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School of Industrial & Manufacturing Science

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# Jig-Less Assembly for Aerospace Manufacture

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**This thesis is submitted in partial fulfilment of the requirements for the degree of Master of Philosophy**

**Dedicated to my parents**

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# Abstract

Due to the high level of investment required to compete successively in the global aerospace and automotive markets, these industries are forced to form partnerships wherever possible and thereby share their resources appropriately. This in turn has brought about the requirement to provide a standardized flexible design and manufacturing capability in which interchangability and compatibility may take place.

Current assembly practices and associated tooling can be traced back to the earliest days of aircraft production and have become relatively expensive and inflexible in