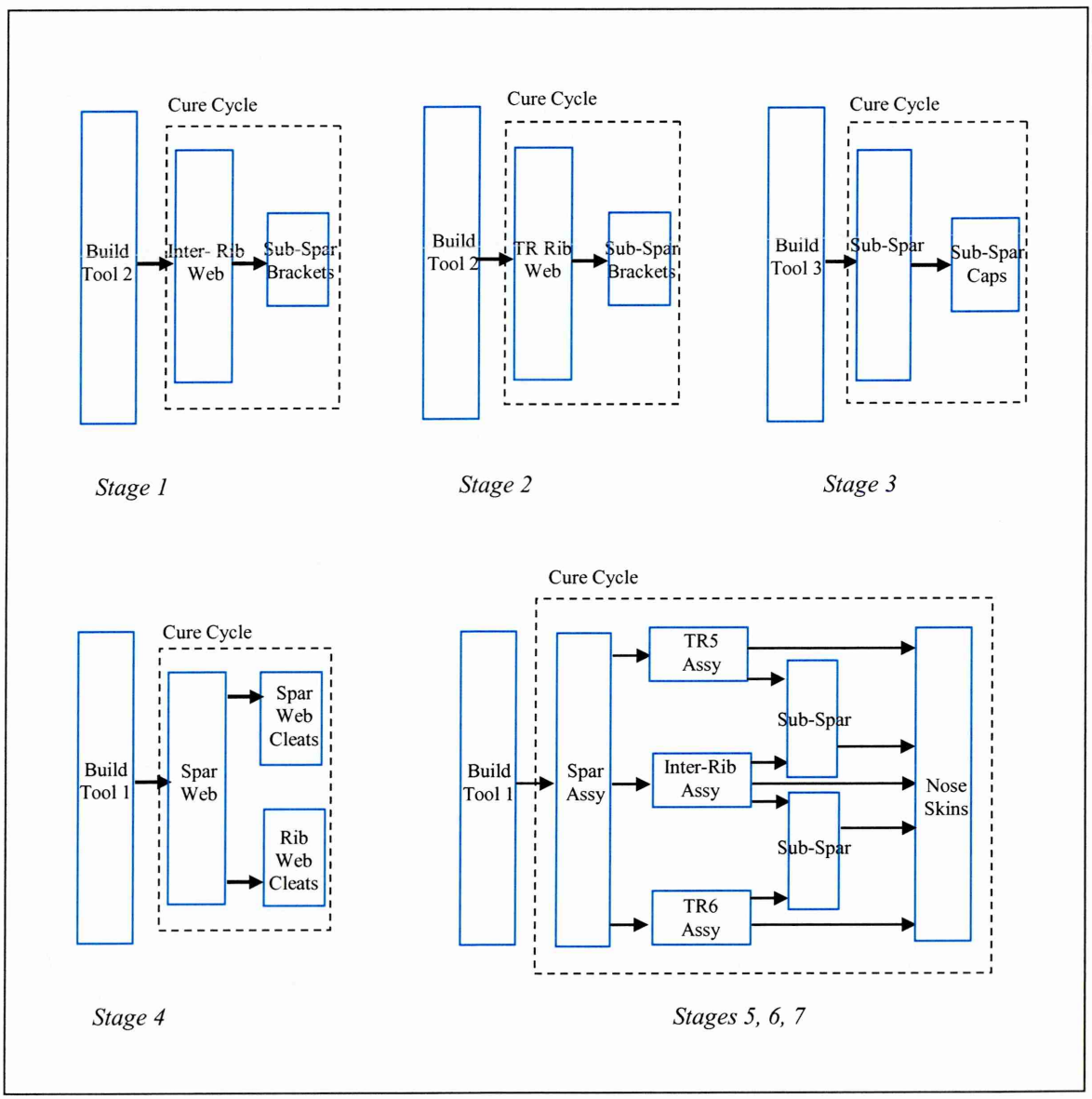
Flat Panels ⇒ Autoclave ⇒ CNC Machine ⇒ Build Tool ⇒ Spar ⇒ Cleats ⇒ (Ribs ⇒ Cleats) ⇒ Sub-Spars ⇒ Skin

Comments on the FDFC Analysis

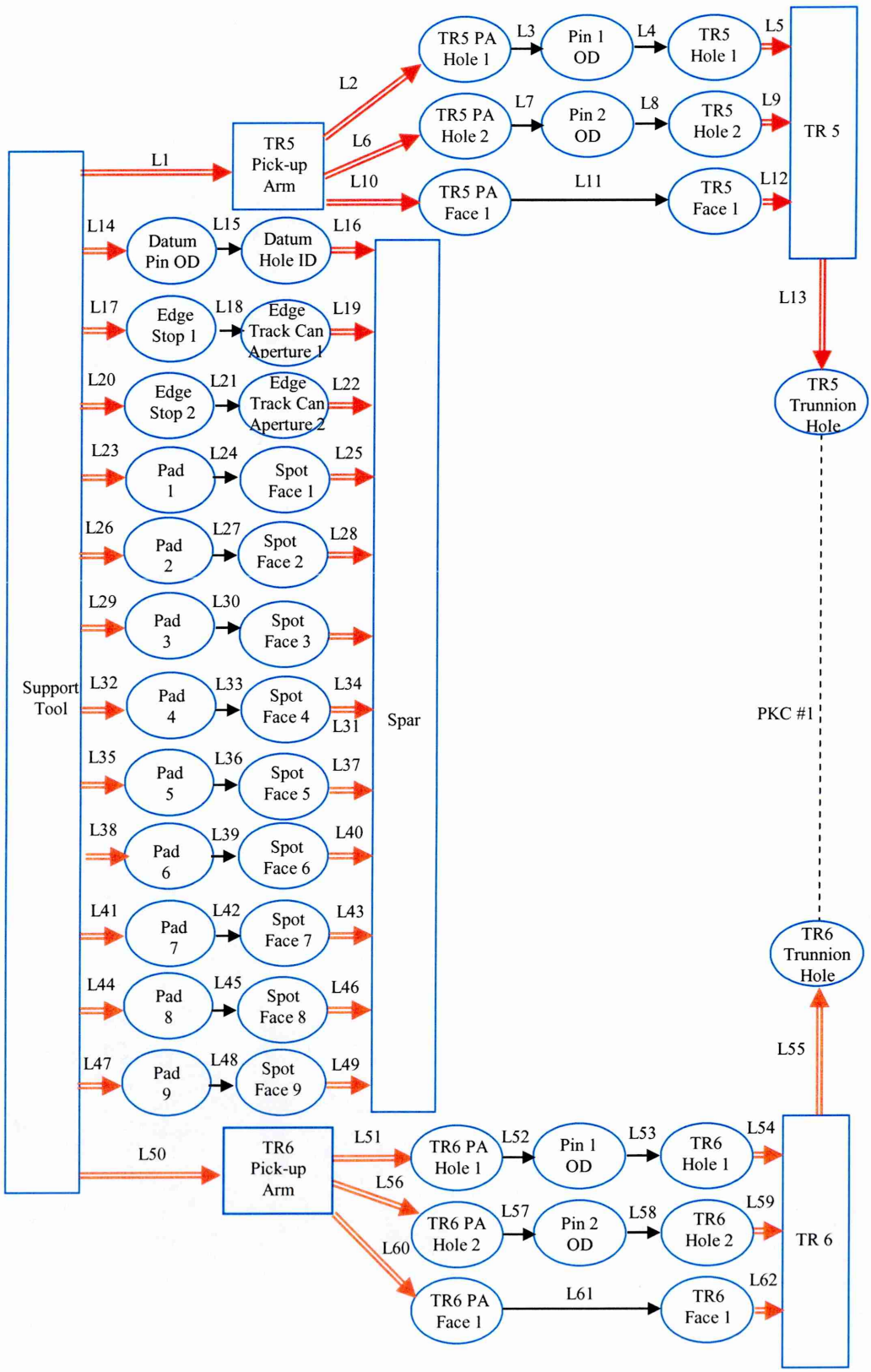
For Case Study 2, Concept 2;

1. The build tool must be carbon/epoxy composite to avoid problems of differential linear thermal expansion between the tool and the carbon/epoxy aerostructure.
2. The rib webs will be located in deep slots formed by pairs of opposing rib caps, (*See Figures 133 and 134*); the depth of the slots allows a small amount of corrective adjustment in the alignment of the trunnion holes. (Aircraft datum reference frame, 'Y-axis'; see *Figure 122*).
3. The slot-widths have clearance to allow for the adhesive bond-lines and the rib-webs are, therefore, located off pick-up arms, which are located off the build tool.
4. The pick-up arms are removable so as not to interfere in the later stages of the assembly.
5. For this concept, the relationship between the tool and the spar location is critical with the primary spar location being established by a diamond shaped datum dowel in the tool mating with a datum hole in the spar, (Datum Pin = 20ϕ. Precision location = H7+0.02+0, g6-0.008-0.02).
6. Location of the spar is not included in this partial analysis, as it is not part of the PKC #1 datum flow chain, (*Figure 141*).

7. Pick-Up arm face 1, flatness errors are included in the positional tolerance zone.
8. The hole diameters in the tooling and assembly are toleranced at LMC, (Least Material Condition), and, therefore, the diameter variations are included in the position callouts.
9. The trunnion bearings are adhesively bonded into the bearing holes of the track-rib pairs, at the sub-assembly stage.
10. The pick-up arms off the build tool achieve the correct positioning and alignment of the bearings. The associated transfer errors are included in the FDFC analysis.



DFC Diagrams for Case Study 2, Concept 2 *Fig. 140*



FDFC Diagram for Case Study 2, Concept 2 *Fig. 141*

Feature Error Table – Case Study 2, Concept 2

PKC#1. Slat track geometry

PART	FEATURE	CALLOUT	LINK	Tx	Ty	Tz
TR5 Trunnion Hole Location						
Pick-Up Arm	Sub-Datum	POS	L1	x		
Pick-Up Arm	Hole 1	POS	L2		x	x
Pick-Up Arm	Hole 1	MMC	L3		0.030	0.030
Pin 1	Shaft	LMC	L4		0.028	0.028
TR5	Hole 1	MMC	L5		0.030	0.030
Pick-Up Arm	Hole 2	MMC	L6		0.030	0.030
TR5	Hole 2	MMC	L7		0.030	0.030
Pin 2	Shaft	LMC	L8		0.028	0.028
TR5	Hole 2	MMC	L9		0.030	0.030
Pick-Up Arm	Face 1	POS	L10	0.160		
Pick-Up Arm	Face 1	FLT	L11	0.050		
TR5	Face 1	FLT	L12	0.050		
TR5	Trunnion Hole	POS	L13		0.025	0.025
TR6 Trunnion Hole Location						
Pick-Up Arm	Sub-Datum	POS	L50	x		
Pick-Up Arm	Hole 1	POS	L51		x	x
Pick-Up Arm	Hole 1	MMC	L52		0.030	0.030
Pin 1	Shaft	LMC	L53		0.028	0.028
TR6	Hole 1	MMC	L54		0.030	0.030
Pick-Up Arm	Hole 2	MMC	L56		0.030	0.030
TR6	Hole 2	MMC	L57		0.030	0.030
Pin 2	Shaft	LMC	L58		0.028	0.028
TR6	Hole 2	MMC	L59		0.030	0.030
Pick-Up Arm	Face 1	POS	L60	0.160		
Pick-Up Arm	Face 1	FLT	L61	0.050		
TR6	Face 1	POS	L62	0.050		
TR6	Trunnion Hole	POS	L55		0.025	0.025
			Sum of the Squares	0.061	0.013	0.013
PKC#1 – RSS Error for Case Study 2, Concept 2				0.294		
If Six Sigma process capability data is used: Then the predicted variations in the resolved Error Values are X0.247, Y0.114, Z0.114 mm						

Feature Error Table for PKC#1 Case Study 2, Concept 2 *Table 19*

Concept	**Metric PKC#1**	**Quality Comparison**
1. Metallic Structure		
Current Method of Assembly	0.363	100%
2. Composite Structure		
1 – Automated Fibre Placement by Directed Air Jet	0.251	145%
2 – Cost-Effective Parts Manufacture	0.294	123%

Initial Error Budgets for Composites PKC#1 *Table 20*

Table 12 allows a comparison between the calculated PKC#1 error budgeting metrics for the two selected composite concepts and the PKC#1 metric for the current method of

assembling the existing metallic structure, (*Table 8*). The results indicate that Concept 1 has the potential to produce assemblies with a 45% assembly quality advantage, and Concept 2 has the potential to produce assemblies with a 23% assembly quality advantage, or reduction in the build error. Chapter 8 discusses the significance of these results.

7.2.7.2 Final Decision Matrix

Concept / Criteria	1	2
Able to achieve PKC requirement?	Yes – Very easily	Yes - Easily
Low risk?	No - Considered to be a very high risk approach	Yes – Simple, well understood, processes
Good build-access?	Yes – Resin impregnated fibres are blown directly into the mould tool.	Yes – Pick-up arms are removable to give clear access during final assembly.
Applicable to entire length of Leading Edge?	Yes – But mould tool will need supporting structure.	Yes – No problem.
Are mouldings expected to be of adequate quality?	No – A lot of uncertainty with this concept.	Yes – No problems envisaged.
Avoidance of post-moulding machining?	Yes – Use of hard inserts in mould.	No - Parts will need to be machined from flat, laminated, panels.
Is concept suitable for automation?	Yes – Ideal for automation using a single robot.	Yes – But will probably require multiple robots
Minimal tooling requirement?	Yes – One master tool, one mould tool and a simple assembly tool to locate bearing inserts.	Yes –But needs very simple form tools and assembly tools. No master mould tools are needed.
Is the overall cost expected to be low compared to existing, metal system?	Yes –but mould tool will be expensive, and will need replacing every ten autoclave cycles.	Yes – very simple manufacturing and assembly processes.

Decision Matrix for Composite Concepts 1 and 2 *Table 21*

The questions in the 'Final Decision Matrix', (*Table 13*), are designed to attract Yes/No answers with qualifying statements. A 'Yes' answer is favourable to selection and a 'No' indicates that the Concept requires further development. The qualifying statements allow the IPD team members to highlight and discuss areas of uncertainty.

Concept 1 has enormous future potential to deliver high quality, monolithic, carbon composite, components, but the air jet technology needs more development and the IPD team agreed that to recommend it as a production process would be an unacceptably high risk.

Concept	Responses	
	Yes	No
1	7	2
2	8	1

Composite Concept Selection Scores *Table 22*

The scores, (*Table 14*), are too close to be accepted as a definitive result and a second iteration was made, (*Table 15*), this time weighting the 'risk' criterion to satisfy the IPD team's concern. (See Section 5.7.4).

Concept	Responses		Weighted Scores		Final Scores
	Yes	No	Σ+	Σ-	(Σ+)-(Σ-)
1	7	2	7	4	3
2	8	1	8	1	7

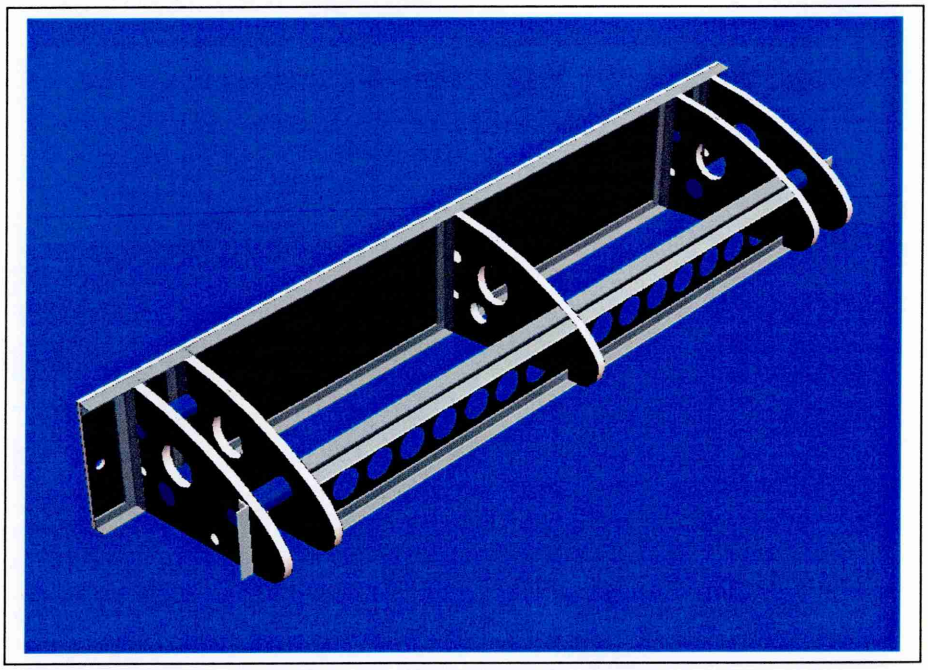
Composites Second Iteration Scores *Table 23*

The scores, (*Table 14*), are too close to be accepted as a definitive result and a second iteration was made, (*Table 15*), this time weighting the 'risk' criterion to satisfy the IPD team's concern. (See Section 5.7.4).

The second iteration, (*Table 15*), indicated that, based on the chosen selection criteria, Concept 2 is the better choice for development.

7.2.8 Embodiment of the Best Concept

Solid models were developed, (*Figure 142*), and the assembly process for Concept 2 was developed in greater detail, (Appendix F).



Solid Model of Composite Concept 2 *Fig. 142*

7.2.8.1 Risk Analysis

Table 16 lists and appraises the risks revealed in the development of the assembly plan, (Appendix H). The identified risks are all quality related and can be controlled and monitored through the introduction and enforcement of strict quality control procedures.

The Risk Analysis gave no reason to modify the assembly plan.

ID No.	Risk Identification	Probability	Impact	Preventative Action	Control & Monitoring
1	Poor quality bonded joints.	1 in 1000 Chance	£100,000 Scrap sub-assembly	Workforce education. Establish and enforce strict quality control procedures.	Management spot-checks. Manufacture and test pull-off specimens.
2	Poor quality parts.	1 in 100 Chance	£1,000 Scrap part or rework by hand	Collect process capability data. Visual inspection.	Statistical process control. Establish 6σ capability.
3	Tooling contaminated with old adhesive.	1 in 1000 Chance	£100,000 Scrap sub-assembly	Workforce education. Establish and enforce strict quality control procedures.	Visual inspection.

Risk Analysis - Composite Concept 2 *Table 24*

7.2.9 Costings Analysis

The composite design was completed after the end of the JAM project and was not fully costed. However, based on the findings of the AMCAPS projects, (Ref. 127), and compared to the existing metal structure and more conventional composite designs, it is reasonable to expect cost savings resulting from;

1. Simplified parts manufacture
2. Simplified assembly procedure
3. Low labour requirement
4. Low skill requirement
5. Simple, cheap, and light-weight assembly tooling
6. Low assembly tooling requirement
7. No in-process drilling
8. No fasteners
9. No insertion and setting of fasteners
10. No requirement to strip down and de-burr
11. No complex form tools
12. No master tooling

Additional Life Cycle cost savings can be expected from a reduced maintenance requirement and a lighter weight airframe, (*Figure 129*).

On the negative side are the higher costs of the raw materials and the cost of waste-disposal, nevertheless, it is reasonable to expect cost and weight savings both approaching 20%, (Refs. 128 and 129).

7.2.10 Presentations

Although the JAM advanced composite design was never formally presented as part of the JAM project, its' merits were discussed with a number of experts, including Dr. Paul Anstice, (Appendix B), who had responsibility for the AMCAPS wing-box design. (Ref. 127), (See *Figure 10*).

In general this concept is considered entirely practical although it is expected that the CAA would insist on some mechanical fasteners to cover the possibility of a bonded-joint failure.

7.3 Process Capability Database

When the JAM project was originally envisaged it was intended that the existing data would be collected and collated to provide the JAM Methodology with a process capability database. As the project progressed it became apparent that very little of the correct data existed, (See Section 3.5.2), and that machining and forming data are only part of the requirements. It was also found that because of commercial work-sharing agreements the front spar of the Airbus A320, for example, may be machined in the United States, China, Chadderton UK, or Chester UK. As the sub-contractors each write their own CNC software, have their own machining criteria, and design their own work-holding and handling systems, they will also have created different 'Manufacturing Key Characteristics', (MKCs – Section 5.5).

Therefore the process capability index, (*Cpk*), (Section 4.12.2), of a part or a critical feature will vary dependent on the sub-contractor and the place of manufacture.

The research also revealed other important factors that can impact on the compliance of parts to the design intention. These are listed below in *Table 3.*

1. Tolerance on material specification	
2. Source of material billet	(Section 3.2.1)
3. Planar milling of billet	(Section 3.2.1 and 3.2.2)
4. Part manufacturing process	(Section 3.2)
5. Machine system	(Section 3.2 and 4.7)
6. Machining sequence	(Section 3.2.1 and 3.2.2)
7. Machining parameters	(Section 5.2 – MKCs)
8. Residual stresses	(Section 3.3.6)
9. Work holding system	(Section 4.3)
10. Ambient Temperature	(Section 4.1)
- machining	
- assembly	
11. Direct solar radiation	(Section 4.1.1)
12. Local heat sources	(Section 4.7)
- lights	
- spindle	
- coolant	
13. Handling	(Section 3.3.1 and 4.5)
14. Transportation	(Section 3.3.4)
15. Surface treatments	(Section 3.2.9 and 3.2.10)
- pickling	
- shot-peening	
- chromate primer	
- painting	
16. Paint curing process	
17. Storage	

Factors Effecting the End Quality of Parts *Table 25*

There are many text and reference books that analyse manufacturing processes and determine the process capabilities in terms of achievable part attributes and generalised tolerances. (Ref. 76). However in many manufacturing industries and as the above list shows, particularly in aerospace manufacture, parts undergo a number of additional processes before reaching the assembly line.

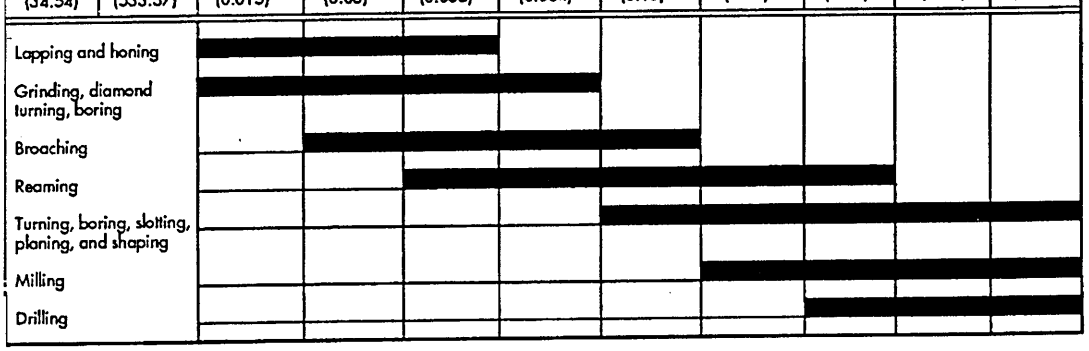
All of these processes must be under statistical control before JAM can be successful and the designer needs to know the, 'as delivered to the assembly line, Six Sigma process capabilities', in order to establish realistic tolerances for the part-features that deliver the Product Key Characteristics, (See Section 5.5).

The best way to compile this compounded process capability data is to:

- Follow existing component parts through machining or forming, finishing processes, storage, handling and transportation.
- To measure and record critical dimensions and geometric profiles at each stage.
- Establish how the processes affect the finished component.
- Determine the 'as delivered to the assembly line', compounded Six Sigma process capabilities.
- Develop a Six Sigma process capability database for JAM.

This is major undertaking and requires considerable support and input from the industrial companies over an extended period. It was accepted that this was not possible within the JAM timetable and is, instead, included in the proposal for a follow-on project.

Range of sizes, in. (mm)		Tolerances, ± inches (mm)								
From	Through									
0.000	0.599 (15.22)	0.00015 (0.0038)	0.0002 (0.0051)	0.0003 (0.008)	0.0005 (0.003)	0.0008 (0.020)	0.0012 (0.030)	0.002 (0.05)	0.003 (0.08)	0.005 (0.13)
0.600 (15.24)	0.999 (25.37)	0.00015 (0.0038)	0.00025 (0.0064)	0.0004 (0.010)	0.0006 (0.015)	0.001 (0.03)	0.0015 (0.038)	0.0025 (0.064)	0.004 (0.10)	0.006 (0.15)
1.000 (25.40)	1.499 (38.07)	0.0002 (0.0051)	0.0003 (0.008)	0.0005 (0.013)	0.0008 (0.020)	0.0012 (0.030)	0.002 (0.051)	0.003 (0.08)	0.005 (0.13)	0.008 (0.20)
1.500 (38.10)	2.799 (71.09)	0.00025 (0.0064)	0.0004 (0.010)	0.0006 (0.015)	0.001 (0.03)	0.0015 (0.038)	0.0025 (0.064)	0.004 (0.10)	0.006 (0.15)	0.010 (0.25)
2.800 (71.12)	4.499 (114.27)	0.0003 (0.008)	0.0005 (0.013)	0.0008 (0.020)	0.0012 (0.030)	0.002 (0.05)	0.003 (0.08)	0.005 (0.13)	0.008 (0.20)	0.012 (0.30)
4.500 (114.30)	7.799 (198.09)	0.0004 (0.010)	0.0006 (0.015)	0.001 (0.03)	0.0015 (0.038)	0.0025 (0.064)	0.004 (0.10)	0.006 (0.15)	0.010 (0.25)	0.015 (0.38)
7.800 (198.12)	13.599 (345.41)	0.0005 (0.013)	0.0008 (0.020)	0.0012 (0.030)	0.002 (0.051)	0.003 (0.08)	0.005 (0.13)	0.008 (0.20)	0.012 (0.30)	0.020 (0.51)
13.600 (34.54)	20.999 (533.37)	0.0006 (0.015)	0.001 (0.03)	0.0015 (0.038)	0.0025 (0.064)	0.004 (0.10)	0.006 (0.15)	0.010 (0.25)	0.015 (0.38)	0.025 (0.64)



Tolerance Ranges for Basic Machining Processes *Table 26*

For the case study analyses to be as realistic as possible, generalised process capability data was compiled from published information, (Refs. 42, 112, 113, 114, 115, 116), and the considerable depth of specialised knowledge within the School of Industrial and Manufacturing Sciences at Cranfield University.

This is summarised in *Tables 26 to 30.*

Dimension	Tolerance (mm, °)
x	± 2.0
x.0	± 0.8
x.00	± 0.30
x.000	± 0.08
Angles	± 0.5 °

General Machining Tolerances *Table 27*

Up to 2M, accuracy = 0.010mm at ±1°C
Up to at 9M, accuracy = 0.020mm at ±1°C
Up to at 17.5M, accuracy = 0.035mm at ±1°C

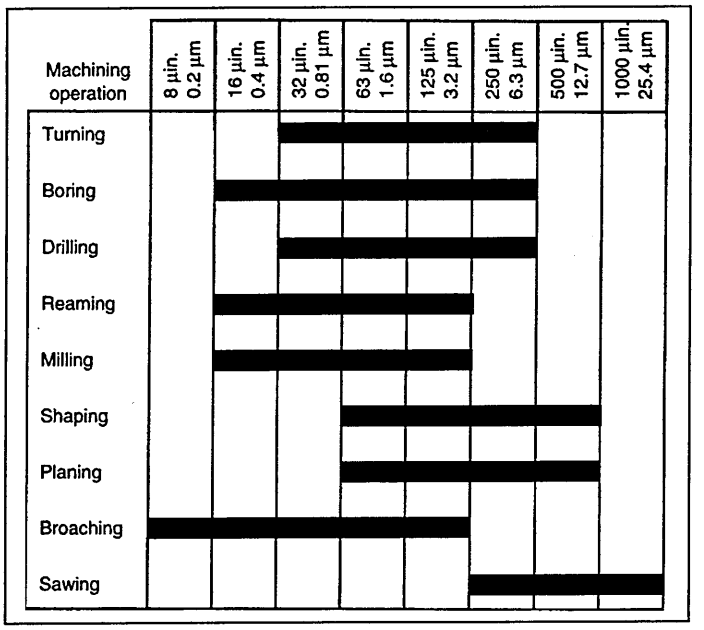
Laser Tracker Accuracy *Table 28*

Reaming	Up to 0.5" (12.7 mm) diameter	±0.0005" (±0.013 mm)
	Over 0.5" to 1" (12.7 mm to 25.4 mm) diameter	±0.001" (±0.03 mm)
	Over 1" (25.4 mm) diameter	±0.015" (±0.04 mm)
Boring	For boring up to 1" (25.4 mm) diameter	±0.0003" (±0.008 mm)
	Over 1" to 1.5" (25.4 mm to 38.1 mm) diameter	±0.0005" (±0.013 mm)

Economical Tolerances for Reaming and Boring *Table 29*

Notes:

1. General machining tolerances to apply unless otherwise stated
2. Sealant and paint allowance = 0.25mm



Surface Finish Values *Table 30*

8.0 DISCUSSION AND CONCLUSIONS

This chapter discusses the JAM research programme and the importance of JAM to the European aerospace industry. It then continues with statements on the 'Weaknesses and Limitations of the JAM Methodology', and the 'Original Contributions to Knowledge', before ending with a numbered list of 'Conclusions'.

8.1 The Industrial Based Research Programme

In a little over thirty years, Airbus Industrie has risen from its conception to overtake Boeing and become the world's premier manufacturer of large passenger aircraft. This has been achieved through the company seeking competitive advantage in design innovation and by encompassing new manufacturing technologies. JAM is seen by many as being the next big technologically competitive step.

All new Airbus designs are now computer generated solid models able to directly supply any required part-manufacturing and tooling information, with a subsequent reduction in tooling gauges, tooling errors, and accumulated build errors, (Section 4.2).

This, however, will not prevent poor tooling design. Examination of the existing tooling revealed that parts are often over-restrained creating competition between locating features that causes build-variables and results in variable assembly errors, (Section 3.5.6).

Design for kinematic restraint is not covered in the tooling design handbook, (Ref. 42), and although the tooling designers talked about the 1-2-3 principle, they were vague about the effect of over-restraint. The research revealed that in practice they 'play safe', and the tooling for a new aircraft is based on the design of tooling for earlier aircraft, only making changes to satisfy new requirements.

This is a design mind-set encountered throughout the industry and is a result of aerospace design being largely derivative with, for example, a new Airbus wing being a smaller or larger version of the original Airbus wing. In addition, the rate of introduction of new aircraft and the time to develop means that designers only ever work on a handful of new designs. Since most training takes place 'on the job', personal acquisition of data is slow, leading to an in-built resistance to change, and the development of a company culture, (Ref. 130). Interview questions were sometimes answered with statements such as, 'We always do it this way', and 'We know that this method works'.

The JAM Methodology is designed to overcome this resistance with a simple, easy to use, assembly analysis tool, together with simplified costing and risk analysis within a logical design algorithm.

The assembly analysis includes any tooling and inspection equipment errors; and by concentrating on the Featurised Datum Flow Chains, and the delivery of the Product Key Characteristics, the Methodology can be used in the very early stages of design.

Thus allowing the validation and comparison of alternative assembly concepts ahead of the commitment to detail design.

The JAM Methodology is unlike existing commercially available DFA packages such as those described by Pugh, (Ref. 95), Boothroyd, (Ref. 131), Miles, (Ref. 132), Swift, (Ref. 133), and Munro, (Ref. 134). These are best applied once the design is complete and have a scoring system that penalises the use of tooling, without the ability to analyse whether or not the tooling is needed for the assembly plan to achieve the PKCs.

Application of the JAM Methodology would have helped to avoid the tooling design error described in Section 3.3.6 by highlighting the unsuitability of the slat track can hole as an assembly datum.

Manufacturing has no equivalent to the design inertia, perhaps, because from the very beginning Airbus Industrie has had a positive attitude of being competitive by identifying and encompassing new manufacturing technology. As a result, the sub-structure of an Airbus wing consists of large monolithic CNC machined parts, whereas the sub-structure of a current Boeing wing consist of fabricated sub-assemblies each having a high part count.

Modern CNC machines have sufficient accuracy to allow part-to-part assembly, (Section 4.7), permitting a reduction in the quantity and complexity of assembly tooling and a simplification of the remaining tooling to supporting and stiffening structure for the larger and more flexible parts. (That is 'Contacts' – Section 5.11.1).

There are three problems identified with proposing part-to-part assembly:

1. After CNC machining the parts are subjected to a number of finishing processes, including painting, which change the part dimensions and possibly form, (Sections 3.2.9, 3.2.10, 3.2.11). To make progress with JAM the process capabilities must be determined and fed into the design and tooling loop.

The need to determine process capability, (Section 4.12), is widely recognised within the industry. Without it the JAM Methodology can still be applied using generalised machining data, but only to generate metrics for comparing alternative assembly concepts, (Section 5.12). Six-Sigma process capability is needed to determine the ability of an assembly plan to deliver the PKCs. This is not just knowledge of the part machining or forming capability, but the knowledge of, when it is delivered to the assembly cell, how closely the part will conform to the original design intent.

2. In-situ drilling of fastener holes is still the best engineering solution due to the positional accuracy necessary to align holes in several different parts, and the diametrical tolerancing necessary to ensure the correct fit of the fasteners. (See Section 2.1.1.7 and *Figure 13*).

The associated disassembly and deburring is an expensive activity that is unnecessary if a sufficiently high and direct clamping force can be applied during drilling, (Section 3.2.6). Alternative methods of burr-free fastener-hole production are being researched,

including laser and ultrasonic drilling, (Section 2.1.1.7), although the real solutions are probably welding and adhesive bonding, (Sections 4.9.1 and 4.9.2). Application of the JAM Methodology will result in simpler and less tooling, giving better access for clamping, drilling, and fastening tools.

Further, once the design is fully solid modelled it will be possible to determine which parts can be adequately clamped during drilling, and which parts will need to be dismantled and deburred.

3. The JAM Methodology requires that the links in the FDFCs are toleranced such that the completed assembly will deliver the PKCs, (Section 5.11). This is a step change from the normal aerospace practice of blanket tolerancing parts by category, (Section 3.4), and then relying on the tooling to ensure delivery of the PKCs.

This change is already well advanced with designers being instructed in the use of GD&T, (Section 5.9). GD&T is the way that the JAM Methodology brings process capability data into the design and tooling tolerance loops, thus enabling the identification of suitable manufacturing technologies, eventually down to being able to identify specific machines. All new Airbus designs will use GD&T dimensioning.

8.2 The Enabling Technologies

It was obvious that JAM cannot be achieved with the application of a single technology; therefore, part of the research focused on identifying existing and emerging 'Enabling Technologies', (Chapter 4), and to consider what their role might be in achieving JAM.

The effect of differential thermal expansion between parts is a major problem that can result in an unacceptable distortion of large parts when they are released from the assembly tooling. The problem is well understood and tooling designers are innovative, but not always successful, in their solutions, (Section 4.1).

The changes needed to achieve JAM provide an opportunity to pursue a holistic approach and the JAM research and associated internal reports highlighted a number of steps that can be taken towards converting the existing large assembly sheds into passive buildings. The one-off cost will be high, but unlike air conditioning, (which is prohibitively expensive for such large volumes of space), there are no recurring costs and the building running costs will be reduced. This part of the research was not well received with the industrialists failing to understand the need for a holistic approach and arguing that the JAM project was about tooling and not building design. However, when the paper on enabling technologies, (Ref. 7), was presented at an SAE conference in Seattle the opposite was true. Boeing later proudly showed the conference delegates around the final assembly of the 747 aircraft explaining that as the building is so large it has its' own micro-climate with a very stable temperature making it conducive to the building of large aerostructure.

The tendency of the aerospace industry to focus on a specific problem and fail to find the complete answer by standing back and looking at the larger picture is a reoccurring

problem. It is probably the result of engineers being confined to work within their own areas and not having the knowledge or seniority to look elsewhere for a solution. This shortcoming is currently being addressed through bespoke short courses run by a consortium of universities[1], and university developed e-Learning modules[2] accessible on company intranets.

The industrialists, who almost certainly had inside knowledge of many of them, including the airframe welding research being undertaken in Russia and Cranfield[3], readily accepted the reviews of the other enabling technologies.

It is planned that future developments of the JAM Methodology will include a decision-making algorithm to identify suitable enabling technologies based on a description of the task and the required process capability. Looking even further into the future, coupled software could look at known and forecast machine and process loading, and suggest alternatives or, to identify the need to purchase duplicate equipment when necessary.

8.3 The Design Methodologies

There was now an understanding of how JAM might be achieved but there was still a need to develop a simple design methodology that designers would be willing to follow. Too complicated or too time-consuming and it was apparent from the interviews, (Appendix B), that it would be paid, 'Lip service', but not followed in practice. Occurring too late in the design process and the cost of changes and the need to commit and meet deadlines would prevent its acceptance.

The approach taken was to start with the traditional, and basic, design algorithm and undertake the re-engineering of the A320 fixed leading edge from a JAM assembly centric perspective. Since this is beyond the scope of the basic algorithm, it was necessary at each stage of the task to stop and research, or develop, suitable tools and methodologies, (Chapter 5). These became additional procedures integrated into the basic design algorithm and eventually forming the assembly centric JAM Methodology.

The traditional design algorithm is essentially a linear process with iterative feedback loops. Over time, a number of tools have been developed to clarify the design requirement, aid the decision making processes, and to make the whole design process more inclusive, (Section 5.4). These tools are important as they encourage discussion, and the inclusion in the design process, of the members of multi-disciplinary IPD teams, (Integrated Product Development).

In recent years Dr. Daniel Whitney and his research students at the MIT, (Massachusetts Institute of Technology), have researched problem solving in existing complex assemblies for the Ford motor company and Boeing aircraft. Their description and use of Key Characteristics, (Ref. 85), to capture the important characteristics of an existing

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[1] BAE SYSTEMS, 'Manufacturing Developing You', short course modules
[2] BAE SYSTEMS, 'Engineering Developing You', e-learning modules
[3] CEMWAM II, 'Arc Welding Process Improvement for Airframe Applications', current EPSRC-IMRC research project at Cranfield University, Principal Investigator – S Blackman.

product is used as a tool in the developing JAM Methodology to establish the focus for a JAM design. This not a new concept as designers have always intuitively identified product key characteristics, (PKCs), and then considered how best to achieve them, (AKCs), and, similarly, manufacturing engineers have always needed to establish the manufacturing key characteristics, (MKCs), (Section 5.5). For many designers and engineers, the terminology will be new, but the thought processes will be familiar.

The MIT researchers have also developed a methodology for conceptualising the design of complex assembles that includes the role of the tooling, (DFCs – Section 5.10), (Ref. 101), and then further extended the concept to include the actual mating features (FDFCs – Section 5.11), (Ref. 102). The JAM research concluded that by developing the MIT work and adding compounded process capability tolerances to the features in the chain, it will be possible to predict the errors in a conceptual assembly. This gives the JAM Methodology the ability to accurately determine the capability of an assembly plan to deliver the PKCs, and to compare the efficiencies of alternative assembly plans by comparing the assembly errors.

The way is now open for JAM designs, and an IPD team can determine when part-to-part assembly is viable or when tooling must be used.

As the need for hard tooling is reduced, it's several roles, (Section 3.5.7), must be embedded in the design of the individual parts and in the capabilities of the manufacturing, and assembly processes, (Ref. 5). This can be achieved by supplying parts that match the design intent, and by incorporating location, holding, and reference features in the detail design of parts.

The JAM project included the compilation of a features library, (Integrated tooling), by Naing, (Ref. 78), (Sections 1.8 and 5.8), together with the outlining of a framework for feature selection, (Ref. 97). A simplified finite element, (FE), analysis by Odi, (Ref. 108), on the effects of adding location features to the existing front spar indicated that the features would be unacceptably high stress raisers. Incorporating them would require a totally new spar design, accompanied by a programme of rigorous, and very expensive, mechanical testing.

This does not mean that location features can never be used, but that they must be designed in at the very beginning of the design process. This fits in perfectly with the developing JAM Methodology where the FDFC analysis is to be performed at the conceptual design change and well ahead of any detail design.

The need to incorporate FE analysis in the features selection had long been recognised, but the specialisation required and the time taken, to complete even a simplified analysis, was disappointing as the aim was to develop a simple, easy to use, design methodology.

However, all was not lost as further research discovered that researchers at the University of Hull, working under Prof. Ken Swift have developed a PC-based expert system called, 'SCONES', (Stress Concentration Expert System), to provide a 'rapid

determination of stress concentration factors for a range of diverse features', (Ref. 135). It is hoped that eventually it will be possible to integrate JAM and SCONES.

At the 'Embodiment of Assembly Concept' stage, finite element analysis will be the province of a dedicated specialist.

Two final, traditional, tools are included in the JAM Methodology; cost analysis and risk analysis, (Sections 4.4.6 and 5.13). As design is an iterative process it is intended that first time around the loop and at the, 'Selection of Best Concepts', stage these should both be at a superficial level within the ability and time-scale of a designer and IPD team discussions.

At the 'Final Assembly Concept Selection' stage, cost and risk will require deeper analysis by dedicated specialists.

Similarly, a dedicated expert, (Ref. 136), is needed to perform the final tolerance tuning using a commercial tool such as VALISYS/Assembly.

8.4 A Design Methodology for JAM

The JAM Methodology embraces and builds on the traditional design process and the published work of other researchers. The result is a Methodology for assembly centric JAM design aimed at reducing the need for product specific tooling. The rationale underlying the Methodology is a conviction, arrived at from the research, that to achieve JAM, the assembly process, the integrated tooling, and integrated reference features, must all be designed simultaneously, and together with any hard tooling considered as an integral part of the assembly. This is at odds with current practice which is to first design the assembly, then design the tooling to manage the assembly, then decide how the completed assembly is to be inspected.

It may seem that this is placing an intolerable burden on the designer, but the designer is no longer working alone; he is part of an IPD team that collectively has the necessary skills and a sharing of the workload.

The main strength of the JAM Methodology is its simplicity in establishing at the conceptual design stage the viability of a given assembly plan and enabling a real comparison between alternative assembly plans.

Unlike existing practice, this is not based on a 'gut feeling' or experience, but on numerical analysis of the links and the mating features that create the FDFCs delivering the relevant PKCs.

This is also a different approach to that originally proposed by the JAM researchers and as presented in a number of the JAM conference papers, (Appendix G and Section 5.12).

Originally, it was proposed that in order to compare the efficiencies of alternative assembly plans and designs, all of the high level PKCs for a given assembly should be

identified and then to calculate and summate the transfer and mate errors making up the FDFCs. This technique proved to be very time consuming and, of course, the single metric gives no indication that an assembly plan will be able to deliver the PKCs. As a result the two case studies, (Chapter 7.0), have been performed using a simplified and much quicker variation of the original technique.

In both case studies only the FDFC delivering the dominant high level PKC is evaluated. The resultant is then used to compare the efficiencies of the alternative assembly schemes. If Six Sigma process capability is used in the FDFC analysis, then the resultant values for the X, Y, and Z errors can be compared directly with the design tolerance attached to the reference dimension controlling that PKC. This will determine whether that PKC will be delivered, (See *Tables 10, 11, 18, 19*). Any known errors or uncertainty of measurement associated with the in-process measuring systems are to be included in the error budget analysis.

8.5 Testing and Evaluation

Case Study 1, the JAM re-engineering Methodology together with the re-engineered A320 leading edge were presented at separate meetings to the University JAM teams and industrial collaborators, the A320 Single Aisle Programme, A320 Leading Edge Assembly Team, A380 Design Team, and EADS. The feedback was extremely positive from the managers and the assembly cell leaders but marginally less so from the designers who claimed to be already doing most of it intuitively, without the need for a formal JAM framework.

This is true and was recognised during the industrial research, but the researchers also discovered that there is company culture and design inertia that are preventing the change to JAM.

As previously explained, most training is, 'On the job', and personal acquisition of data is slow due to the very low number of new aircraft that designers will work on. The JAM Methodology provides a simple, easily followed, framework that guides a relatively inexperienced designer towards a JAM solution. Few design graduates have been recruited in recent years and the retention rate between new projects is poor making the adoption of the JAM Methodology even more important for future competitiveness.

With permission of the JAM collaborators, the Methodology only, was presented at conferences in the United States, France, Israel, and the UK. Both nationally and internationally, the Methodology was extremely well received and led to the later development of short course and e-learning modules for BAE SYSTEMS, related work from Airbus France, two workshops for Saab Aerospace in Sweden and fact-finding visits from Boeing.

Case Study 2, the JAM design Methodology applied to an advanced composite design, was not formally presented as part of the JAM project. However, the new design has been discussed with a number of experts, including Dr. Paul Anstice, (Appendix B), who had been responsible for the AMCAPS wing-box design. (Ref. 127).

In general, this concept is considered entirely practical although it is expected that the CAA would insist on some mechanical fasteners to cover the possibility of a bonded-joint failure.

The application of the design Methodology to a composite structure raised an interesting anomaly. For although the Methodology is intended to reduce assembly tooling, when applied to composites this can result in very complicated and expensive mould tools with a corresponding increase in development costs, and a high risk of moulding failure, (Section 7.2.5). Additionally, carbon/epoxy mould tools are moulded over master tools, and the mould tools can only be used approximately ten times as the heating and cooling cycles gradually degrade the resin.

The approach taken for Case Study 2 was to opt for a minimal mould tool requirement knowing that it would result in an increase in assembly tooling. Consciences were, however, assuaged, in the knowledge that the assembly tooling can very simple and very cheap, and, because it does not have to withstand in-process machining forces, can be assembled from readily available modular aluminium sections, (Section 7.1.6, Concept 5).

This is in line with the stated need to reduce cost, (Sections 1.3 and 1.4), and demonstrates that the Methodology is not single-mindedly focused on reducing tooling, 'at all costs'.

8.6 Research Methodology

There was some frustration in the first year of the programme when the team's industrial 'Champion', (Section 1.10), was unable to be fully involved with the research.

During that period, it became difficult to find the right people to interview, and to obtain the necessary engineering drawings and structural parts. This problem was resolved with the appointment of another, 'Champion', and the research programme was then able to surge ahead.

The decision to follow the interpretive research method proved to be a good one, as it allowed data collecting, and hypotheses forming and testing, to happen almost simultaneously. This worked best when the Cranfield researchers formed an IPD team and 'Brainstormed' the research data, occasionally with the research teams from the other Universities and the industrialists.

The 'Brainstorming' sessions proved an excellent way of collectively analysing the data and getting everyone involved. The occasional involvement of the other University teams and the industrialists also created friendships and gave those present a sense of ownership and an interest and awareness outside of their own particular research field.

Similarly the decision to go for private, 'face-to-face', interviews also proved to be the correct one. The interviewees were often very open in private suggesting solutions to problems but became 'Company' men in public. As before, the ability to form hypotheses and to discuss them with these very experienced practitioners proved an

excellent way of getting them interested in the JAM project and of testing the hypotheses.

In between travelling and interviewing the research team shared part of a large office at Cranfield a situation that further encouraged cross-fertilisation of ideas and allowed easy supervision by the author of their personal research projects, (Section 1.8).

Summarising it can be said that the research methodology worked extremely well, probably because the researchers worked well together and complimented each other.

8.7 Results

The JAM Methodology was evaluated through a re-engineering project, (Section 7.1), and an original design project, (Section 7.2). The purpose was to find out how easily the Methodology could lead a designer to a JAM design and assembly plan, and whether the end result would be cheaper that the existing design without any loss of quality - where quality is defined as the size of the error associated with the FDFC delivering the dominant PKC.

The JAM design process is covered in depth in Chapter 7 and worked extremely well with the algorithm being simple and easy to follow. The testing was undertaken as IPD team exercises and again emphasises how important group activity is in creating a sense of involvement and in getting the best out of everybody.

It is recognised that as the Methodology stands there is a great reliance on the teams' joint knowledge in creating alternative concepts and in selecting the enabling technologies. It is planned that eventually these tasks will be aided by, 'Knowledge Based', computer programmes.

Once the basic principles were established, the effectiveness of the, 'Error Budgeting', technique in establishing the efficacy and quality of alternative assembly concepts was impressive in its simplicity.

The re-engineering exercise resulted in a JAM assembly process that needs only a single hard tool to support the spar. The composite, original design, JAM assembly process requires additional light-weight tooling to support parts during adhesive bonding, but at a cost saving over opting for monolithic components and very complex form tools.

A cost model, (Section 7.1.10), was used to evaluate the re-engineering exercise and found that the proposed design complete with automated drilling and fastening systems would produce a 6% recurring cost saving. The real saving is even greater as the cost model included the cost of the new base tool and the automated systems. However, it did not include the cost of the original tooling as that already exists and has been amortised over twenty five years into the cost of the end product.

At the same time the Error Budgeting returned a comparative quality value of 117% for Case Study 1 and 123% for Case Study 2 establishing that all three criteria for success, (Section 1.13), had been achieved.

As reported in Section 7.1.11 the many presentations generated a lot of enthusiasm for using the Methodology including from the head of design, but his enthusiasm was not shared by his designers. There could be several reasons for this including the fear of change, or perhaps the 'Not invented here', syndrome.

8.8 Weaknesses and Limitations of the JAM Methodology

The JAM Methodology has been proven to be successful but there are three issues that are considered to be its' weaknesses and limitations:

1. The aerospace industry must know its' process capabilities before JAM can become a reality. Without that knowledge it will have no alternative, but to continue with embedding the desired end-quality of its structure into hand-built hard tooling.

2. The JAM Methodology is unlikely to be used outside of the aerospace industry, because although it is generic and applicable to other industries, there are no other industries using hard tooling in the same manner as the aerospace industry.

3. In the form described in this thesis, the JAM Methodology relies too much on the joint experience and knowledge of the IPD team, particularly in the selection of enabling technologies and assembly features. There is a need for the development of computerised expert systems to aid the decision making processes.

8.9 Original Contributions to Knowledge

From the list of fifteen given by Phillips and Pugh, (Ref. 137), the following eight reasons are used to claim the originality of this thesis.

1. Using already known material but with a new interpretation

This thesis is radical in arguing that JAM DFA must be applied at the conceptual design stage. By doing so it completely changes the existing aerospace design sequence in making the tooling design concurrent with the structural design and allowing DFA analysis at the conceptual design stage, (See Chapter 6).

2. Making a synthesis that has not been done before

The JAM Methodology is a unique assembly centric design process consisting of many traditional design tools, plus new tools and databases specifically developed for JAM.

3. Being cross-disciplinary and using different methodologies

The research was cross-disciplinary requiring interviewing techniques, field research and analysis, library and Internet research, multi-disciplinary brain storming sessions, development of new methodologies, re-engineering and engineering design, solid modelling, and case study evaluation.

4. Adding to knowledge in a way that has not previously been done before
By using Six Sigma process capability data in the design and analysis of the FDFCs it is now possible to accurately predict the ability of a given assembly plan to meet the PKC requirements, ahead of any expensive detail design.

5. Using already known material but with a new interpretation
Although aerospace companies use IPD teams and talk of concurrent engineering, in reality the assembly has to be at an advanced stage of design before the tooling to manage the assembly can be designed, and only then can the inspectors decide how to inspect the completed structure.

The JAM Methodology allows the assembly, the integrated tooling and integrated reference features to be designed simultaneously, with any hard tooling being considered as an integral part of the assembly, (Chapter 6).

This will result in reduced lead times, fewer design errors, fewer shop-floor problems, and ultimately cost savings.

6. Looking at areas that other people in the discipline haven't looked at before
The JAM Methodology is the first methodology designed specifically to reduce the need for type-specific hard tooling.

7. Taking a particular technique and applying it in a new area
The MIT researchers developed their techniques of assembly modelling and conceptualisation to solve problems in existing complex assemblies, (Section 5.5). The JAM Methodology includes aspects of their work, but applies it to the design and analysis of new, conceptual, assemblies.

8. Showing originality in testing somebody else's ideas
The Error Budgeting System developed by Odi, (Ref. 104), proved to be very time consuming and the single metric, although useful for comparing alternative assembly plans, gives no indication that an assembly plan will be able to deliver the PKCs. As a result, the two case studies, (Chapter 7.0), are performed using a simplified and much quicker variation of the original technique. In both case studies, only the FDFC delivering the dominant high level PKC is evaluated and the resultant used to compare the alternative assembly plans, and to determine the efficiency of the selected assembly plan, (Chapter 7). Case Study 2 assumes the use of Six Sigma process capability data and it is therefore possible to accurately predict that PKC#1 will be delivered.

8.10 Conclusions

1. The research programme described in this thesis has resulted in the successful development and presentation of an assembly centric design Methodology for JAM.

2. The JAM Methodology is unique in bringing enabling technologies and process capability data into the design process and in concentrating on the delivery of the assembly Key Characteristics.

3. Applicable design methodologies have been identified and incorporated into the design algorithm.

4. The enabling technologies have been identified and incorporated creating an holistic approach to JAM design.

5. Case studies have demonstrated how process capability data can be used for realistic tolerancing and assembly analysis.

6. Uncertainties of measurement and errors from datum transpositions can be included in the analysis of an assembly plan.

7. The assembly analysis includes all hard tooling and tooling errors.

8. The JAM Methodology is applied in the conceptual stage of the design process, before any commitment to expensive detail design.

9. The JAM Methodology can predict the success of part-to-part assembly or the need for hard tooling to achieve the assembly PKCs.

10. The JAM Methodology is essentially a simple process that can be followed by practical engineers.

11. Guidelines, graphical depictions of the Methodology, and case studies are presented to guide the design engineers.

12. The adoption of the JAM Methodology will result in a reduction in the development, lead time, and build costs of aerospace structures.

9.0 RECOMMENDATIONS FOR FURTHER WORK

The JAM project demonstrated the potential of the Methodology and attracted a lot of industrial interest, but before it can become a practical proposition there are a number of areas where it is necessary to do more work.

1. Creation of a Process Capability Database

JAM design and manufacture is impossible unless there is full knowledge of the process capabilities, (Section 4.12.4).

Without that knowledge, the industry must continue to embed the required end quality of the aerostructure into hand-built, type-specific, hard tooling.

With that knowledge, it will be possible to predict the feasibility of part-to part assembly and the viability of integrated assembly features, (Section 5.8). It is suggested, (Section 7.3), that the best way to compile this compounded process capability data is to:

- Follow existing component parts through machining or forming, finishing processes, storage, handling and transportation.
- To measure and record critical dimensions and geometric profiles at each stage.
- Establish how the processes affect the finished component.
- Determine the 'as delivered to the assembly line', compounded Six Sigma process capabilities.
- Develop a Six-Sigma process capability database for JAM.

2. Creation of an Enabling Technologies Database

The Enabling Technologies information needs to include advanced composites information, and to be regularly updated with data on new and emerging technologies.

The data is best held on a computerised database and searched by the JAM Methodology using an algorithm written to identify suitable enabling technologies, knowing the task and the required process capability, that is the allowable error.

3. Creation of a Database for Assembly Features

Continuation of the work by Naing, (Ref. 78), and described in his PhD thesis, with the assembly features organised and classified according to application. There is a need for a selection and sizing process, (Section 5.8), to fulfil specific tooling functions;

- Adjustment of detail parts. For selection when the manufacturing processes are unable to deliver the AKCs.
- Temporary support of detail parts before fitting the permanent fasteners.
- Temporary location and fastening.
- Full kinematic restraint, allowing fastener hole drilling with the parts in-situ.

4. JAM and SCONES

The integration of JAM and SCONES[1] to formalise the selection of assembly features based on restraint theory, process capabilities and stress concentration factors.
At the conceptual design stage, this will enable the selection and sizing of assembly features without the need for a full FE analysis, (Section 8.3).

[1] SCONES – Stress Concentration Expert System, by the University of Hull and BAE SYSTEMS

REFERENCES

REFERENCES

1. Anon.; 'Materials Research Agenda for the Automotive and Aircraft Industries', National Materials Advisory Board; pub. National Academy Press., Washington, DC, USA. 1993.

2. LEWIS A; 'Wing Assembly Jigs - The Strategy for the Future', restricted publication, BAe Fellowship in Aerospace Manufacture, Cranfield University. October 1993.

3. BRIAND C, MURRAY L, PETTIGREW A, ZESEWITZ J; 'A Tooling Study to Reduce the Cost of Aircraft Manufacture, pub. European Consortium for Advanced Training in Aerospace, (ECATA), Final Report 1995.

4. BURLEY G, CORBETT J; 'Flyaway Tooling for Higher Quality, more Cost-Effective, Aerostructure', SAE Aerospace Manufacturing Technology Conference, Long Beach, CA, USA. June 2 - 4, 1998.

5. BURLEY G, NAING S, ODI R, CORBETT J; 'Using Structurally Integrated Location and Reference Features in the Assembly of Large Aerospace Structures', AEROFAST 2000, SAE Aerospace Automated Fastening Conference, New Orleans, USA. September 20-22, 2000.

6. BURLEY G, ODI R, NAING S, CORBETT J; 'An Algorithm for Assembly Centric Design', AEROFAST 2002, SAE Aerospace Automated Fastening Conference, October 1-3, 2002, Chester, United Kingdom

7. BURLEY G, ODI R, NAING S, CORBETT J, WILLIAMSON A; 'Jigless Aerospace Manufacture - The Enabling Technologies', SAE Aerospace Manufacturing Technology Conference, Seattle, Washington, USA. June 8 - 10, 1999.

8. CORBETT J, BURLEY G; 'IMI: Jigless Aerospace Manufacture (JAM)', EPSRC/IMI Final Report –GR/L8922/01, 31 May 2001.

9. PHILLIPS E, PUGH D; 'How to get a PhD', pub. Open University Press, Buckingham, United Kingdom, reprinted 1996.

10. ROBSON C; 'Real World Research', ISBN 063121304X, pub. Blackwell Publishing, Oxford, England. 1992.

11. DAFT R, LENGEL R, 'Organisational Information Requirements, Media Richness and Structural Design', Management Science, Journal of the Institute for Operations Research and Management Sciences, Vol. 32(5), Hanover MD USA 1986.

12. SILVERMAN D; 'Doing Qualitative Research – A Practical Handbook', pub. Sage Publications, London, UK, 2004.

13. WALTON T; 'Steel ships: their construction and maintenance; a manual for shipbuilders, ship superintendents, students, and marine engineers', pub. C. Griffin London, UK. 1944.

14. Anon.; '6kW laser cuts big plate', page 32, Tooling and Production, Vol. 70 Issue 12, pub. Nelson Publishing, Nokomis Florida, USA. December 2004

15. Anon; 'Shipbuilding and Ship Repair - Process: Fabricating and Repairing Large Structural Components', U.S. Department of Labor Occupational Safety & Health Administration, Washington, DC, USA. 2005. http://www.osha.gov

16. MOORE S; 'The Bailey Bridge – Design for Fabrication and Ease of Assembly', pages 14 – 19, Engineering Designer, pub. The Institution of Engineering Designers, Westbury, Wiltshire, UK. July/August 2000.

17. PERRIER N D, NGUYEN V X; 'A Connection Design Methodology for Automated Assembly and the Framing of Buildings', pages 37-49, Journal of Manufacturing Science and Engineering, Vol. 119, No. 1, pub. ASME, Fairfield, NJ, USA, February 1997

18. BOKULICH F; 'An Optimist from Britain', page 3, Aerospace Engineering pub. SAE, Washington, DC, USA, July 1998

19. DAVID L, 'Snap-Together Satellites', pages 34-37, New Scientist, pub. Reed Business Information Ltd., England, 23 March 1996.

20. MASSÉ X; Avions Jodel, Dossiers aéronautiques, ISBN : 2723305201, (1996).

21. BURLEY G J, MILLS A R; 'The Development of Automated Processes for the Manufacture of Cost-Effective Composite Wing-Boxes', SAE Aerospace Manufacturing Technology Conference, Long Beach, CA, USA. June 2 - 4, 1998.

22. Anon.; 'Building Structures in Space', Paper FS-1996-08-09-LaRC, pub. Office of Public Affairs, NASA Langley Research Center, Hampton, VA, USA. August1996

23. LE VACON P; 'AUTOWAY – Automated One Way Assembly', research proposal for the 6th European Framework Programme, submitted by EADS CCR, Suresnes, France. 2004

24. LEGO System A/S; Billund, Denmark. http//www.lego.com/eng/info/default.asp

25. Flight Miniature; aircraft models, Genesis Worldwide Enterprises, Cottonwood, Arizona, U.S.A.
http//www.genesisworldwide.biz.

26. ANDREASEN M, KAHLER S, LUND T; 'Design for Assembly', page 123, pub. IFS (Publications) Ltd., Bedford, UK.1983.

27. Anon; 'Janes All The Worlds Aircraft', page 335, pub. Jane's Publishing Company Ltd., London, England, 1985.

28. Anon; Aerospatiale study on Boeing 777 production methods. DTI/F No. 6681/94/GA. Cited in: BRIAND C, MURRAY L, PETTIGREW A, ZESEWITZ J; 'A Tooling Study to Reduce the Cost of Aircraft Manufacture, Section 2.3.4, page 33, pub. European Consortium for Advanced Training in Aerospace, (ECATA), Final Report 1995.

29. Anon; 'Orders and deliveries April 30, 2002'. Airbus on-line information, http://www.airbus.com/media/orders_n_deliveries.asp

30. Anon; Airbus A300 Engineering Notes; Edition 2, Vol. 1, pub. Airbus Industrie, Toulouse, France, 1981.

31. Anon ; Titanium LGP® Lockbolt, 'Huck International Inc.', on-line product catalogue, Tucson, Arizona, USA.
http://www.huckaerospace.com/products/lockbolt/titanium_lgp/pull_intro.html

32. NIU M; 'Airframe Structural Design', P. 17 'Shot-peen Forming', pub. Conmilit Press Ltd., Wanchai, Hong Kong, 1998. ISBN 962-7128-04-X

33. Anon; 'Fatigue Technology Inc.', on-line product catalogue, Seattle, Washington, USA.
http://www.fatiguetech.com/index.html

34. ULLMAN D; 'The Mechanical Design Process', P. 6, Section 1.3, 'The History of the Design Process', 2nd Edition, ISBN 0-07-065756-4, pub. The McGraw-Hill Book Co, New York, USA. 1997.

35. NEVILLE A; 'Properties of Concrete', pub., Sir Isaac Pitman and Sons Ltd, London, United Kingdom, 1973.

36. Anon; 'The Celsus Library (Ephesus)', pub., Focus Multimedia On-Line Magazine, 1997.
http://www.focusmm.com/aceph_26.htm

37. Anon; 'Passive Solar Design', Jointly published by the US and UK Departments of Energy, May 1995

38. BANSAL N, HAUSER G, MINKE G; 'Passive Building Design - A Handbook of Natural Climatic Control', pub., Elsevier Science B.V., 1994.

39. Anon; 'DS PPR Hub', 'ReView', 'Process Engineer', 'Industrial Engineer', 'DPM ASSEMBLY', 'ENVISION/ASSEMBLY', 'ERGO', 'Cell Control', 'IGRIP', 'UltraArc', 'UltraSpot', 'UltraPaint', 'PLC Verification', 'Virtual NC', 'Zip Mill', 'Quest', 'Quest Express', 'INSPECT', integrated virtual engineering software programmes marketed by the, Delmia Corporation, Troy, Michigan, USA. 2003.

40. Anon; 'Solid Edge Users Guide, Version 6; Chapter 5 – Constructing an Assembly', pub., Unigraphic Solutions Inc., 13736 Riverport Drive, Maryland heights, MO 63043, USA, 1998.

41. SLOCUM A; 'Precision Machine Design', pub., Prentice Hall Inc., New Jersey, USA. 1992. ISBN 0136909183

42. DIXON V; 'Tool Design Handbook', British Aerospace Ltd., Military Aircraft and Aerostructures, Chadderton, BAE/CTB/TDH.1, 1998.

43. DIXON V; 'Tool Design Handbook – Section 4.2', British Aerospace Ltd., Military Aircraft and Aerostructures, BAE/CTB/TDH.1, 1998.

44. RUDNICK F C; 'Assembly Simulation for the Joint Strike Fighter', Aerospace Engineering, pub. SAE, Washington, DC. USA, December 1998.

45. COHEN A, GJESSING C, FINE L, BERNARD B, MCGLOTHLIN J; 'Elements of Ergonomics Programs - A Primer Based on Workplace Evaluations of Musculoskeletal Disorders', pub., National Institute for Occupational Health and Safety, Washington, DC, USA. 1997.

46. Anon; 'Delmia Process Engineer – Information Brochure', Delmia Ltd., Knutsford, Cheshire, United Kingdom. 2002.

47. Anon; Tecnomatix Technologies Ltd, 'Making Virtual Manufacturing A Reality', Sales Brochure. 2003.
http://www.tqei.com/hotline.html

48. Anon; Variation Systems Analysis, Inc., 300 Maple Park Boulevard, St. Clair Shores, Michigan 4801-3771, Sales Brochure. 2003
http://www.vsa.com/company.htm

49. CUNNINGHAM T W, MANTRIPRAGADA R, LEE D J, THORNTON A C, WHITNEY D E; 'Definition, Analysis, and Planning of a Flexible Assembly Process', Proceeding of the ASMA Japan/USA Symposium on Flexible Automation, Boston, MA, 1996.

50. SANDS B, STEPHENS D, LALIBERTY T J, and RAJA N; 'Manufacturing Simulations Based on Integrated Product/Process Models', Proceedings of DETC97: ASME Design Engineering Technical Conference, Sacramento, CA, USA, September 14- 17, 1997.

51. WILLIAMSON A, MARSHALL G A; 'Recent Ideas in Aerospace Cost Modelling', presented at the OR 40 Conference, Lancaster, UK, September 7-10, 1998.

52. ASTLEY R J; 'Finite Elements in Solids and Structures - An Introduction', 1st. edition, pub. Chapman & Hall, London, UK, 345 pp. 1992.

53. THOMPSON D, McKEOWN P; 'The Design of an Ultra-Precision CNC Measuring Machine', Annals of the CIRP, Vol. 38/1, pp. 501-504, pub. International Institution for Production Research (CIRP), Uetendorf, Switzerland,1989.

54. SARTORI S, COLENNETTI G, ZHANG G; 'Geometric Error Measurement and Compensation of Machines', Annals of the CIRP Vol. 44/2/1995.

55. WRIGHT K W; 'High Speed Machining (Milling): New Realisations', Research paper, Airbus UK, Broughton, Chester, UK. September 14, 1993.

56. Anon; 'The Ultimate Solution for High Speed Machining and Total Flexibility', Sales brochure, M. Torres, Disenos Industriales, SA, Navarre, Spain. 2001.

57. Anon; CNA Flexible Tooling Systems, 18103 N.E. 68th St., Suite C-100, Redmond, Washington 98052, USA., 2002.
http://www.cnaflextool.com/

58. KALLEE S, NICHOLAS D; 'Friction Stir Welding at TWI', website article, The Welding Institute, Abington Hall, Abington, Cambridge, CB1 6AL, UK, 2002.
http://www.twi.co.uk/

59. MOSS C J; 'Aeronautical Engineering - Bonding by Redux', 'The Aeroplane' No. 329. Back issues available from 'Aeroplane Monthly', King's Reach Tower, Stamford Street, London SE1 9LS. September 20, 1946.

60. HIGGINS A; 'Structural Adhesive Bonding of Aircraft', The Institute of Materials, Fifth International Conference on Structural Adhesives in Engineering, Bristol, UK. 1-3 April 1998.

61. Anon; 'AdhFAST®', website publication, The Welding Institute, Abington Hall, Abington, Cambridge, CB1 6AL, UK, 2003.
http://www.twi.co.uk/j32k/unprotected/band_1/adhfast.html

62. BHAUMIK P K; 'Building Aircraft Assembly Tools from a 3-D Database', SAE, Aerospace Technology Conference and Exposition, Anaheim, Cal, Oct. 3 - 6, 1988.

63. Anon; 'Tutorial: Laser Trackers', Optical Metrology Centre, City University, London, England. 2004.
http://www.city.ac.uk/omc/tut-lasertracker.htm

64. Anon; On-line information from 'PTC (NASDAQ: PMTC), the product development company™', Needham, Mass., United States of America. 2004.
http://www.ptc.com/products/sw_landing.htm

65. Anon; On-line information from Leica Geosystems AG, CH-9435 Heerbrugg, Switzerland. 2004.
http://www.leica-geosystems.com/about/location/index.htm

66. Anon; 'Big jig is taking shape...', Airbus News, pub., Airbus UK, New Filton House, Filton, Bristol, UK. Issue No. 72 February 1999.

67. ANDERSON J, KYLE S; 'Metrology for Automated Systems', pub., BAE Systems, Sowerby Research Centre, Filton, Bristol, UK. February 2000
http://www.leica-geosystems.com/solutions/aerospace/index.htm

68. MUGNIER C J, et. al ; 'Digital image photogrammetry; Final report', New Orleans Univ., LA., Gulf Coast Region Maritime Technology Center, 1996.

69. BARCLAY B; 'Close Range Photogrammetry in the Aerospace Test Environment', Proceedings. Institute of Environmental Sciences, p.135-149, Aerospace Testing Seminar, 11th, Manhattan Beach, CA, Oct. 11-13, 1988,

70. FRASER C S; 'A Resume of Some Industrial Applications of Photogrammetry', ISPRS Journal of Photogrammetry and Remote Sensing, 48(3): pages12-23, 1993.

71. N-NAGY F, SIEGLER A; 'Engineering Foundations of Robotics', Section 1.5, pub., Prentice-Hall International, Hemel Hempstead, UK. 1987.

72. CRAIG J J; 'Introduction to Robotics: Mechanics and Control', 2nd. Edition, pp.278-280, ISBN 0-0201-09528-9, pub. Addison Wesley, Reading, MA, USA. 1989.

73. BURLEY G J, RATHMILL K; 'Autonomously Controlled Error Correcting Wrist', SERC Contract G.R/B/73828, Final Report, September 1985.

74. DOES R J, ROES K C, TRIP A; 'Statistical Process Control in Industry – Implementation and Assurance of SPC', ISBN 0-7923-5570-9, pub. Kluwer Academic Publishers, Dordrecht, The Netherlands. 1999.

75. DOES R J, ROES K C, TRIP A; 'Statistical Process Control in Industry – Implementation and Assurance of SPC', Section 5.10 Process Capability Study, ISBN 0-7923-5570-9, pub. Kluwer Academic Publishers, Dordrecht, The Netherlands. 1999.

76. BOOTHROYD G, DEWHURST P, KNIGHT W; 'Product Design for Manufacture and Assembly', 2nd edition, Section 2.4 – 'Process Capabilities', pub. Marcel Dekker Inc., New York, USA. 2002. ISBN 0-8247-0584-X

77. CORBETT J, BURLEY G, ODI R; 'AIM-for-JAM - An Integrated Design Methodology for Jigless Assembly and Manufacture'. A proposal to the EPSRC for the integration and automation of the Cranfield JAM Methodology plus the development of teaching material and an E-learning module'.

78. NAING S; 'Feature Based Design for Jigless Assembly', PhD thesis, Page 38, Cranfield University, UK. 2003.

79. BOOTHROYD G, DEWHURST P, KNIGHT W; 'Product Design for Manufacture and Assembly', 2nd edition, Section 15.2.1, ISBN: 0-8247-0584-X pub. Marcel Dekker, Inc. New York, USA. 2002.

80. FRENCH M J; 'Conceptual Design for Engineers', 3rd edition, Section 1.2, ISBN: 1852330279, pub. Heinemann Educational Books, London, England, 1999.

81. WRIGHT I; 'Design Methods in Engineering and Product Design', Chapter 1, ISBN: 0-07-709376-3, pub. The McGraw-Hill Companies, London, England. 1998.

82. WRIGHT I; 'Design Methods in Engineering and Product Design', Chapter 6, ISBN: 0-07-709376-3, pub. The McGraw-Hill Companies, London, England. 1998.

83. WRIGHT I; 'Design Methods in Engineering and Product Design', Chapter 12, ISBN: 0-07-709376-3, pub. The McGraw-Hill Companies, London, England. 1998.

84. LEE D J, THORNTON A C; 'The Identification and Use of Key Characteristics in the Product Development Process', Paper No.96-DETC/DTM-1235, 12pp, Proceedings of the 1996 ASME Design Engineering Technical Conferences and Computers in Engineering Conference, Irvine, California, USA. 18-22 August 1996.

85. THORNTON A C; 'Using Key Characteristics to Balance Cost and Quality During Product Development', Paper No. DETC97/DTM3899, Proceedings of DETC'97 1997 ASME Design Engineering Technical Conferences, Sacramento, California, 14-17 Sept. 1997.

86. LEE D J, et al.; 'Key Characteristics for Agile Product Development and Manufacturing', Agility Forum 4th Annual Conference Proceedings, Pages 258-268, Bethlehem, PA, USA. 1995.

87. PALMER C; 'An Evaluation of Leading Computer Aided Conceptual Design Software and Techniques', Pages 6-7, MSc Thesis, Cranfield University, England, 1997.

88. OSBORN A; 'Applied Imagination – Principles and Practice of Imaginative Thinking', ISBN 0023895209, pub. Charles Scribeners Sons, New York, USA, 1957.

89. BUZAN T; 'Use Both Sides of Your Brain', ISBN 0-452-26603-3, pub. Penguin Books Inc., New York, USA, 1991.

90. WRIGHT I; 'Design Methods in Engineering and Product Design', pages 122 – 123, Chapter 7, ISBN: 0-07-709376-3, pub. The McGraw-Hill Companies, London, England. 1998.

91. BRADSHAW A, COUNSELL J, (editors); 'Computer Aided Conceptual Design '99', Proceedings of the Lancaster International Workshop on Engineering Design, Windermere, England, May 1999.

92. VAZIRY-Z M A F, FIELDING J P; 'Computer Aided Conceptual Aircraft Design (CACD) for Transport Aircraft', ISBN 1871564905, College of Aeronautics Report No. 9608, Cranfield University, England, 1996.

93. ULLMAN D G; 'The Mechanical Design Process', Chapter 8, ISBN 0-07-115576-7, pub. The McGraw-Hill Companies, Inc., New York USA. 1997.

94. PICKERING S; 'The Disposal of Composites', Proceedings of 3rd International Conference on Automated Composites, pages 7/1-7/6, ICAC91, The Hague, Holland, 15-17 October 1991.

95. PUGH S; 'Total Design - Integrated Methods for Successful Product Engineering', ISBN 0-201-41639-5, pub. Addison-Wesley, Wokingham, England. 1995.

96. ULLMAN D G; 'The Mechanical Design Process', Section 8.6, ISBN 0-07-115576-7, pub. The McGraw-Hill Companies, Inc., New York USA. 1997.

97. NAING S, BURLEY G, ODI R, CORBETT J; 'Design for Tooling to Enable Jigless Assembly', SAE Aerospace Manufacturing Conference, Fort Worth, Texas, USA, May 16-18, 2000.

98. Anon; 'ANSI Y14.5M-1994 Dimensioning and Tolerancing', ISBN 07918222, pub. American Society of Mechanical Engineers, (ASME) International, USA, 1994.

99. Anon; 'ISO 1101:1983 Geometrical Tolerancing', pub. International Organisation for Standardisation, Genève 20, Switzerland, 1993.

100. MEADOWS J; 'Geometric Dimensioning and Tolerancing Applications and Techniques for Use in Design, Manufacturing, and Inspection', ISBN 0-8247-9309-9, pub. Marcel Dekker, New York, USA, 1995.

101. MANTRIPRAGADA R, CUNNINGHAM T, WHITNEY D; 'Assembly Oriented Design: A new approach to designing assemblies', Proceedings of the Fifth IFIP WG5.2 Workshop on Geometric Modelling in Computer-Aided Design', Airlie, Virginia, USA., May 18-23, 1996.

102. SCHWEMMIN R; 'Predicting Assembly Performance with Featurised Datum Flow Chains', Paper No. 1999-01-2271, SAE Aerospace Manufacturing Technology Conference, Seattle, Washington, USA. June 8 - 10, 1999.

103. WILLS-MOREN W; 'Error Budgeting in Machine Design', unpublished lecture notes, Cranfield University, England, 1993

104. ODI R, BURLEY G, NAING S, CORBETT J; 'The Role of Error Budgeting in the Use of Structurally Integrated Location and Reference Features for Aerospace Assembly', AEROFAST 2000, SAE Aerospace Automated Fastening Conference, New Orleans, USA. September 20-22, 2000.

105. CREVELING C M; 'Tolerance Design. A Handbook for Developing Optimal Specifications', p. 193, ISBN 0-201-63473-2, pub. Addison Wesley Longman Inc, Reading, Massachusetts, USA. 1997.

106. Anon; 'AMCAPS II Mobilisation Notes', Section 9 – Risk Management and Structured Problem Solving, Airbus UK, Filton, UK. February 1997.

107. Anon ; 'VALISYS Product Descriptions', website publication, Technomatrix Technologies Ltd, Herzlia, Israel. 2002.
http://www.tecnomatix.com/

108. ODI R, BURLEY G, NAING S, CORBETT J; 'Effect of Assembly Features on Structures - FE Modelling', Report JAM/PR/012, Cranfield University, UK. May 2001.

109. ROBINSON P, SWIFT K, GRAHAM R, PECKOVER S, GILL L; 'An Expert System for the Determination of Stress Concentration Factors', Proceedings of the Institution of Mechanical Engineers, Vol. 215, Part G, UK. 2001.

110. Anon; 'Envelope Tooling – Building Airframe Units from the Skin Inwards', Aircraft Production, January 1950

111. Anon; 'Airframe Assembly Practice, A Review of the Fairey Envelope System and Method of Jig Construction', Aircraft Production, May 1950

112. BAKERJIAN R, (Ed); 'Tool and Manufacturing Engineers Handbook, Vol. 6, Design for Manufacturability', Society of Manufacturing Engineers, Michigan, USA. 1992.

113. Anon; 'Limits for Special Machining Features', British Aerospace Document S99. 1973.

114. Anon; 'General Manufacturing Limits (Metric)', Hawker Siddeley Aviation Document S104. 1977.

115. GROOVER M P; 'Fundamentals of Modern Machining, Materials, Processes, and Systems', Prentice Hall, New Jersey, USA. 1996.

116. BOOTHROYD G, DEWHURST P, KNIGHT W; 'Product Design for Manufacture and Assembly, 2nd Edition', Table 2.1, Pages 50 -53, ISBN: 0-8247-0584-X, pub. Marcel Dekker Inc., New York, USA. 2002.

117. ODI R, BURLEY G, NAING S, CORBETT J; 'Re-Engineered Demonstrator – VALISYS Assembly Model', Report JAM/PR/011, Cranfield University, UK. February 2001.

118. WHITNEY D E, NEVINS J L; 'What is the Remote Centre Compliance (RCC) and What Can it Do?', Proceedings of the 9th International Symposium on Industrial Robots (ISIR), Washington DC, USA. March 13-15 1979.

119. NAING S, BURLEY G, ODI R, CORBETT J; 'Costings Analysis of Current Assembly Versus JAM Demonstrator Structure'. Internal Report (Restricted), Cranfield University, UK. August 2001.

120. RILEY B L; 'AV-8B/GR5 Airframe Composite Applications', 22nd John Player Lecture, Institution of Mechanical Engineers, London, UK. March 26, 1986.

121. BURLEY G J, MILLS A R; 'The Development of Automated Processes for the Manufacture of Cost-Effective Composite Wing-Boxes', SAE Aerospace Manufacturing Technology Conference, Long Beach, CA, USA. June 2 - 4, 1998.

122. TURNER M, et al.; 'Automated Fibre Lay-Down Techniques for Preform Manufacture', Pages 245-252, Proceedings of the 5th International Conference on Automated Composites, Glasgow, UK. 6-7 September 1997.

123. MILLS A R, BURLEY G J, BACKHOUSE R; 'Innovative Manufacturing Processes and Equipment for the Cost-Effective Manufacture of Composite Airframe Structures', 19th SAMPE Europe/JEC, Paris, France, April 22 - 24, I998.

124. BURLEY G J, KAYE A, LEE J; 'The Roll Forming of Thick Carbon/Epoxy Laminates', SAE Aerospace Congress, Montreal, Quebec, Canada, September 8-12, 2003.

125. WONG R; 'Adhesively Bonded Composite Structures: Process Control, Non-Destructive Inspection, and Strength Effects', SAE Technical Paper 891044, General Aviation Aircraft & Exposition, Kansas, USA, April 11-13, 1989.

126. RUDD C, LONG A, MIDDLETON V; 'Application of Advanced Preforming Methods for Liquid Composite Moulding', EPSRC/LINK Project, Final Report No. GR/J96246, Nottingham University , UK. November 1997.

127. BROOKMAN D J, et al; 'Affordable Manufacture of Composite Aircraft Primary Structure', Overview Report (Restricted), Report No. R&T/B4503/22368, pub. BAe Airbus, Filton, September 1995.

128. CROWSON A, MAYER G; 'Army Research Activities in Advanced Composite Materials', Proceedings of the Conference on Advanced Composites, pages 243 – 250, Dearborn, Michigan, USA, 1985.

129. RILEY B L; 'AV-8/GR5 Airframe Composite Applications', 22nd John Player Lecture, Institution of Mechanical Engineers, London, UK, March 26, 1986.

130. GREGORY M J, 'A Framework Relating Producibility Problems to the use of Manufacturing Information in Design', PhD Thesis, Section 8.6, Cranfield University, UK, October 2001.

131. BOOTHROYD G, DEWHURST P, KNIGHT W; 'Product Design for Manufacture and Assembly', 2nd Edition, pub. Marcel Dekker, New York, USA. 2002.

132. MILES B L; 'Design for Assembly – A Key Element within Design for Manufacture', pages 29 – 38, Proceedings of the IMechE Part D Transport Engineering, volume 203 n D1, pub. Institution of Mechanical Engineers, London, UK, 1989.

133. SWIFT K G; 'Techniques in Design for Manufacture', pages 25 – 28, Proceedings of the IMechE Part D Transport Engineering, volume 203 n D1, pub. Institution of Mechanical Engineers, London, UK, 1989.

134. MUNRO A S, 'Design Prophet/Design Profit', Munro and Associates Inc, Troy, Michigan, USA. 1997.

135. MARSHALL M, PAULLS A, RAINES M, ROBINSON P, SWIFT K, GILL L; 'Knowledge Based Systems in Stress Concentration Analysis', SAE Paper No. 2002-01-1532, General Aviation Technology Conference, Wichita, KS, USA. April 2002.

136. ODI R, BURLEY G, NAING S, CORBETT J; 'Geometric and Dimensional Tolerances in Error Budgeting for Assembly-Centric Design of Aerostructures', International CIRP Tolerance Seminar, Cachan, France, April 24-25, 2001.

137. PHILLIPS E, Pugh D; 'How to get a PhD', pages 61-62, pub. Open University Press, Buckingham, United Kingdom, reprinted 1996.

138. WHITNEY D; 'The Potential for Assembly Modelling in Product Development and Manufacturing', Proceedings of the IEEE International Symposium on Assembly and Task Planning, 10 August 1996, Pittsburgh, USA.

139. WALLACE G; 'An Integrated Approach for the Application of Design for Assembly', PhD Thesis, Cranfield University, UK. 1995.

140. LEANEY P G, WITTENBERG G; 'Design for Assembling – The Evaluation Methods of Hitachi, Boothroyd and Lucas', Assembly Automation, Vol. 12, No. 2, pp.8-17.

141. WONG J, STURGES R; 'An Extension of Design for Assembly Methods for Large and Heavy Parts', Advances in Design Automation ASME, Vol. 1, pp.67-73 1992.

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John was also the Principal Investigator for the JAM project and along with my two colleagues, Randolph and Soe, we formed a good research team. Each of us bringing his own speciality and intellect into the discussions; trading ideas, developing themes, debating points, sharing late nights and very early mornings, presenting papers at home and abroad.

Cranfield has been good to me and I am indebted and very grateful to the University, its officers and my Head of School. Cranfield has been my working life, and like all of its employees I have always been encouraged to reach out and grasp what I once thought was impossible.

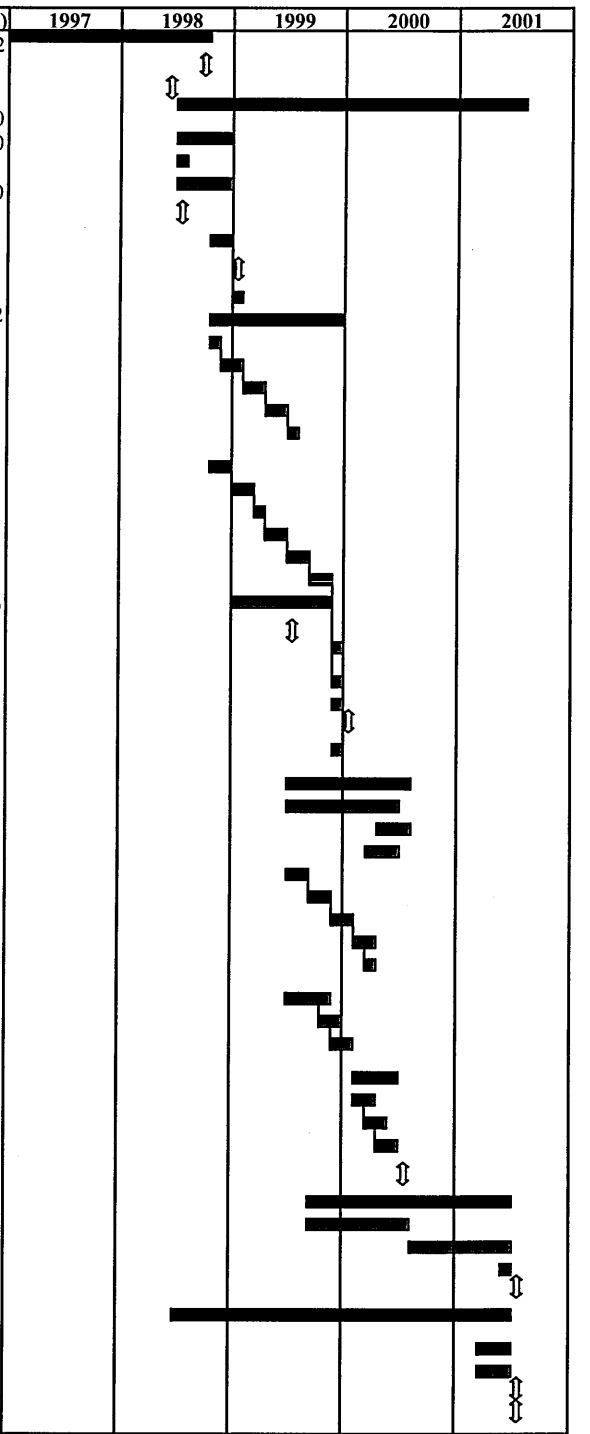
Finally I want to say a special thank you to my lovely wife Anne. She has had to endure several years of lonely evenings wondering if I will ever finish; and whether our home will ever be redecorated. So I know what I must do next; but first I need a short break under a warm sun.

APPENDICES

APPENDIX A

JAM Project Plan and GANNT Chart

ID	Task Name	Duration (Days)
1	**Case Studentship**	392
2	Presentations to JAM	1
3	**JAM Cranfield Start Date**	1
4	JAM Research	780
5	**Preliminary Research**	130
6	Site Visits	20
7	Literature Searches	130
8	**SAE Conference**	6
9	**Interim Report**	39
10	Present Report	1
11	**Write Paper**	10
12	**Investigate Properties of Demonstrator Assembly**	302
13	Relationship of Part design to Manf Process	20
14	Dim. & Geometric Variance between Parts	45
15	Accry. of Current Manf. Processes	45
16	Identify Sources of Geometric/Dim. Variance	45
17	**Write Paper**	10
18	Current Assembly and Processes	45
19	Analyse Tooling Principles/Design Efficiency	45
20	Methods of Parts Restraint/Kinematics	20
21	Assembly Logic and Sequence	45
22	Effects of Manf. Proc. On the Assembly	45
23	Establish Dimensional/Geometric Variance	45
24	Prepare Volumetric Error Budget	239
25	**Demonstrate Error Budgeting Techniques**	1
26	Compare with Requirements for ICY	22
27	Identify QA Control Techniques	20
28	**Interim Report**	20
29	Present Report	1
30	**Write Paper**	10
31	Investigate Jigless Design, Manf., Assembly	257
32	Develop Jigless Concepts	241
33	Manufacture Demo Parts	60
34	R&D Support Structure	85
35	Research Target Errors for JAM	43
36	Calculate Target Errors for Support Structure	44
37	Calculate Target Errors for Sub-Assemblies	43
38	Calculate Target Errors for Single Parts	44
39	Establish Methods for In-Process Measurement	22
40	Analyse suitability of Existing Manf. Processes	109
41	Research Improvements to Ex. Manf. Processes	65
42	Research Alternative Manf. Processes	63
43	**Interim Report**	60
44	Processes Capability Catalogue	20
45	Decision Tree & Design Algorithms	20
46	Design Concepts Catalogue	20
47	**Present Report**	1
48	**JAM Design Exercises**	413
49	Stage 1 – Re-Engineering	217
50	Stage 2 – New Design	217
51	**Interim Report**	20
51	**Present Report**	1
52	**Costings Analysis**	719
53	Final Report	44
54	Prepare Report	44
55	Present Report	1
56	**Project End**	0



Project JAM Date 01/03/98	**Jam Project Plan and GANNT Chart**

Jam Project Plan and GANNT Chart *Fig. 143*

APPENDIX B

List of Interviewees

Interviewees

The following specialists were interviewed for the JAM Project;

1. ANDERSON John, BAE Sowerby Research Centre, UK - Principal Scientist
2. ANDREWS Neil, Airbus UK - TANGO Lead Engineer (Design)
3. ANSTICE Paul, Consultant, Pera Technology, Melton Mowbray, Leicestershire, England
4. BANFORD Stuart, Airbus UK - Parts Manufacturing Specialist
5. BLOT Philippe, Airbus France - Composites Methods Engineer, RTM Development
6. BRANDRICK Paul, Airbus UK - Engineering Team Leader
7. CALVERT Peter, BAES Marine, UK - Steel Fabrication and Planning Manager
8. CLAY Regis, Airbus France - Group Manager Industrial Technology Assessment
9. DARTUS Alain, Aerospatiale Matra, France - R&D Engineer, Composites
10. EDMONDSON Wayne, BAES MA&A, UK - Liaison Engineer Machining & Treatments
11. ENGSTROM Magnus, SAAB Aerospace, Sweden - Aircraft Manufacturing Technology
12. ENMAR Mats, SAAB Aerospace, Sweden - Senior Designer, Grippen Aircraft
13. FAIRCLOUGH Craig, Airbus UK - Chief Mechanical Engineer
14. FOWKES Clifford, Matra BAE Dynamics, UK - Chief Manufacturing Technologist
15. FOWLER Kevin, BAES MA&A, UK - Principal Engineer - Assembly Operations
16. GRIBBEN, Michael, Bombardier Aerospace, Northern Ireland - Section Head, Tool and Technology
17. GRIFFITHS Raymond, Airbus UK - Manager Manufacturing Development
18. HARDI Robin, Airbus UK - Team Leader, Manufacturing Systems Engineering
19. HARDY Bill, BAES MA&A, UK - Tooling Engineer, Nimrod and Hawk Aircraft
20. HOLGATE Paul, BAES MA&A, UK - Effective Manufacturing
21. JARMAN Martin, BAES RO Defence, UK - Head of Manufacturing Engineering
22. JOHNSON Ben, BAES MA&A, UK - Engineering Tooling Manager
23. LINDQVIST Richard, SAAB Aerospace, Sweden - Assembly Tooling
24. LUNN Richard, Airbus UK - Engineering Specialist - Design
25. MARGUET Benóit, EADS CCR, France - Product Modelling and Assembly
26. McGOVERN Sean, Airbus UK - Chief Engineer, Single Aisle
27. McKEOWN Ross, BAES MA&A, UK - Tooling Engineer
28. McLARTY Scott, BAES MA&A, UK - IPT Leader, Airbus Leading Edge
29. MISTRY Raj, Airbus UK - Assembly Technologies Group Leader
30. MITCHELL Colin, Airbus UK - R&D Project Manager
31. MOORE John, Airbus UK - Automated Assembly
32. MUNK Roger, Advanced Technology Group, UK – Airship Designer
33. MUNRO Sandy A, Munro & Associates, Inc., Troy, Michigan, USA.
34. NAMER Luc, Snecma Moteurs, France - CAD Support and Methods Coordination
35. NIJSSEN Pieter-Jan, Airbus UK - A340-500/600 Composite Leading Edge Team
36. PALMER Ray, Senior Engineering Specialist, (Composites), The Boeing Company, Long Beach, California, USA.
37. SARH Branko Dr., Senior Engineering Specialist, (Airframes), The Boeing Company, Long Beach, California, USA.
38. SHAW John, BAE Aerostructures, Filton, UK - Assembly Technologies Consultant

39. SMAILES Martin, BHW (Components) Ltd, UK - Production Project Engineer
40. STRETTON Paul, Airbus UK - Team Leader (Structures Engineering)
41. TANO Jan, SAAB Aerospace, Sweden - Aircraft Manufacturing Technology
42. TAYBURN Dave, BAES MA&A, UK - Senior Manufacturing Engineer (Composites)
43. THORNTON Anna, MIT, Massachusetts, USA – Research Scientist
44. TURNER Brian, Airbus UK - Group Leader, Manufacturing Engineering
45. TURNER Ian, Nissan Technical Centre, Cranfield, UK - Senior Design Engineer
46. VAUGHAN David, Airbus UK - EPD Implementation Team
47. WATTS Michael, Boeing Commercial Airplane Group, USA - Principal Engineer
48. WEILAND Maria, SAAB Aerospace, Sweden - Manager Manufacturing Technology
49. WHITNEY Daniel, MIT, Massachusetts, USA - Senior Research Scientist
50. WRIGHT Ken, Airbus UK - Specialist: Machining Technologist

APPENDIX C

List of Sites & Companies Visited

List of Sites & Companies Visited

The following sites and companies were visited for the JAM Project;

1) Airbus France SAS,
   31060 Toulouse, France.
2) Airbus UK,
   Broughton, Chester, CH4 0DR, UK
3) Airbus UK,
   New Filton House, Filton, Bristol, BS99 7AR, UK
4) Advanced Technologies Group
   No. 2 Hangar, Shortstown, Bedford, MK42 0TJ, UK
5) AMS Radar Systems,
   Cowes, Isle of Wight, PO31 8PF, UK
6) BAE SYSTEMS – Advanced Technology Centre,
   Filton, Bristol, BS34 7QW, UK
7) BAE SYSTEMS Aerostructures,
   Samlesbury, Balderstone, Lancs. BB2 7 LF, UK
8) BAE SYSTEMS Air Systems,
   Warton, Preston, Lancs. PR4 1AX, UK
9) BAE SYSTEMS – Naval Ships,
   Scotstoun, Glasgow, G14 0XN, UK
10) BAE SYSTEMS – Submarines,
    Barrow-in-Furness, Cumbria, LA14 1AF, UK
11) BHW (Components) Ltd.,
    Hawkley Brook, Wigan, WN3 6XE, UK
12) Boeing Commercial Airplane Group,
    Seattle, WA 98124, USA.
13) Bombardier Aerospace,
    Belfast BT3 9DZ, Northern Ireland, UK
14) EADS CCR,
    92152 Suresnes Cedex, France
15) Matra BAE Dynamics,
    Stevenage, Herts. SG1 2DA, UK
16) Nissan Technical Centre Europe Ltd.,
    Cranfield Technology Park, Beds. MK43 0DB, UK
17) SAAB Aerospace,
    SE-581 88 Linköping, Sweden

APPENDIX D

Case Study 1
Modified Part Drawings

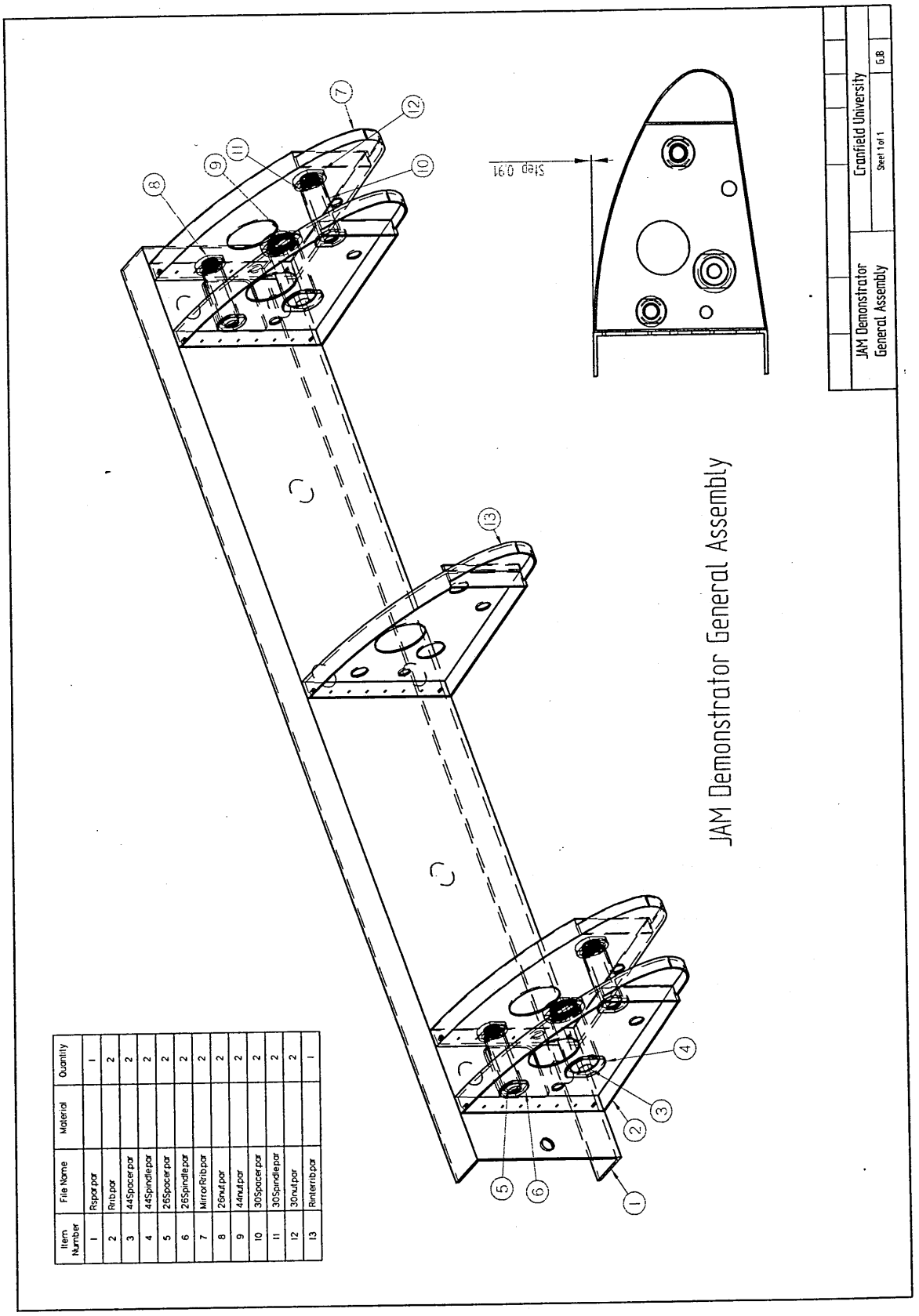
Modified Part Drawings

List of Drawings

1. JAM Demonstrator General Assembly

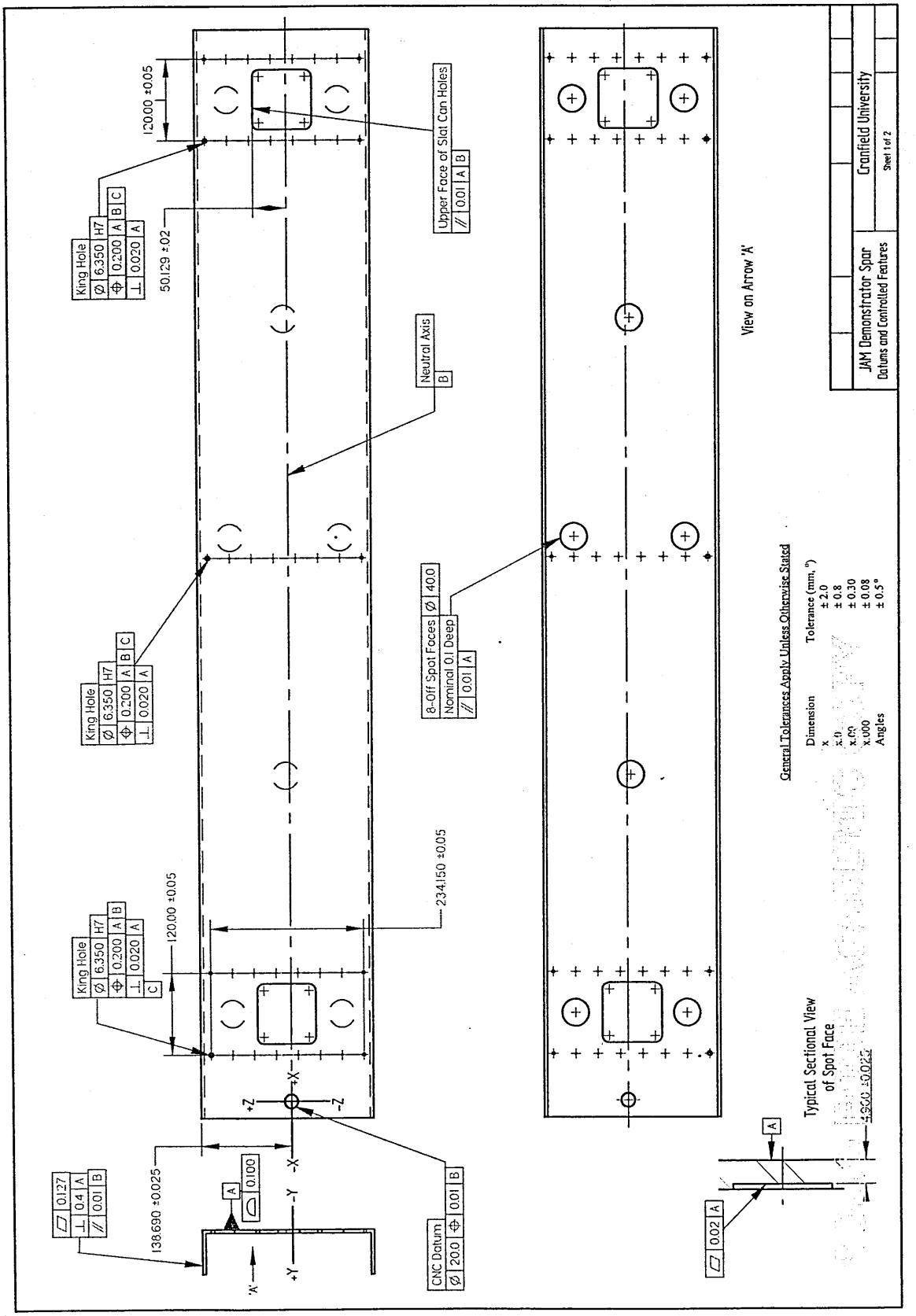
2. JAM Demonstrator Spar - Sheet 1 of 2
3. JAM Demonstrator Spar - Sheet 2 of 2

4. JAM Demonstrator Rib - Sheet 1 of 4
5. JAM Demonstrator Rib - Sheet 2 of 4
6. JAM Demonstrator Rib - Sheet 3 of 4
7. JAM Demonstrator Rib - Sheet 4 of 4

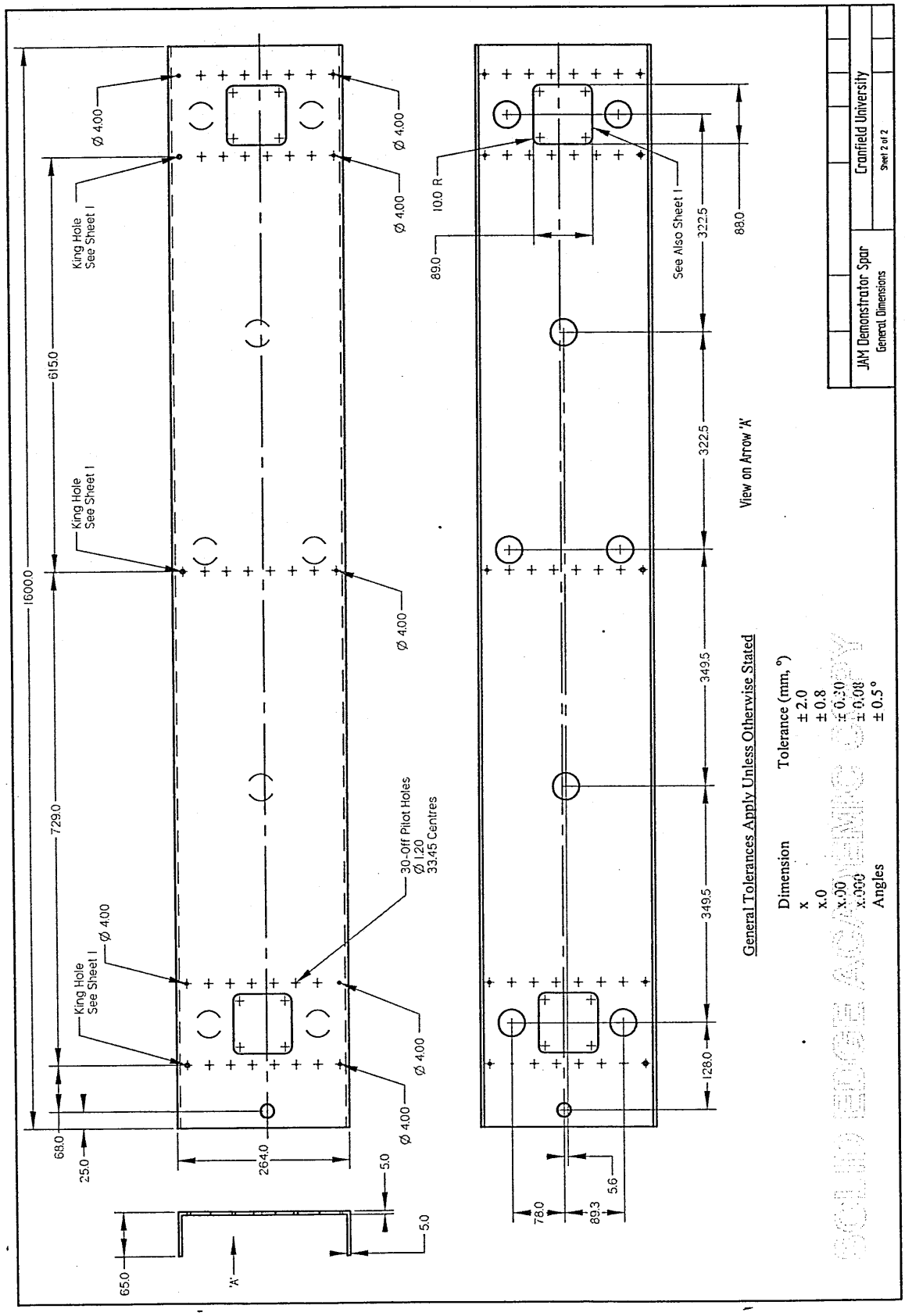


JAM Demonstrator – General Assembly

Fig. 144

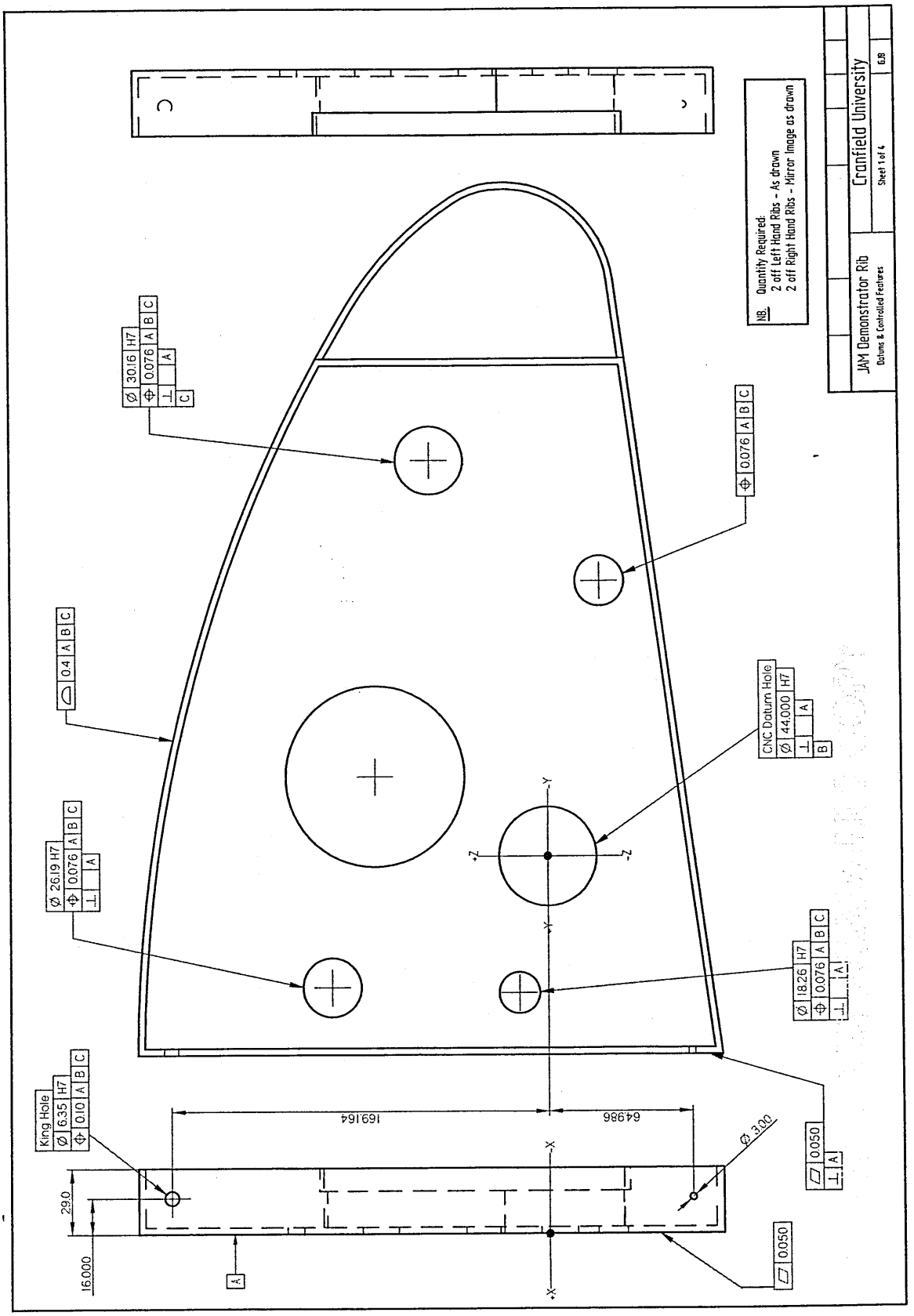


JAM Demonstrator Spar – Sheet 1 of 2 *Fig. 145*

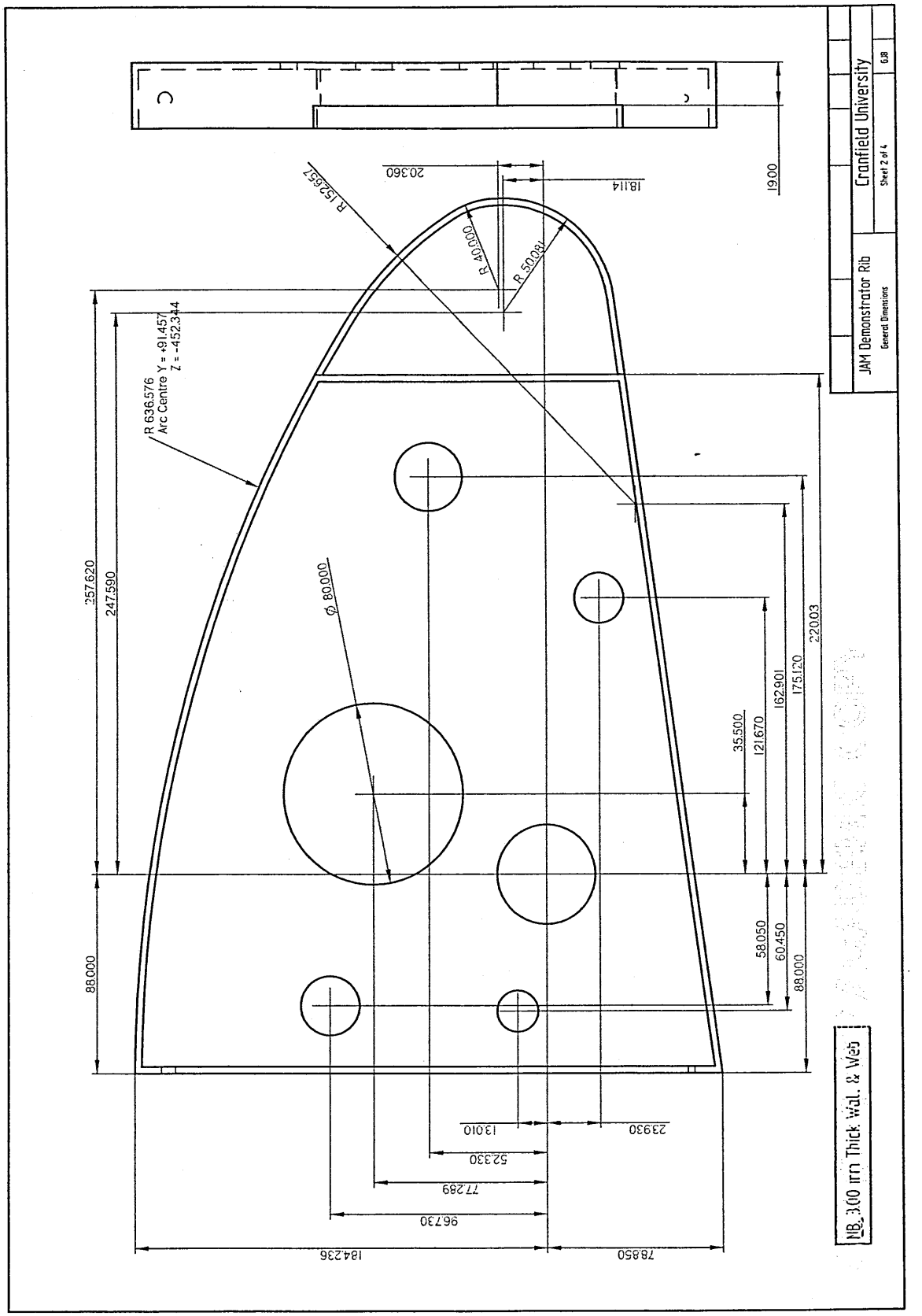


JAM Demonstrator Spar – Sheet 2 of 2

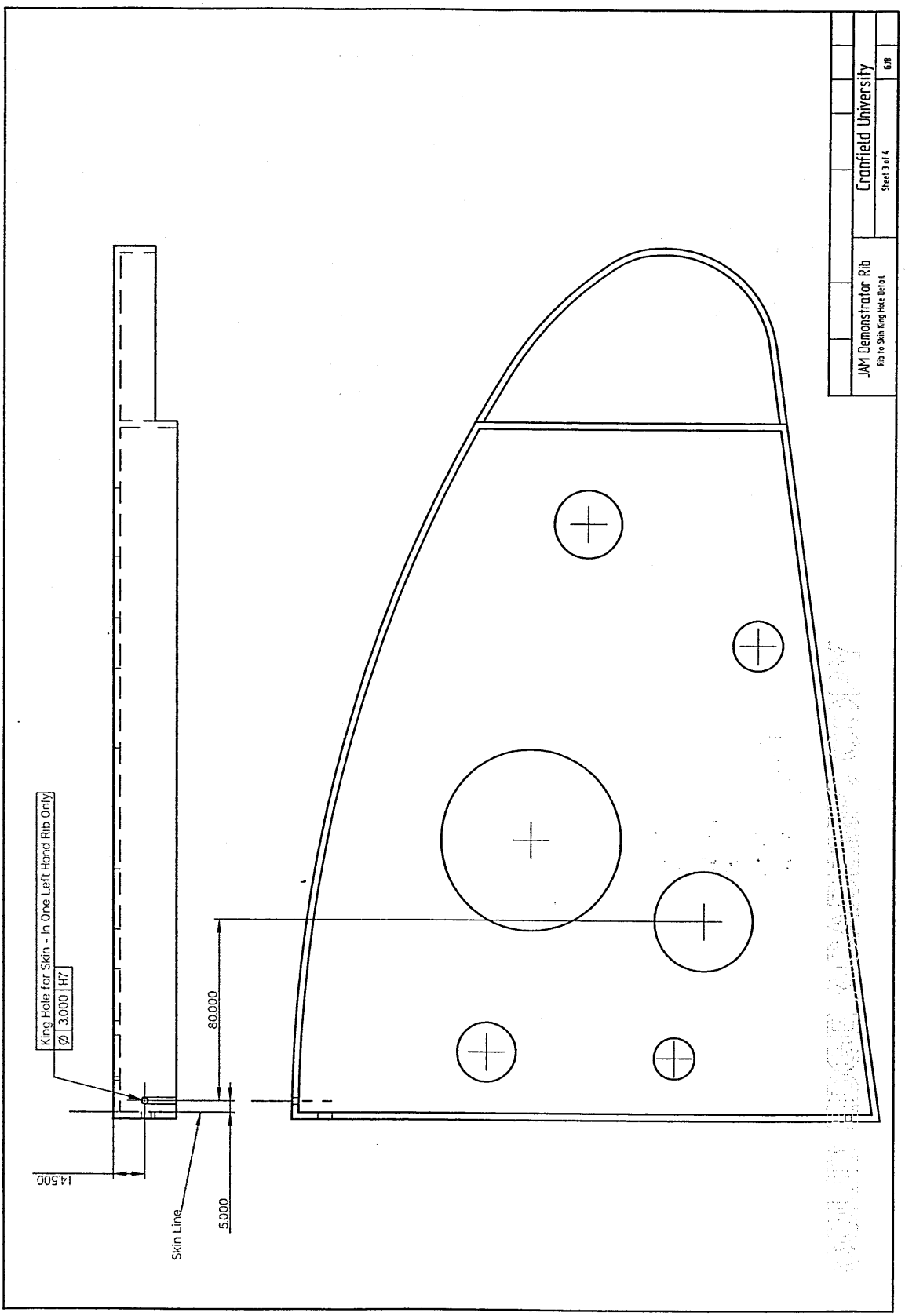
Fig. 146



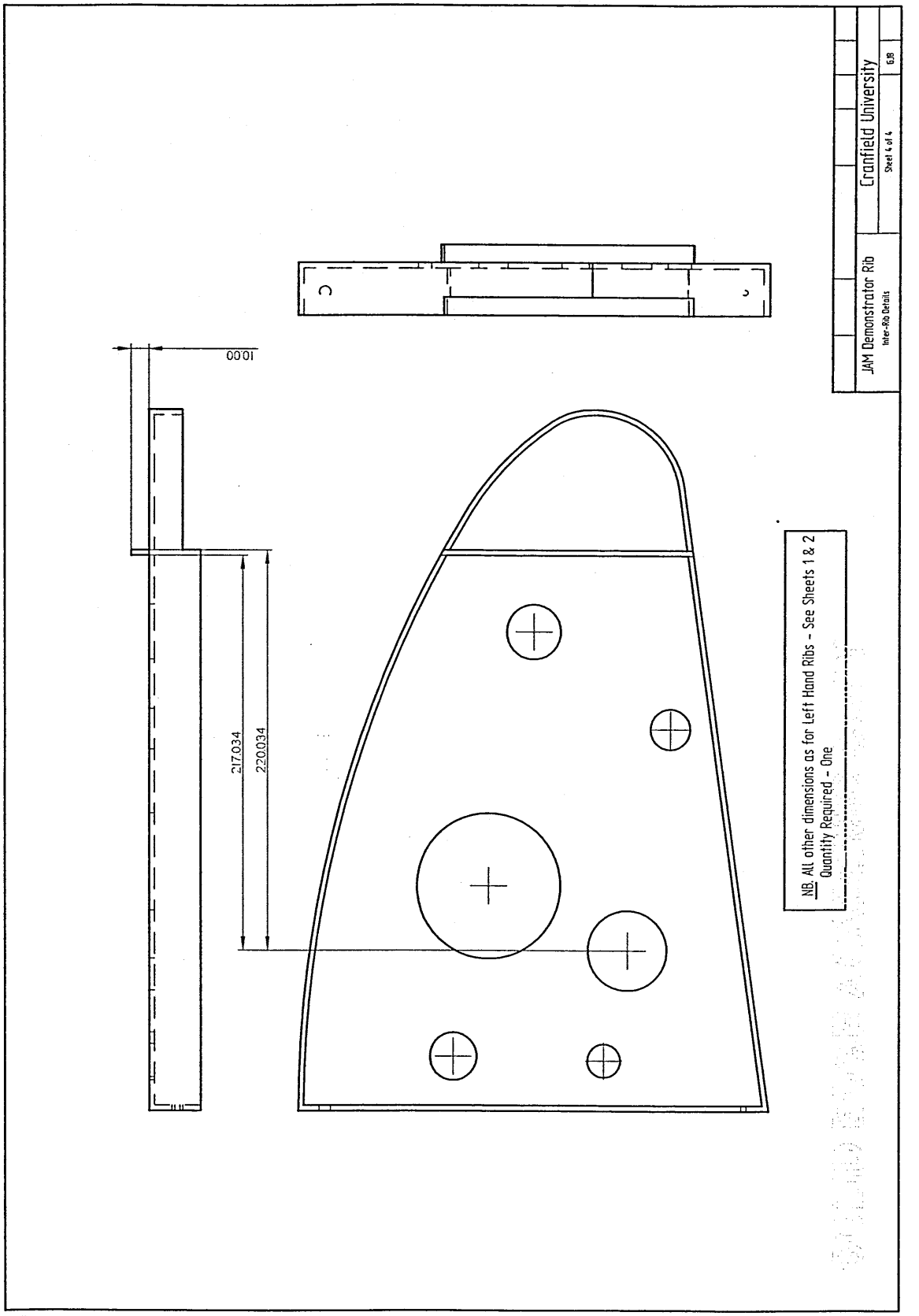
JAM Demonstrator Rib – Sheet 1 of 4 *Fig. 147*



JAM Demonstrator Rib – Sheet 2 of 4 *Fig. 148*



JAM Demonstrator Rib – Sheet 3 of 4 *Fig. 149*



JAM Demonstrator Rib – Sheet 4 of 4 *Fig. 150*

APPENDIX E

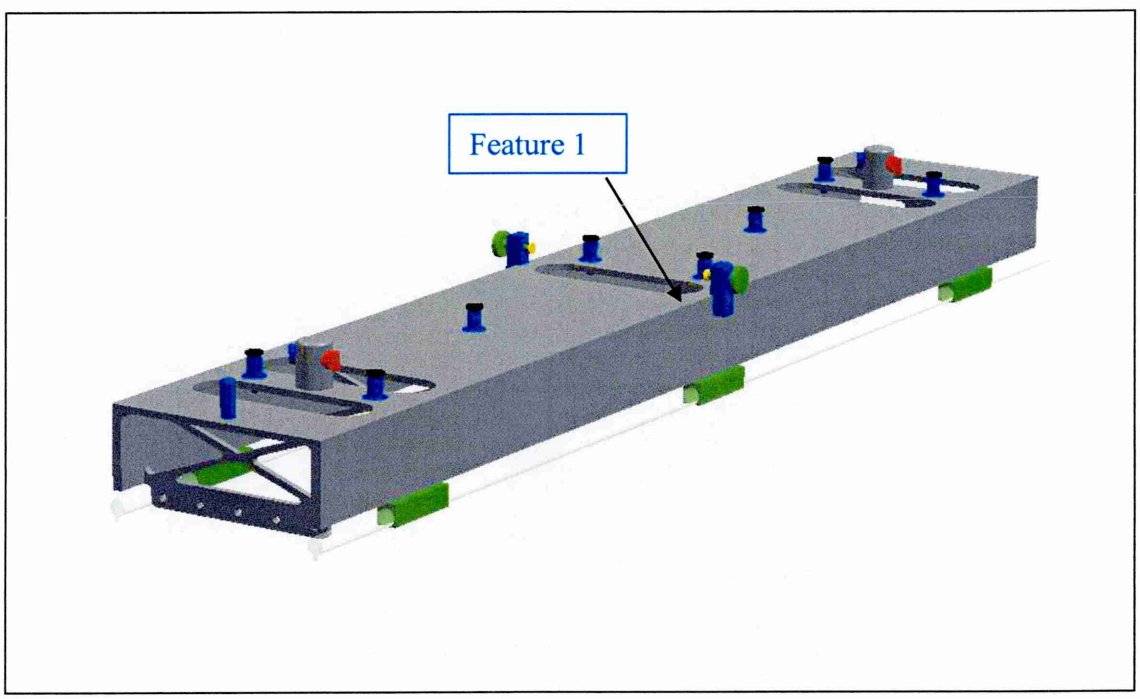
Case Study 1
Assembly Plan

Case Study 1 –Assembly Plan

E.1 Build-Tool

The spar is a long, flexible, monolithic CNC machining, (See Section 3.2.1), and simple stiffness calculations indicated that it must be supported during the build cycle.

A build-tool was designed to support and locate the spar and to enable a semi-automated build sequence using two, rail-mounted, machining and fastening heads, one operating above, and the other below the spar. The tool, *(Figure 151)*, incorporates a number of features, *(Figures 152 and 153)*, that help to achieve the final Product Key Characteristics;



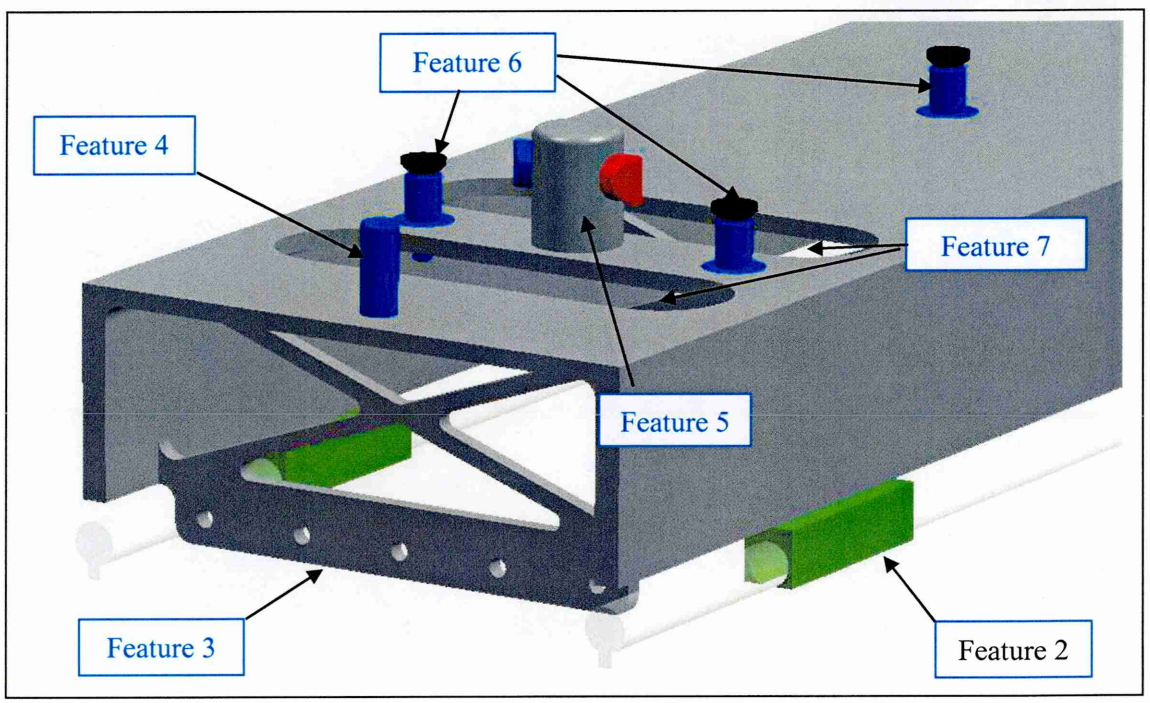
Build-Tool *Fig. 151*

Feature 1. The build-tool, (*Figure 151*), is a light alloy reinforced channel structure. To reduce the effects of differential thermal expansion between the build tool and the aerostructure, the material has the same specification, or at least, the same co-efficient of linear expansion as the spar, (See Section 4.1).

In line with current Airbus thinking, the design of the tool allows the build process to be semi-automated using two multi-axis CNC drilling heads; one head running on rails below the tool, and the second head running on rails above the tool, (See Section 4.11). The concept risk analysis indicated that the drilling heads should be fitted with machine vision to locate each of the king holes. This strategy is to cope with the spar growth following shot-peening plus the growth due to temperature expansion. Combined these can be as much as, (2.0+1.7), 3.7 mm. for a 5^0C increase in ambient temperature.

Feature 2 The build-tool is mounted on either a fabricated steel or cast iron base structure. To reduce the effects of differential thermal expansion between the build tool and the base structure, the tool is mounted on linear bearings.

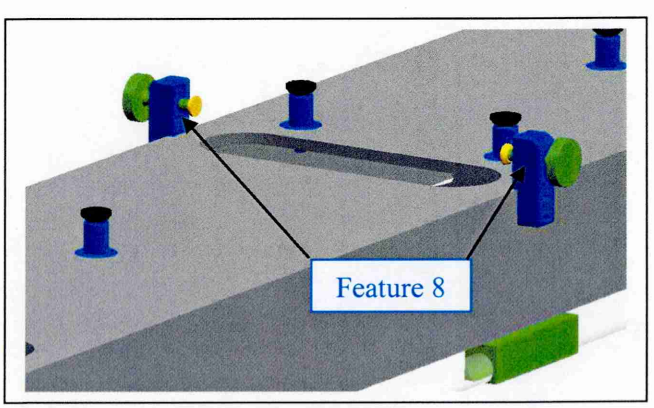
Feature 3. The build-tool is anchored at one end only, allowing the tool to expand lengthways.



Build- Tool Features *Fig. 152*

Feature 4. The tool has a diamond dowel pin to provide longitudinal location of the spar. This is not a high precision location as the automated drill heads will seek, and drill the matrix of fastener holes, relative to the king-holes.

Feature 5. To cope with the problems of spar flexibility and distortion, the spar is aligned along its reference axis by automated centring devices, consisting of one fixed pin, and one hydraulically operated, expanding pin. These locate in the slat can apertures and ensure the correct lateral positioning of the spar at the track rib positions.



Manual Adjusters *Fig. 153*

Feature 6. Kinematically arranged pads, locate to precision spot-faces on the back of the spar, and achieve the planar alignment of the spar at the rib positions. Each pad is fitted with a flexible vacuum cup to ensure that the spar is pulled down and fully

clamped for drilling and assembly. The use of raised pads helps to reduce the risk of trapping swarf between the spar and the tool.

Feature 7. Large cut-outs at each rib position allow access for the automated drilling and fastening operations, and for the swarf to fall clear.

Feature 8. At the inter-rib positions, pairs of manually operated adjusters enable any necessary correction of the spar reference axis, (*Figure 153*). These are necessary as there is no convenient hole in the spar to locate automated positioning devices. During assembly they are used in association with a sighting telescope and a location feature in the inter-rib, (*Figure 179*).

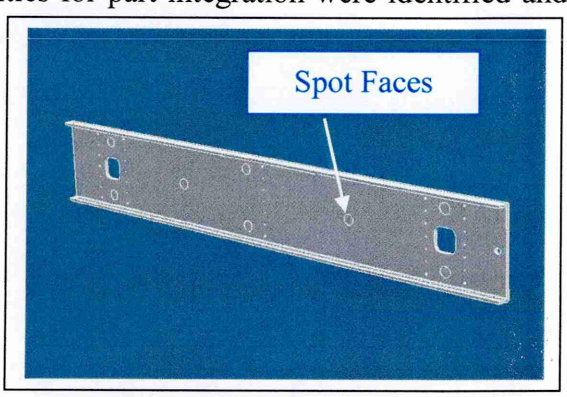
The cost of the build-tool complete with the two CNC drilling heads is included in the cost model, (Ref. 119).

E.2 Parts Design Modifications

The re-engineering process does not involve any major redesign of component parts, (See Section 7.1.1). A number of opportunities for part integration were identified and are detailed in Section 7.1.5. Also mentioned is the possible use of extruded section as an alternative to fabricating sheet metal sub-spars.

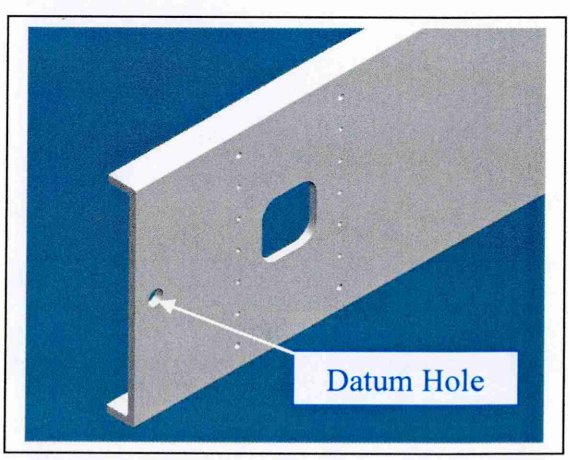
All modifications are fully costed and included in the cost model, (Ref. 119).

Detail part drawings showing the re-engineering changes are included in Appendix D.



Spot Faces on Back of Spar *Fig. 154*

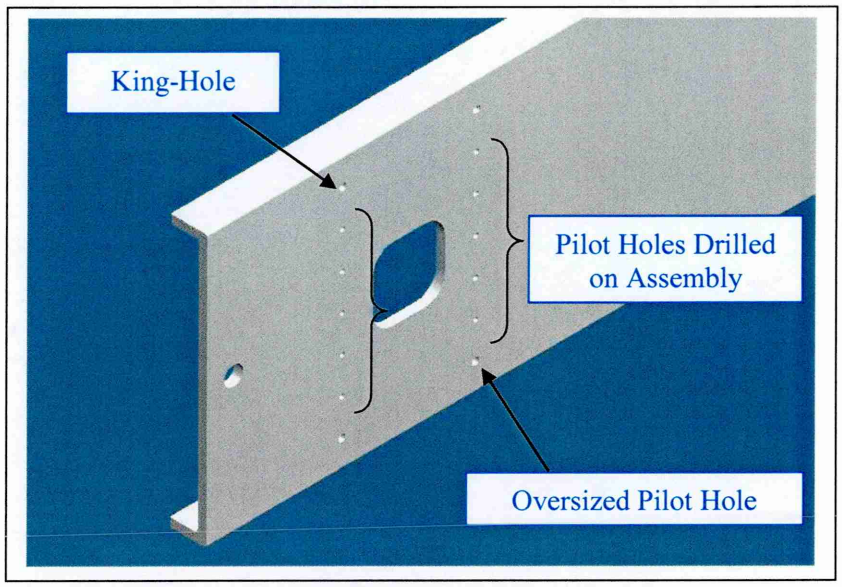
1) Front Spar - New additions to the design of the front spar are sets of shallow spot faces on the back face, (*Figure 154).* These are kinematically arranged in groups of three at each inter-rib and track-rib pair position. Their centre positions and diameters are not tightly toleranced. However, their depth, in relation to the front face of the spar is closely toleranced as this is an assembly key characteristic, necessary to achieve the correct planar alignment of the slat track bearings.



Spar Reference Feature *Fig. 155*

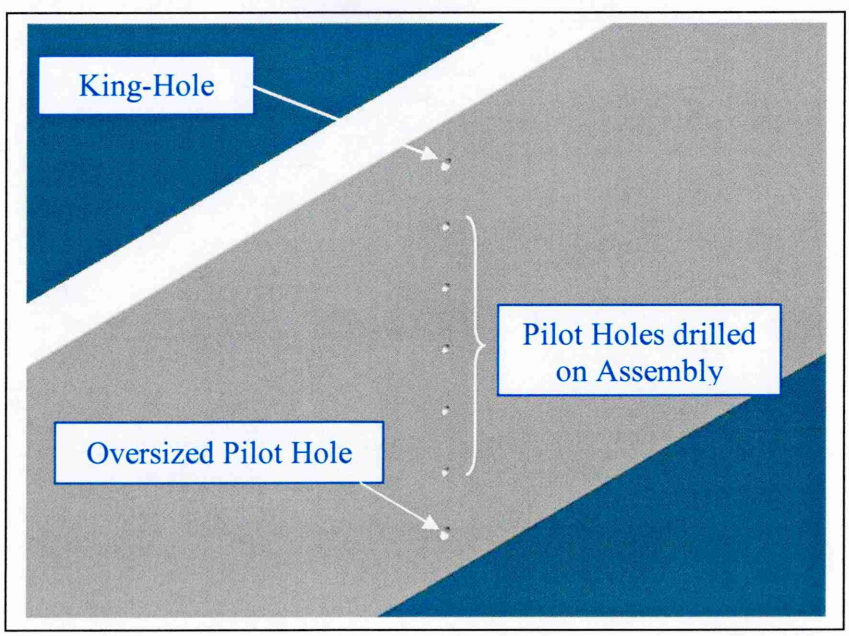
The spar has a datum hole reference feature. (*Figure 155*). This is a local datum related to the main aircraft datum, and overcomes the existing problem of the datum being lost when the spar is removed from the M/T fixture, (*Figure 234*), (See Sections 3.2.1, 3.3.6 and 3.3.7). The spar reference hole is used for;

- CNC machining datum in association with the centre-line of the spar billet.
- Dimensional verification during the build. (For confidence only).
- Reference feature for in-service repairs. (Lack of built-in reference features is described as a current problem).



King-Hole and Pilot Holes at Track Rib Pair Location *Fig. 156*

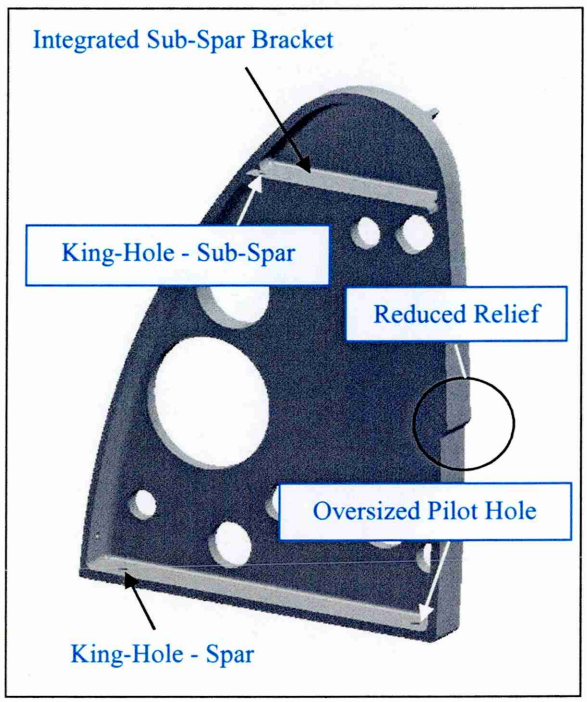
At each track rib pair location, *(Figure 156)*, and inter-rib location, *(Figure 157),* there is a single king-hole, a matrix of pilot holes, and an oversized pilot hole.



King-Hole and Pilot Holes at Inter-Rib Location *Fig. 157*

The positions of the king-holes and the king-hole diameters are tightly toleranced, and are CNC drilled during the spar machining together with the oversized pilot holes. The matrix of pilot holes are drilled and opened out to full diameter on assembly.

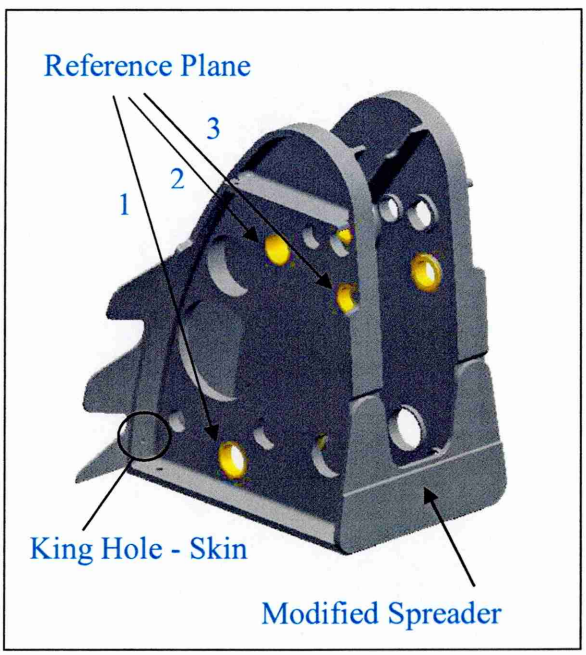
The king-holes are the primary rib-to-spar location features. The oversized pilot holes are used in conjunction with undersized, temporary-fasteners to allow a small amount of radial correction and temporary clamping. The 'spar face/king-hole/oversize pilot hole', provide the necessary '1-2-3' minimal kinematic restraint, and the stress-intensifying effects of round holes are well understood.



Additional Track Rib-Design Features *Fig. 158*

2) Track-Rib - The re-engineered track rib, (Figure 158), has the following modifications;

- An integrated sub-spar bracket, replacing the riveted sheet metal bracket. (See Section 7.1.5).
- Reduced relief, as a result of eradicating the double packers. (See Section 7.1.5).
- A single king-hole to locate the top edge of the sub-spar.
- A king-hole to effect the rib to spar location.
- An oversized pilot hole to allow minor radial adjustment about the king-hole.
- The mirror track rib of the pair is identical apart from having two oversized pilot holes to effect the rib to spar location, and no king-hole.



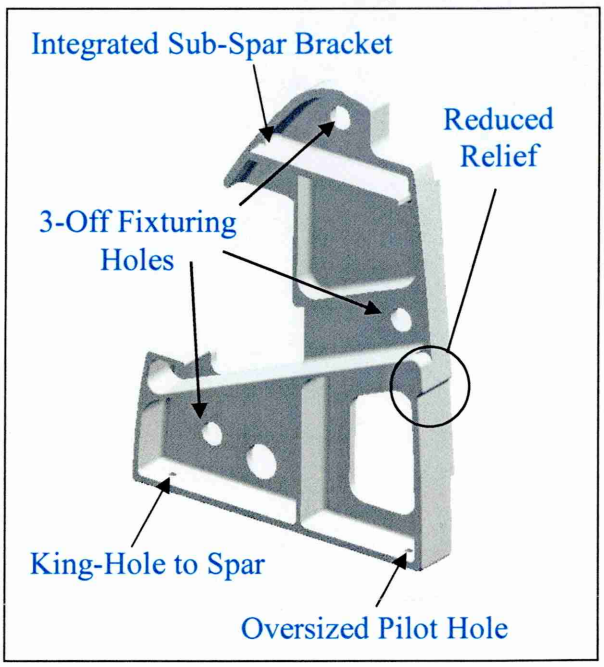
Modified Track-Rib Pair Sub-Assembly *Fig. 159*

3) Track-Rib Pair Sub-Assembly - The track-rib pair sub-assembly, *(Figure 159)*, has the following modifications;

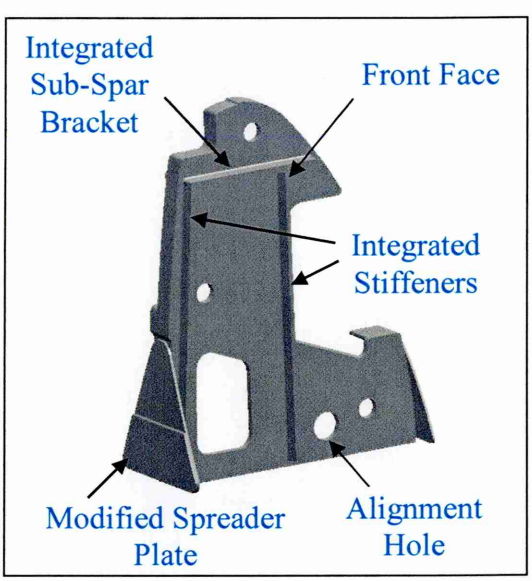
- A single king-hole to locate the top edge of the skin.
- During assembly the in-board faces of three bearing inserts are used to establish a reference plane.
- The re-engineered track-rib pair sub-assembly has a modified spreader plate. This is the result of eradicating the double packers, (See Section 7.1.5),
- The CNC profiled spreader plate has surplus metal to enable the demonstration of robotic fettling in the JAM demonstrator cell.

4) Inter-Ribs - The re-engineered inter-rib has the following modifications, *(Figures 160 and 161)*;

- An integrated sub-spar bracket on both sides, (See Section 7.1.5), replacing the riveted sheet metal brackets.
- Reduced depth of relief, (See Section 7.1.5), following eradication of the double packers.
- A single king-hole to locate to the top edge of the spar.
- An oversized pilot hole to allow minor radial adjustment about the king-hole.
- The three fixturing holes are used to locate the inter-rib for the machining of the king-hole and the oversized pilot hole. (*Figure 164*).
- The in-board face of the inter-rib at the three fixturing holes is used to establish a reference plane on assembly.
- Integrated stiffeners replacing the riveted angles. (See Section 7.1.5).
- The inter-rib sub-assembly is fitted with a machined spreader plate. This has surplus metal to enable the demonstration of robotic fettling in the JAM demonstrator cell.
- The alignment hole is used on assembly to align the inter-rib with the track-rib pairs. (*Figure 179*).



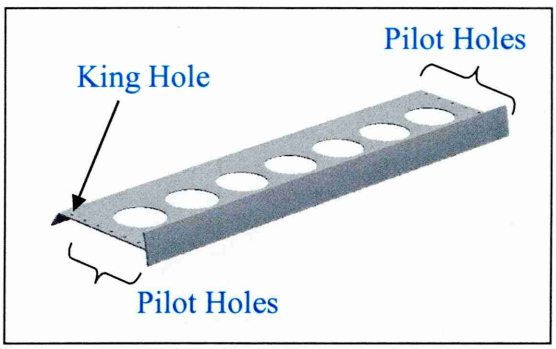
Re-Engineered Inter-Rib *Fig. 160*



Re-Engineered Inter-Rib Sub-Assembly *Fig. 161*

5) Sub-Spars - The re-engineered design for the sub-spars, *(Figure 162)*, proposes the use of extruded sections replacing the present sheet metal sub-assemblies. (See Section 7.1.5).

- The sub-spar sections supplied to the assembly cell are to length and pre-drilled with a single king-hole and a matrix of pilot holes.
- On assembly the king-hole mates with the king-hole in the track rib sub-spar bracket.
- After aligning and temporary fastening, the pre-drilled pilot holes act as a jig for drilling the two sub-spar brackets.



Re-Engineered Sub-Spar *Fig. 162*

E.3 Manufacturing Plan

The proposed re-engineering process requires that much of the assembly-precision moves from the assembly tooling to the part manufacturing. (See Section 5.8).

This does not necessarily mean that the parts must be produced more accurately than at present. It does, however, mean that the reference features and the primary, assembly, location features, such as king-holes, must be within the given tolerances of the part reference features, commonly edges and planes.

Blanket tolerancing is not suitable for this approach, (See Section 3.4).

The assembly strategy requires that the parts themselves become drilling jigs and assembly tooling. The major parts are also now manufactured with integrated reference features. This requires the additional sequences and changes to the established machining sequences described in Section F.3.1, but does not require major changes to the overall part-design.

E.3.1 Parts Manufacturing

This section describes machining methods and set-ups to establish the best possible chance of achieving the required tolerances.

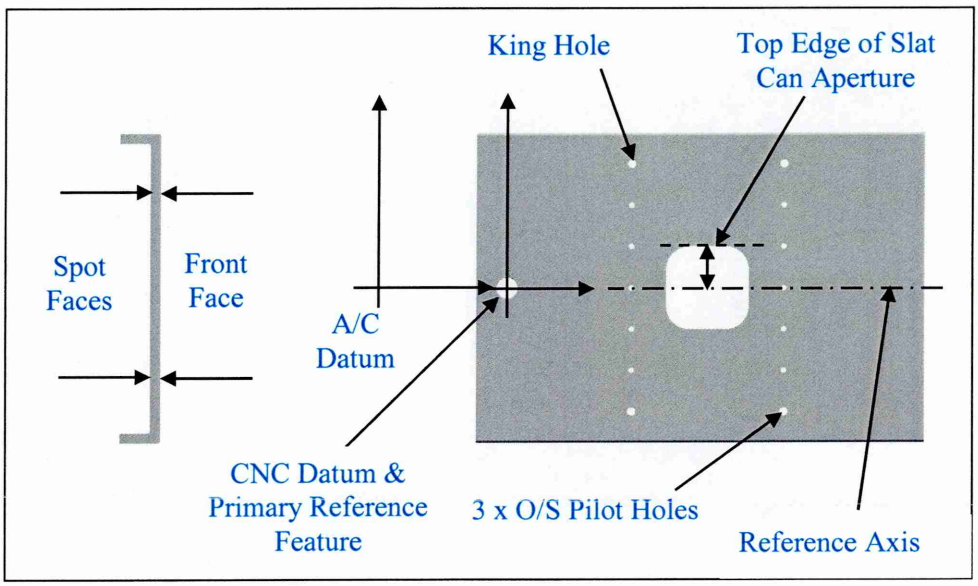
1) Front Spar

The material for the front spar arrives as a planar milled billet. During manufacture, 75% or more of the material is machined away. The spar becomes very flexible and it must be adequately supported. Lengthways, it must be prevented from bowing away from the cutter. (See Section 3.2.1).

Outline Machining Sequence:

- Use enclosed spar mill with temperature controlled coolant, (See Section 4.1). The M/T will need a high speed spindle for small-hole drilling. This can be an autonomous unit loaded from the tool carousel.
- Allow spar and tooling to temperature soak for 24 hours.
- Skim front face. Turn over and skim the rear face.
- Machine the main datum hole.
- Establish CNC datum at primary reference feature. *(Figure 163).*
- Rough machine.

- Stress relieve.
- Finish machine pockets.
- Finish machine edges.
- Machine spot-faces.

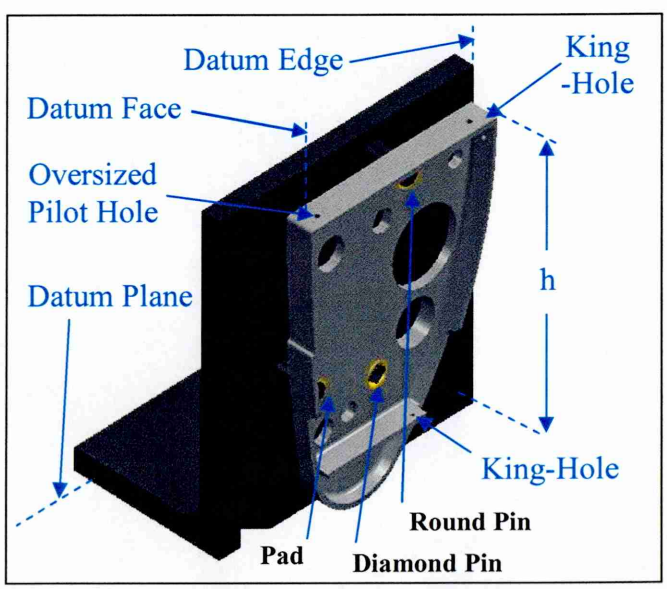


Spar Reference and Assembly Features *Fig. 163*

- At each track-rib pair/inter-rib location - machine the single, full sized, king-hole, referenced to the main datum.
- Drill the associated oversized pilot holes.
- The king-holes must be masked during shot peening, (See Section 3.2.10).

2) Track-Rib Pairs

- Following the normal manufacturing process and the fitting and final machining of the plain bearings, (See Section 3.2.2).
- Return to mill or jig-borer.
- Fixture on an angle plate locating to the bearing holes.
- The fixture sets rib orientation and position referenced to the bearing holes and faces.
- Machine rib/spar flange to height, 'h'.
- Machine rib/spar king-hole and oversized pilot hole.



Machining King-Hole in Track-Rib *Fig. 164*

For a horizontal machine tool with a rotary table;

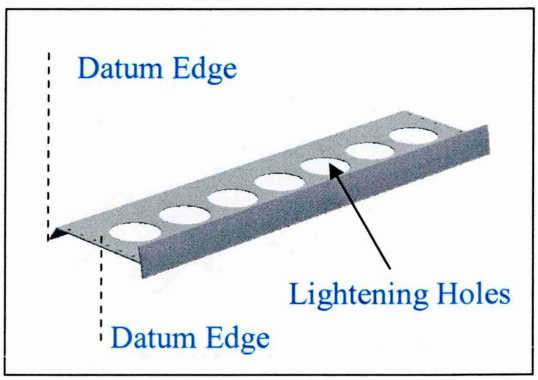
- Rotate table 180^0.

- Shift datum.
- Machine king-hole to locate sub-spar.

For a vertical machine tool, *(Figure 164)*
- With the rib vertically rotated $180^{0,}$ fixture on a second angle plate using the bearing holes.
- Set datum referenced to bearing faces and top, 'rib to spar', edge.
- Machine king-hole to locate sub-spar.

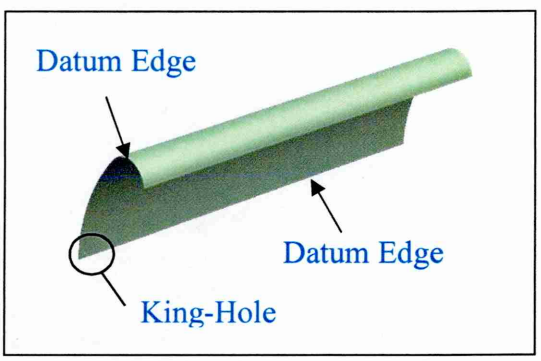
NB. The 'rib to skin' king-hole is drilled at the sub-assembly stage.

Inter-ribs Use the three fixturing holes and fixture as for the first setting of the track ribs.
- Set datum referenced to front face, (*Figure 164*), and top, 'rib to spar', edge.
- Machine rib to spar king-hole, and oversized pilot hole.



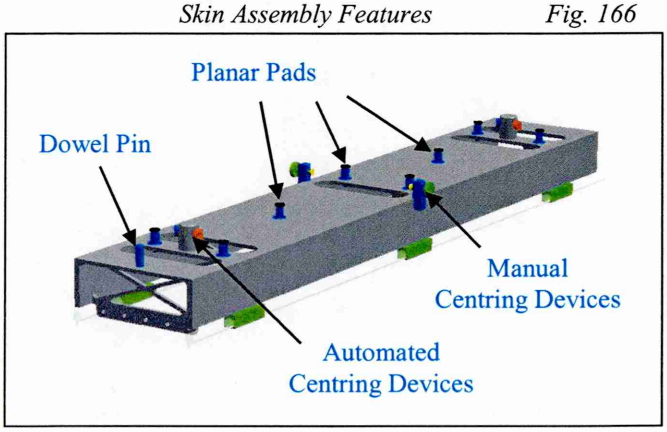
Sub-Spar Assembly Features *Fig. 165*

3) Sub-Spars
- Use a slitting saw to machine sub-spar extrusions to length.
- Fixture on a milling machine and planetary mill lightening holes.
- Datum to the track-rib end and top edge, *(Figure 165).*
- Machine king hole and pilot holes. (*Figure 162).*



Skin Assembly Features *Fig. 166*

4) Skins
- The skins are stretch formed, then pulled flat for pilot hole drilling and profiling. (See Section 3.2.6).
- The re-engineered design requires that a single king-hole be used to locate one end, only, of the skin to a track rib pair. (*Figure 166*).



Assembly Step 1 *Fig. 167*

E.4 Assembly Sequence

The fixed leading edge is built vertically upwards from the spar, allowing gravity to be an aid rather than a hindrance.

Assembly sequence;

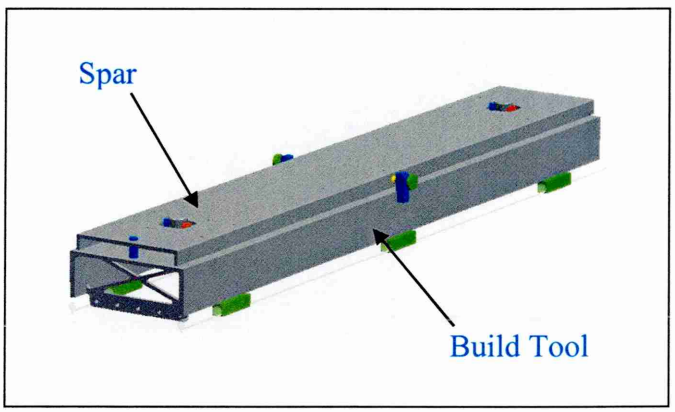
Tool ⇒ Spar ⇒ Track-Rib Pair ⇒ Inter-Rib ⇒ Track-Rib Pair ⇒ Sub-Spars ⇒ Skin

Assembly Step 1

- Prepare the build tool, *(Figure 167)*, by thoroughly cleaning it and removing all swarf.
- Pay particular attention to the location features.

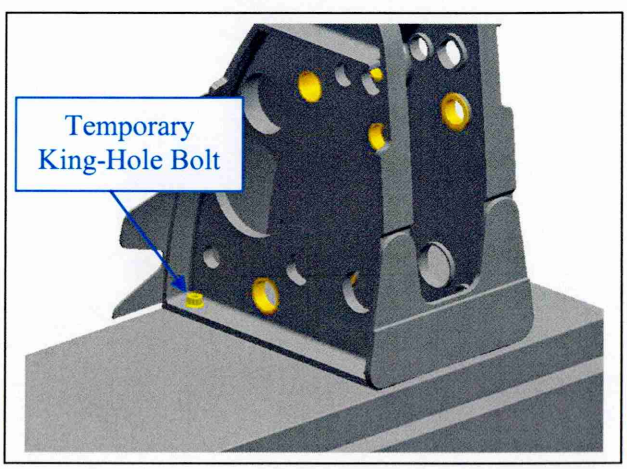
Assembly Step 2

- Check the cleanliness of the spot faces on the underside of the spar.
- Using vacuum lifting equipment carefully lower the spar into position, (*Figure 168*).
- Check that the automated centring devices are retracted and the manual centring devices are wound back.
- Locate on the Reference Dowel.
- Allow the partial weight of the vacuum lifting equipment to press the spar onto the pads.
- Pull partial vacuum on the pads to ensure that spar is located in the planar position.
- Activated the automated centring devices.
- Pull full vacuum on the planar pads to fully locate and lock the spar in position.



Assembly Step 2 *Fig. 168*

Assembly Steps 3 to 5



Assembly Step 3 *Fig. 169*

To maintain a clear line-of-sight with reference to the primary reference feature, (See *Figure 155*), work from the outboard end towards the wing root;

- Zero robot to king-hole using machine vision and an RCC.

- Position the first of the track-rib pairs and secure with a temporary fastener in the king-hole. (*Figure 169*).

- The temporary fastener should be a sliding fit, and not an interference fit as for the final fasteners.

- Fit a secondary fastener in each of the three oversized pilot holes. These allow a small amount of radial adjustment about the king-hole. (*Figure 170*).

- The king-hole fasteners, secondary fasteners, and permanent fasteners are coloured coded to avoid incorrect usage.

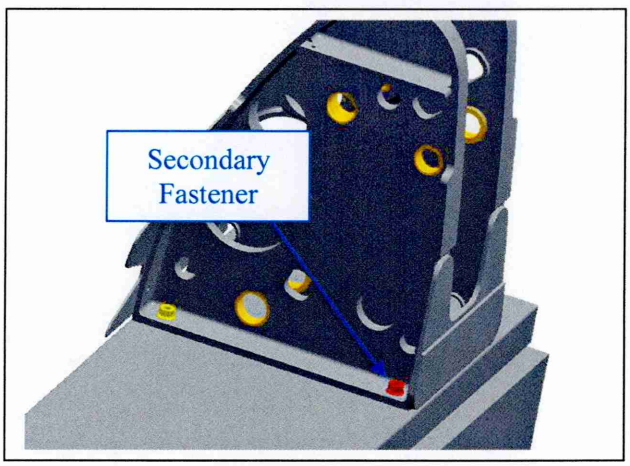
- Use optical targets at three separate bearing hole positions to establish the correct alignment of the track-rib sub-assembly. (*Figure 171*).

- Working diagonally; tighten the temporary fasteners and verify the position of the track-rib sub-assembly.

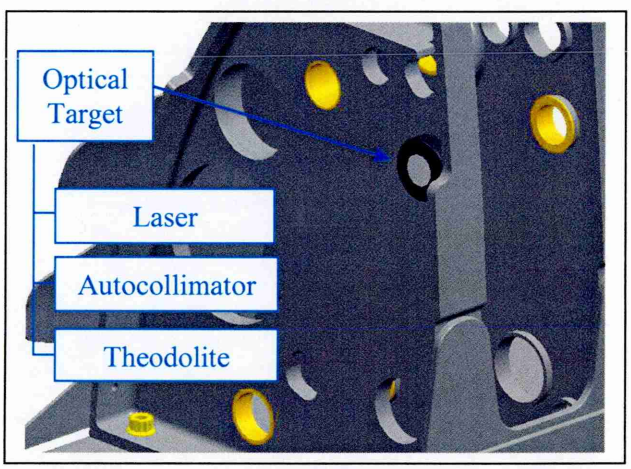
- Initiate the programmed drilling sequence.

- Strip down, deburr, and reassemble with permanent fasteners.

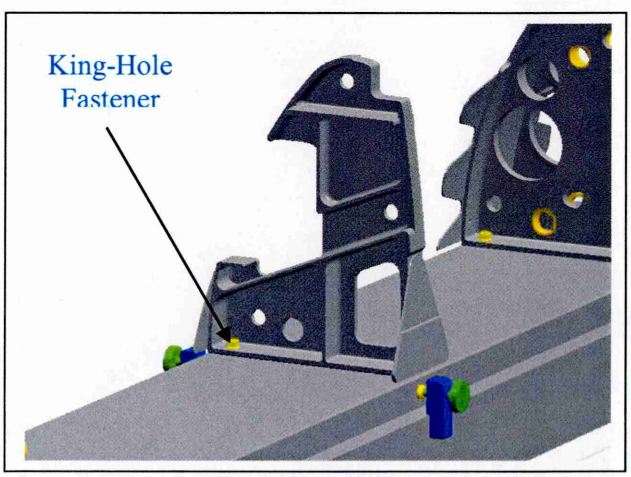
- Drill out oversize pilot holes to final size. (The high clamping forces exerted by the set fasteners will prevent the growth of inter-facial burrs). (See Section 3.2.6).



Assembly Step 4 *Fig. 170*



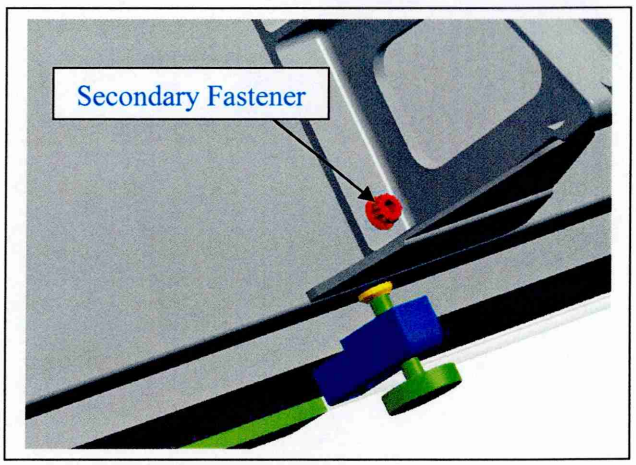
Assembly Step 5 *Fig. 171*



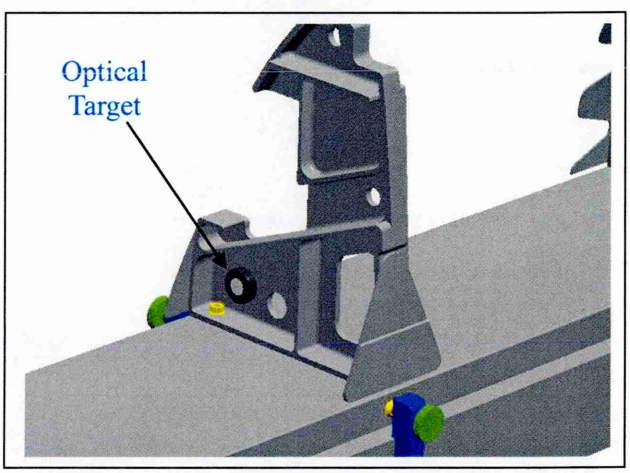
Assembly Step 6 *Fig. 172*

Assembly Steps 6 to 8

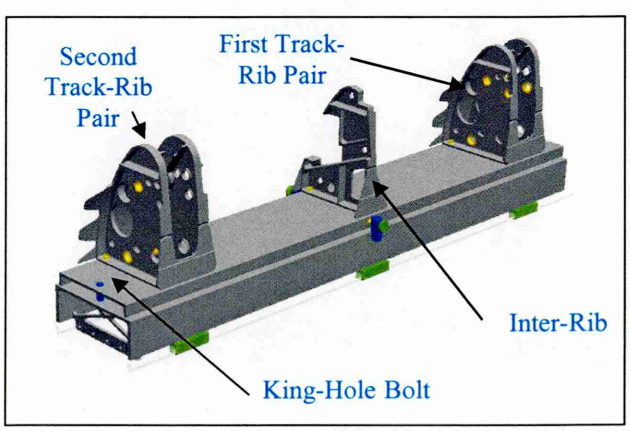
- Zero robot to king-hole using machine vision and an RCC.
- Position the inter-rib and secure with a temporary fastener in the king-hole. (*Figure 172*).
- The temporary fastener should be a sliding fit, and not an interference fit as for the final fasteners.
- Fit a secondary fastener in the oversized pilot hole. This is to provide a small amount of radial adjustment about the king-hole. (*Figure 173*).
- Use optical targets at each of the three fixturing holes to establish the correct orientation of the inter-rib sub-assembly, (*Figure 174*).
- Tighten the temporary fasteners and verify the orientation of the inter-rib sub-assembly.
- Initiate the programmed drilling sequence.
- Strip down, deburr, and reassemble with permanent fasteners.
- Drill out oversize pilot holes to final size. (The high clamping forces exerted by the set fasteners will prevent the growth of inter-facial burrs). (See Section 3.2.6).



Assembly Step 7 *Fig. 173*



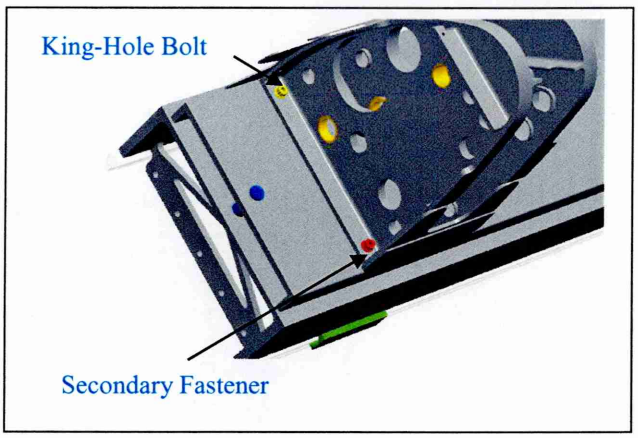
Assembly Step 8 *Fig. 174*



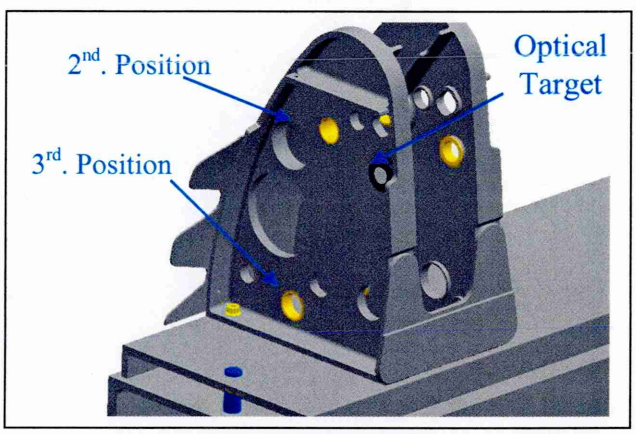
Assembly Step 9 *Fig. 175*

Assembly Steps 9 to 13

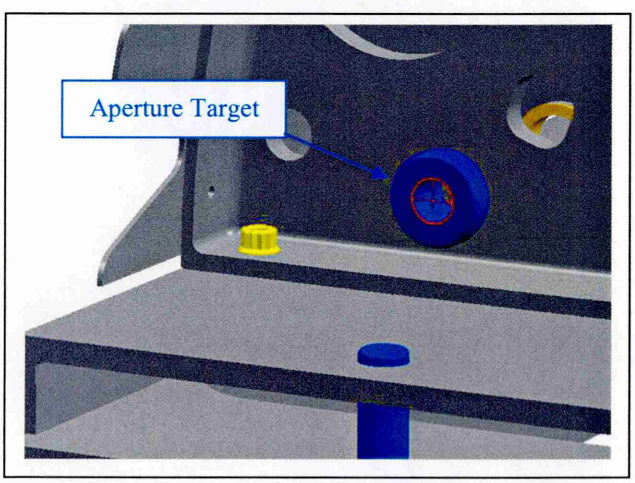
- Zero robot to king-hole using machine vision and an RCC.
- Position the second of the track-rib pairs and secure with a temporary fastener in the king-hole. (*Figure 175*).
- The temporary fasteners should be a sliding fit, and not interference fit as for the final fasteners.
- Fit secondary fasteners in the three oversized pilot holes. These are to provide a small amount of radial adjustment about the king-hole. *(Figure 176).*
- The king-hole bolts, the secondary fasteners, and the permanent fasteners are coloured coded to avoid incorrect usage.
- Use optical targets at three separate bearing hole positions to establish the correct alignment of the track-rib sub-assembly, (*Figure 177).*
- Tighten the temporary fasteners and verify the position of the track-rib sub-assembly.
- Initiate the programmed drilling sequence.
- Strip down, deburr, and reassemble with permanent fasteners.



Assembly Step 10 *Fig. 176*



Assembly Step 11 *Fig. 177*



Assembly Step 12 *Fig. 178*

- Drill out oversize pilot holes to final size. (The high clamping forces exerted by the set fasteners will prevent the growth of inter-facial burrs). (See Section 3.2.6).

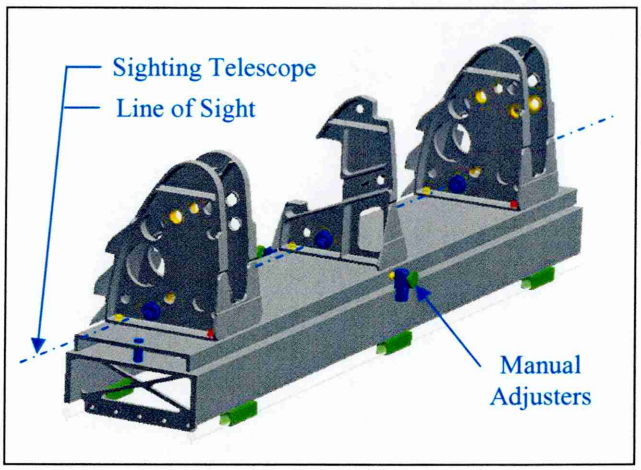
- Complete the fastening of the inter-rib.

- Using a sighting telescope and aperture targets, (*Figure 178*), align the inter-rib with the associative track-rib pairs by use of the manual spar adjusters, (*Figure 179*).

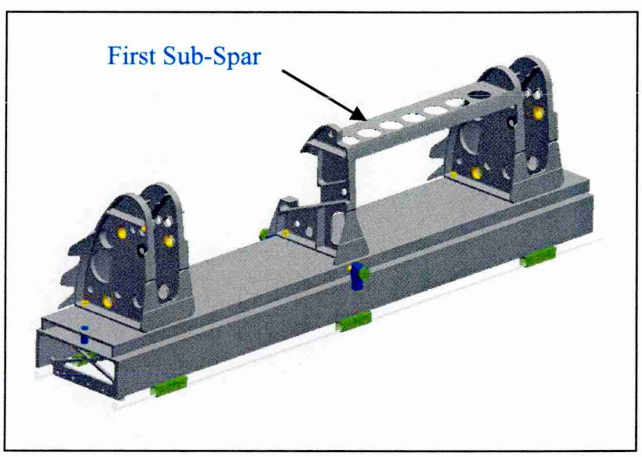
- Initiate the programmed drilling sequence.

- Strip down, deburr, and reassemble with permanent fasteners.

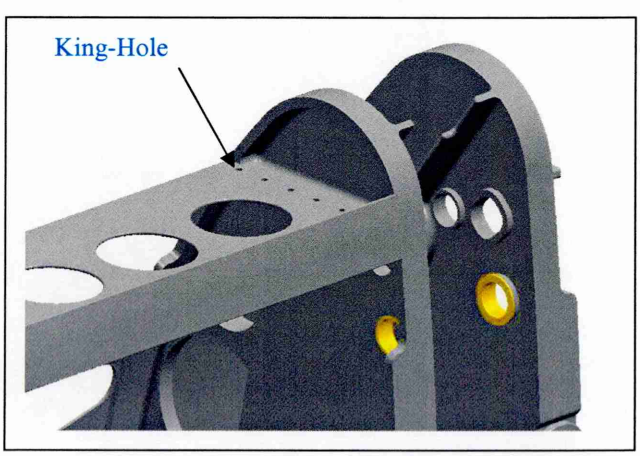
- Drill out oversize pilot holes to final size. (The high clamping forces exerted by the set fasteners will prevent the growth of inter-facial burrs). (See Section 3.2.6).



Assembly Step 13 *Fig. 179*



Assembly Step 14 *Fig. 180*



Assembly Step 15 *Fig. 181*

<u>Assembly Steps 14 to 16</u>

- Zero robot to king-hole in sub-spar bracket using machine vision and an RCC.

- Position first sub-spar and align king-holes. (*Figures 180 and 181*).

- Secure using a temporary fastener in the king-hole.

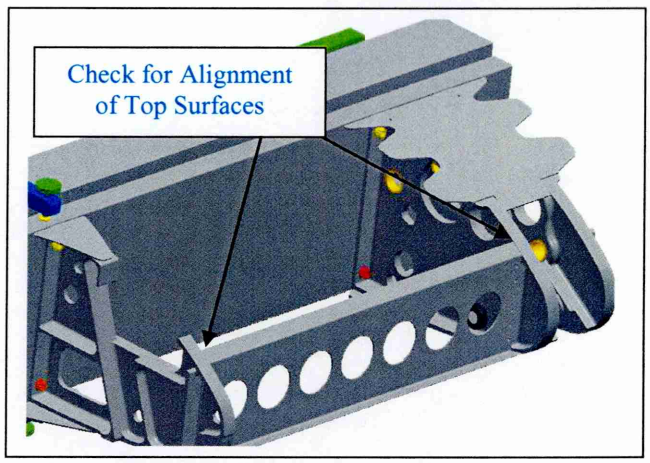
- Using a G-cramp, temporarily fasten the inter-rib end of the sub-spar.

- Manually align the top edge of the sub-spar with the top edge of the inter-rib. (*Figure 182*).

- Check that the sub-spar is aligned with the top edge of the track-rib.

- Initiate the programmed drilling sequence.

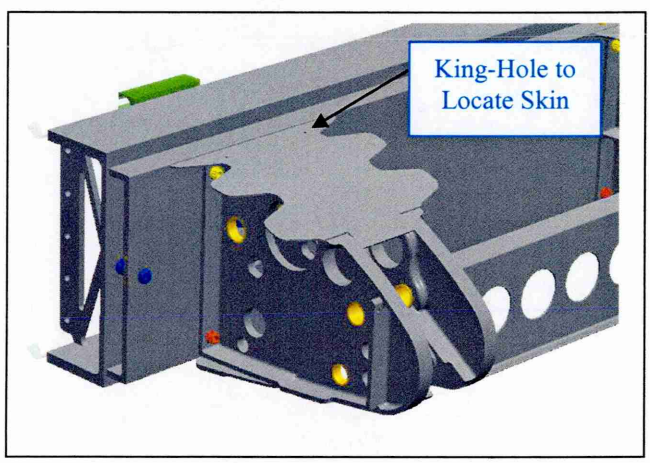
- The sequence will automatically stop to allow more temporary pinning and repositioning of G-cramps.
- Strip down, deburr, and reassemble with permanent fasteners.
- Following the same procedure fit the second sub-spar.



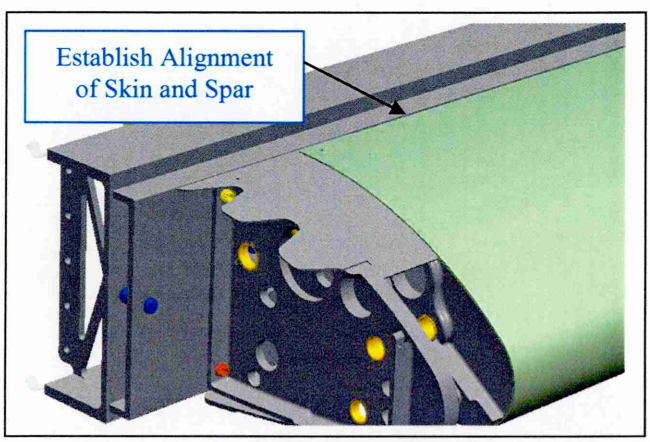
Assembly Step 16 *Fig. 182*

Assembly Steps 17 and 18

- Thoroughly clean structure, and ensure removal of all swarf.
- Position skin and align king-holes. (*Figure 183*).
- Secure using a temporary fastener in the king-hole.
- Loosely fit strap clamps.
- Manually establish the alignment of the top edge of the skin and the spar, and systematically tighten the strap clamps, pulling the skin down into position. (*Figure 184).*
- Use the overhead robot to drill the fastening holes through the skin and the sub-structure.
- Initiate the programmed drilling sequence.
- Strip down, deburr, clean and reassemble with permanent fasteners. (*Figure 185*).

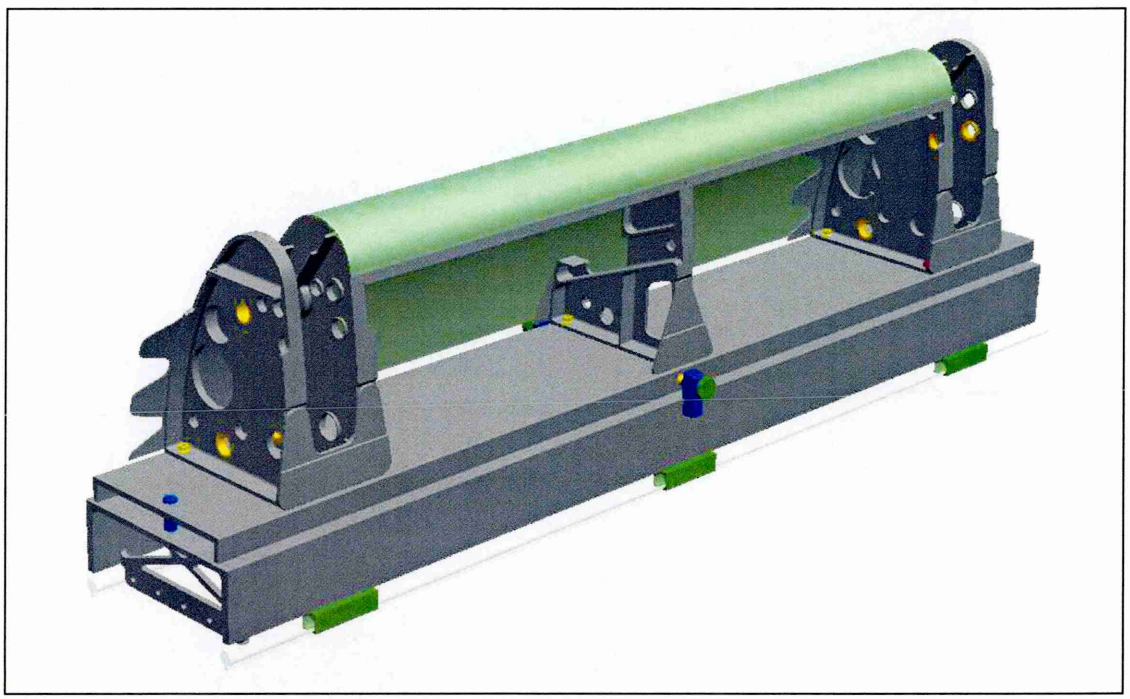


Assembly Step 17 *Fig. 183*



Assembly Step 18 *Fig. 184*

This completes the assembly of the JAM demonstrator structure.



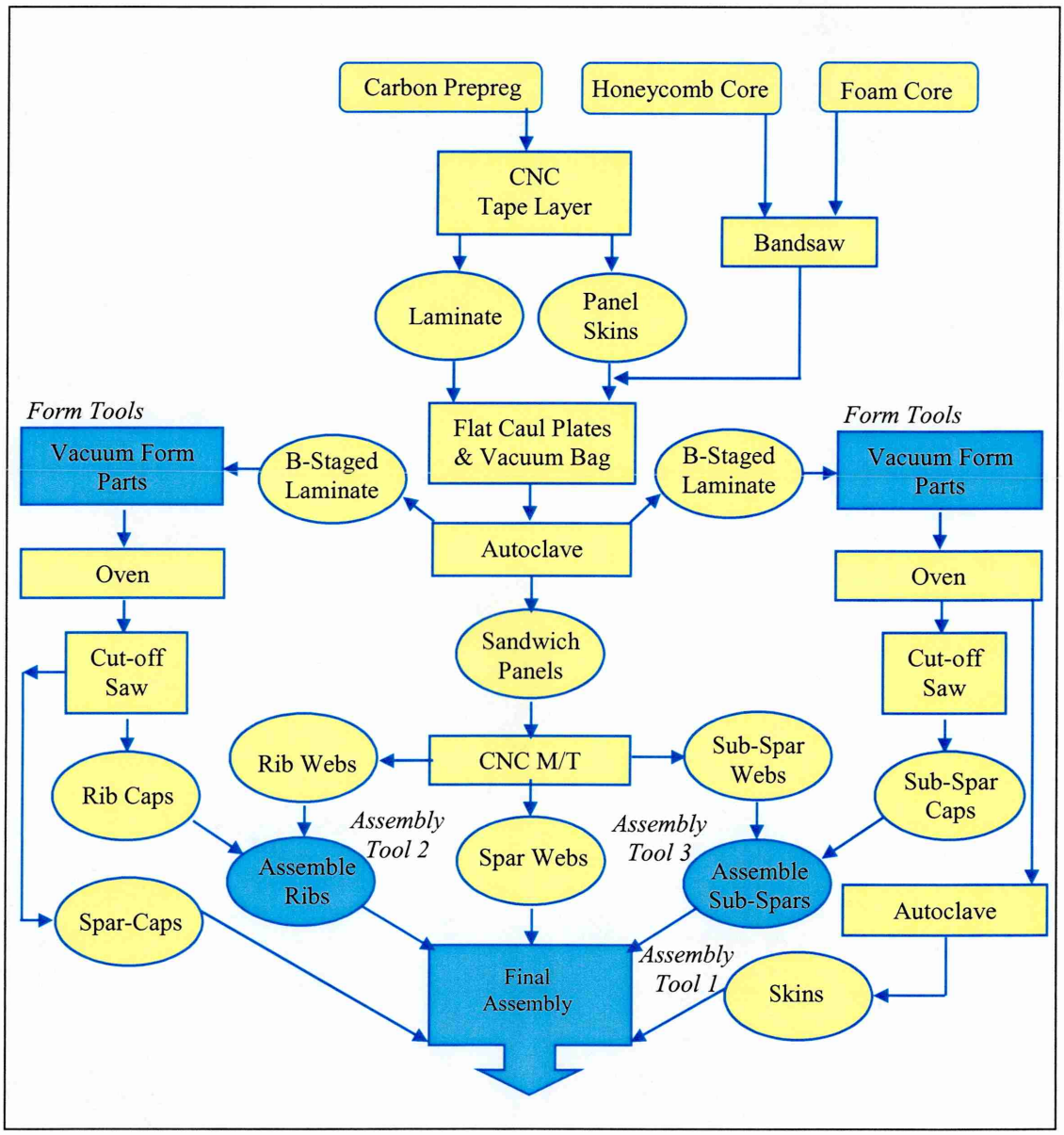
The Assembled Demonstrator and Build-Tool *Fig. 185*

APPENDIX F

Case Study 2
Assembly Plan

Case Study 2 – Assembly Plan

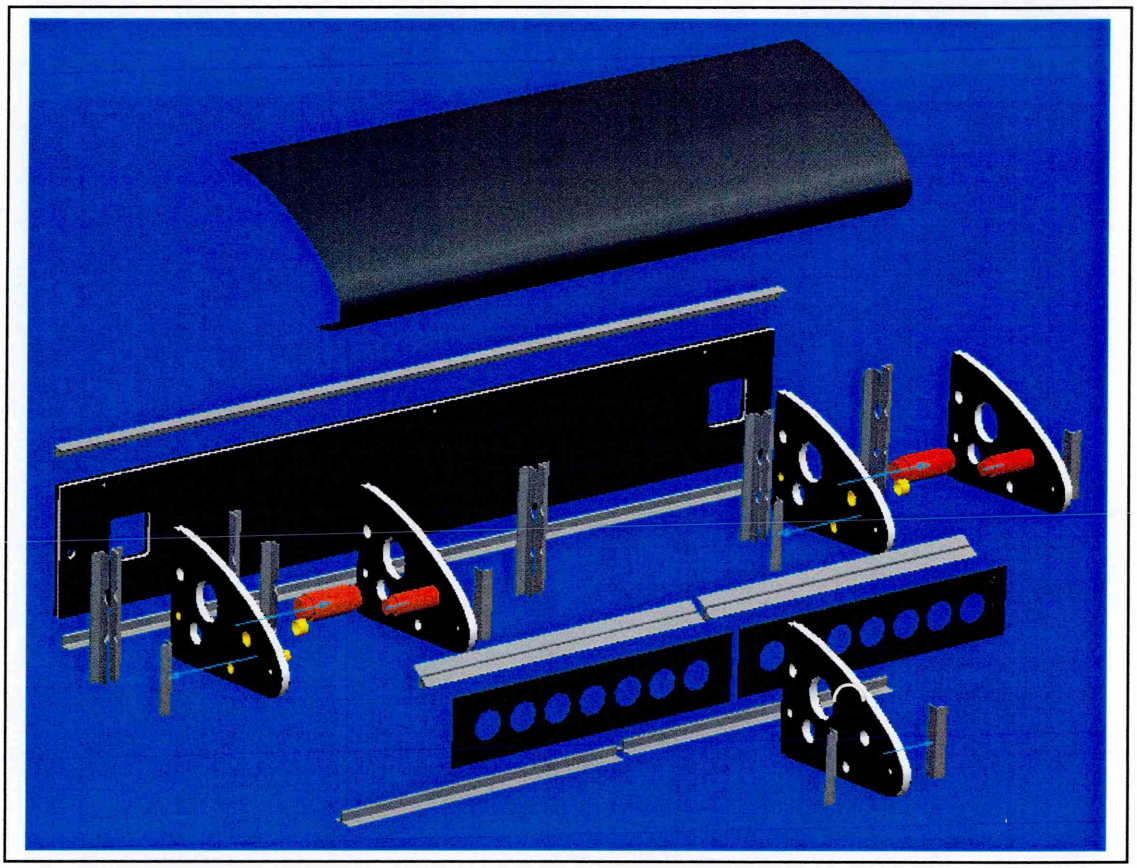
F.1 Cost-Effective Parts Manufacture



Proposed Parts-Manufacturing Route *Fig. 186*

Figure 186 is a graphical representation of the part-manufacturing up to the final assembly. Unlike conventional composite design, this concept requires the minimum of dedicated form tooling. The major parts, (*Figure 187*), are of sandwich construction cured between flat, steel, caul plates, with the caps and brackets vacuum formed and cured over very simple angle-steel tooling. The necessary degree of precision is established through the CNC machining of the rib-profiles and through the simple assembly tooling that ensures the correct positioning and alignment of the bearing inserts and of the location features; the spar caps and rib caps, and the sub-spar brackets.

The use of slotted joints, (Section 5.8), and the acceptable variation in the bond-line thickness allows most of the manufacturing and assembly tolerances to be relaxed without compromising the quality of the finished structure.



The Kit of Parts *Fig. 187*

F.2 Assembly Sequence

Build Tool 2 ⇒ Inter-Ribs ⇒ Brackets
Build Tool 2 ⇒ Track Ribs ⇒ Brackets ⇒ Bearings ⇒ (Dummy Rollers)
Build Tool 3 ⇒ Sub-Spars ⇒ Caps
Build Tool 1 ⇒ Spar ⇒ Caps ⇒ Track Ribs ⇒ Inter-Ribs ⇒ Sub-Spars ⇒ Skin

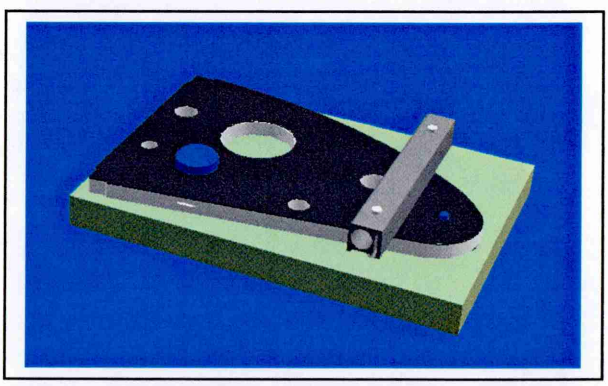
Assembly Stage 1 (*Figure 188*)
Build Tool 2 ⇒ Inter-Ribs ⇒ Brackets

Prepare Build Tool 2

- Thoroughly clean and remove old adhesive.
- Pay particular attention to the location features.

Inter-Rib Sub-Assembly

- Prepare bonding surfaces.



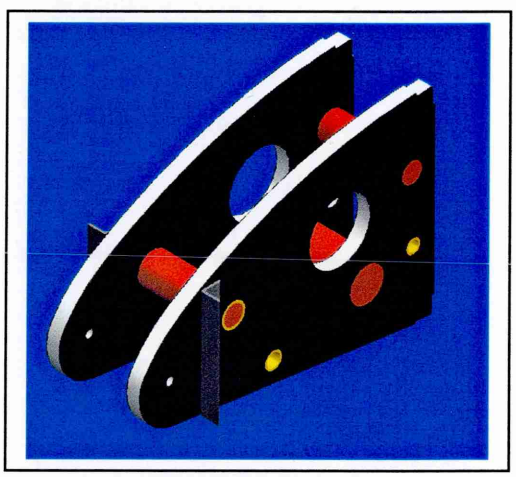
Step 1 - Build Tool 2 *Fig. 188*

- Load first bracket into Build Tool 2.
- Apply adhesive.
- Locate rib web to the two dowel pins. (One round pin and one diamond pin).
- Apply adhesive.
- Load second bracket into Build Tool 2.
- Oven cure adhesive.

Assembly Stage 2 (*Figure 189*)
Build Tool 2 ⇒ Track Ribs ⇒ Brackets ⇒ Bearings ⇒ (Dummy Rollers)

Track-Rib Pair Sub-Assembly

- Prepare bonding surfaces.
- For left hand rib; load left hand bracket into Build Tool 2.
- Apply adhesive.
- Locate rib web to the two dowel pins.
- Locate bearing inserts to mandrels.
- Apply adhesive.
- Oven cure adhesive.



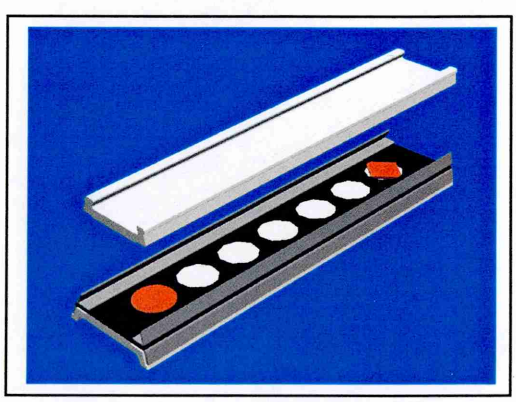
Assembled Track-Rib Pair *Fig. 189*

- Prepare bonding surfaces.
- For right hand rib; load right hand bracket into Build Tool 2.
- Apply adhesive.
- Locate rib web to the two dowel pins.
- Locate bearing inserts to mandrels.
- Apply adhesive.
- Oven cure adhesive.
- Using the two-piece dummy rollers; assemble the left and right hand ribs together to form a Track-Rib pair. (One of the three rollers is a clearance fit to avoid over restraint).
- Repeat for the second Track-Rib pair

Assembly Stage 3
Build Tool 3 ⇒ Sub-Spars ⇒ Caps

Prepare Build Tool 3

- Thoroughly clean and remove old adhesive.
- Pay particular attention to the location features.



Sub-Spar & Build Tool 3 *Fig.190*

Sub-Spar Sub-Assembly

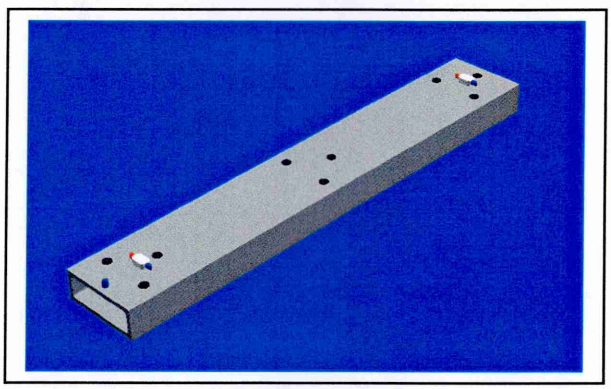
- Prepare bonding surfaces.
- Load rearward facing caps into the lower half of Build Tool 3, (*Figure 190*).
- Apply adhesive.
- Locate rib web to the two location features.
- Apply adhesive.

- Load forward facing caps into Build Tool 3.
- Oven cure adhesive.

Assembly Stages 4, 5, 6, 7

Build Tool 1 ⇒ Spar ⇒ Caps ⇒ Track Ribs ⇒ Inter-Ribs ⇒ Sub-Spars ⇒ Nose Skin

The fixed leading edge is built vertically upwards from the spar, allowing gravity to be an aid rather than a hindrance.



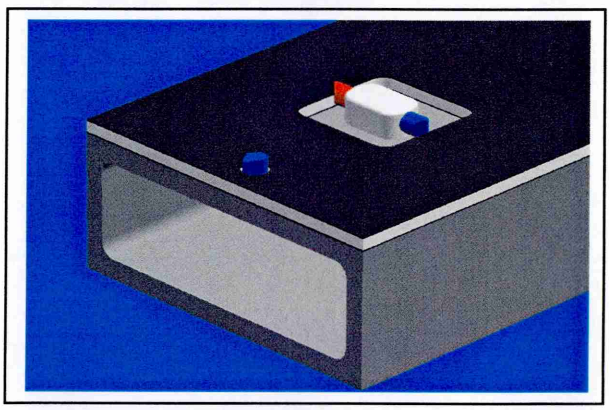
Build Tool 1 *Fig. 191*

Build Tool 1, is a closed hollow box of carbon composite construction having three sets of, three kinematically arranged, machined, vacuum pads to provide planar location and clamping. The tool has a diamond dowel providing longitudinal location and two hydraulically operated centering devices that ensure the lateral positioning of the spar along the reference axis.

Assembly Stage 4

Prepare Build Tool 1, *(Figure 191)*

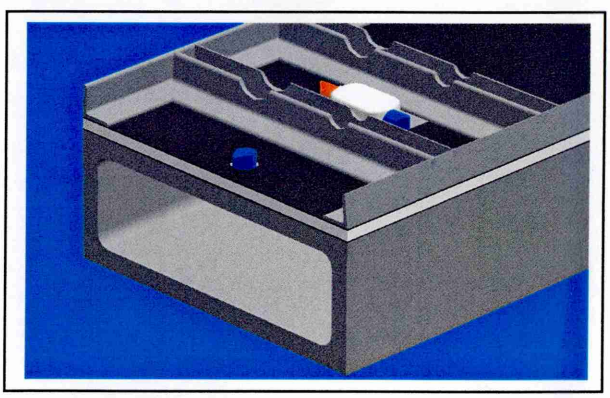
- Thoroughly clean and remove old adhesive.
- Pay particular attention to the location features.



Spar Web Location *Fig. 192*

Build Tool 1 ⇒ Spar

- Prepare bonding surfaces.
- Check the cleanliness of the underside of the spar web.
- Check that the automated centring devices are retracted.
- Using vacuum lifting equipment carefully lower the spar web into position, (*Figure 192*).
- Locate on the Reference Dowel.
- Allow the partial weight of the vacuum lifting equipment to press the spar onto the vacuum tool.

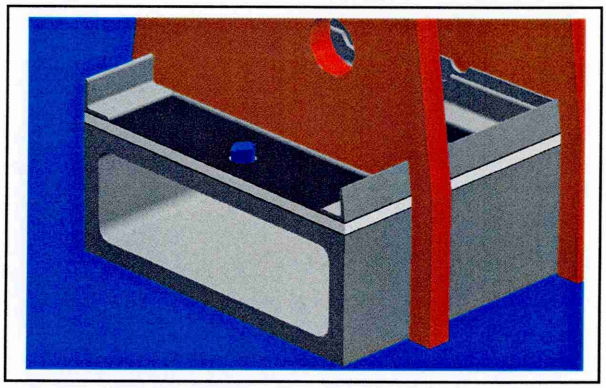


Addition of Spar and Rib Caps *Fig. 193*

- Pull partial vacuum on the pads to ensure that spar is located in the planar position.
- Activated the automated centring devices.
- Pull full vacuum on the pads to fully locate and lock the spar in position.

Build Tool 1 ⇒ Spar ⇒ Caps

- Prepare bonding surfaces.
- Apply adhesive.
- Position spar-caps.
- Prepare bonding surfaces.
- Apply adhesive.
- Position rib-caps. *(Figure 193).*
- Add pick-up arms to provide definitive location. *(Figure 194).*
- Oven cure adhesive.

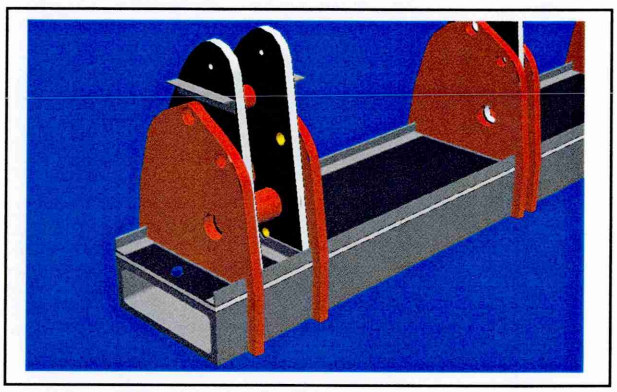


Pick-Up Arms Provide Location *Fig. 194*

Assembly Stage 5

Build Tool 1 ⇒ Spar ⇒ Caps ⇒ Track Ribs ⇒ Inter-Ribs

- Prepare bonding surfaces and shot blast deep slots.
- Apply adhesive.
- Locate rib-webs to pick-up arms. *(Figure 195).*
- Oven cure.



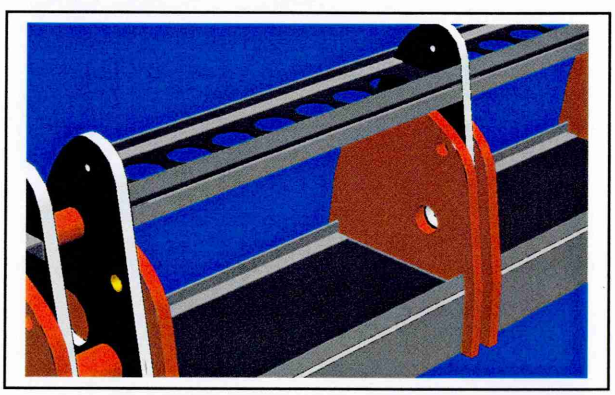
Addition of Rib Webs *Fig. 195*

Assembly Stage 6

Build Tool 1 ⇒ Spar ⇒ Caps ⇒ Track Ribs ⇒ Inter-Ribs ⇒ Sub-Spars

(Figure 196)

- Bond sub-spars in position and hold with G-cramps until the adhesive is cured.
- Oven cure adhesive.
- Remove pick-up arms and G-cramps.

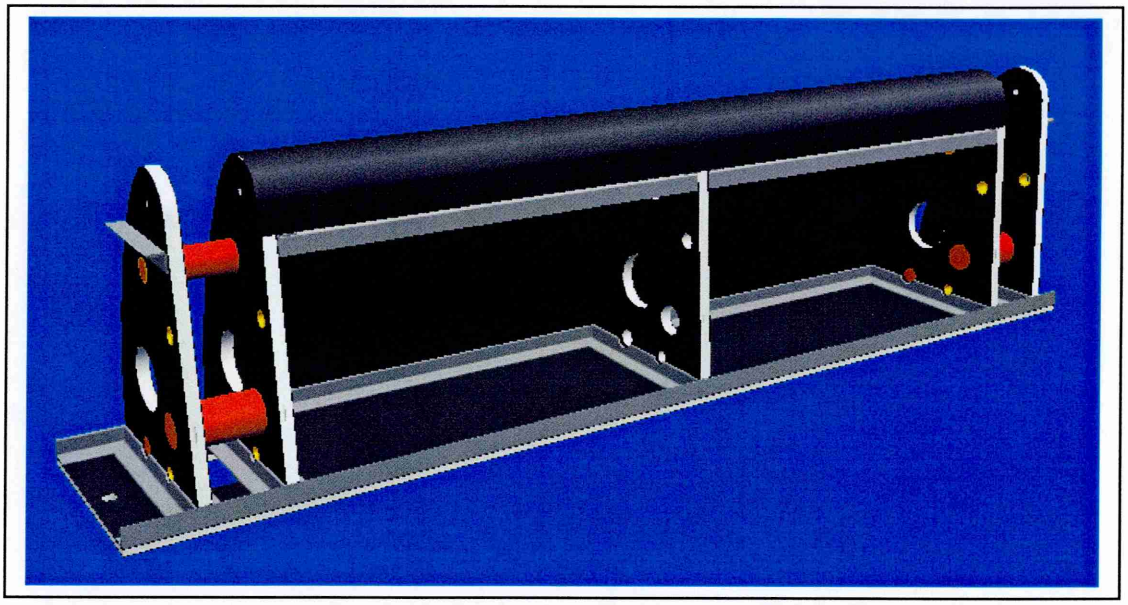


Sub-Spars in Position *Fig. 196*

Assembly Stage 7

Build Tool 1 ⇒ Spar ⇒ Caps ⇒ Track Ribs ⇒ Inter-Ribs ⇒ Sub-Spars ⇒ Nose Skin

- Abrade or cryogenic shot blast bonding faces; and clean.
- Locate nose skins, bond in position, and secure with strap-clamps.
- Oven cure adhesive.
- Release from Build Tool 1.
- This completes the assembly of the JAM composite design study. *(Figure 197).*



Completed Assembly *Fig. 197*

APPENDIX G

JAM Research Publications

JAM Research Publications

- BURLEY G, ODI R, NAING S, CORBETT J; 'An Algorithm for Assembly Centric Design', AEROFAST 2002, SAE Aerospace Automated Fastening Conference, Chester, UK. October 1-3, 2002.

- CORBETT J, BURLEY G; 'IMI: Jigless Aerospace Manufacture (JAM)', EPSRC/IMI Final Report – GR/L8922/01, Cranfield University, May 31, 2001.

- ODI R, BURLEY G, NAING S, CORBETT, J; 'Geometric and Dimensional Tolerances in Error Budgeting for Assembly-Centric Design of Aerostructures', International CIRP Tolerance Seminar, Cachan, France. April 24-25, 2001.

- NAING S, BURLEY G, ODI R, CORBETT J; 'Design for Jigless Assembly Case Study of a Civil Airliner Fixed Leading Edge'. Proceedings of the American Institute of Aeronautics and Astronautics (AIAA) 42nd Structures, Structural Dynamics and Materials Conference and Exhibit, Seattle, Washington, USA. 16-19 April 2001.

- ODI R, BURLEY G, NAING S, CORBETT, J; 'Error Budgeting for Assembly-Centric Design of Aerostructures'. Proceedings of the American Institute of Aeronautics and Astronautics (AIAA) 42nd Structures, Structural Dynamics and Materials Conference and Exhibit, Seattle, Washington, USA. 16-19 April 2001.

- BURLEY G, ODI R, NAING S, CORBETT J; 'Using Structurally Integrated Location and Reference Features in the Assembly of Large Aerospace Structures', AEROFAST 2000, SAE Aerospace Automated Fastening Conference, New Orleans, USA. September 20-22, 2000.

- ODI R, BURLEY G, NAING S, CORBETT J; 'The Role of Error Budgeting in the Use of Structurally Integrated Location and Reference Features for Aerospace Assembly', AEROFAST 2000, SAE Aerospace Automated Fastening Conference, New Orleans, USA. September 20-22, 2000

- ODI R, BURLEY G, NAING S, CORBETT J, WILLIAMSON A; 'Error Budgeting and the Design of Large Aerostructures', ICAS 2000 – 22nd International Congress of Aeronautical Sciences, Harrogate, UK. 27 August – 1 September 2000.

- NAING S, BURLEY G, ODI R, CORBETT J, WILLIAMSON A; 'Design for Tooling to Enable Jigless Assembly - an Overview'; 2000 International CIRP Design Seminar, Haifa, Israel. May 16-18, 2000.

- CORBETT J, BURLEY G; 'CRANFLY – A Novel Approach to the Design of Aerospace Structures'; EPSRC/IMI Final Report – GR/L39971/01, Cranfield University, June 2000.

- NAING S, BURLEY G, ODI R, CORBETT J, WILLIAMSON A; 'Design for Tooling to Enable Jigless Assembly', SAE Aerospace Manufacturing Conference, Fort Worth, Texas, USA. May 16-18, 2000.

- BURLEY G, ODI R, NAING S, CORBETT J, WILLIAMSON A; 'Jigless Aerospace Manufacture - The Enabling Technologies', SAE Aerospace Manufacturing Technology Conference, Seattle, Washington, USA. June 8 - 10, 1999.

- BURLEY G, CORBETT J; 'An Innovative Manufacturing Environment', Aerospace Engineering, Vol. 18, No. 9, pages 50-52, pub. SAE International, Warrendale, PA, USA. September 1998.

- BURLEY G, CORBETT J; 'Flyaway Tooling for Higher Quality, more Cost-Effective, Aerostructure', SAE Aerospace Manufacturing Technology Conference, Long Beach, CA, USA. June 2 - 4, 1998.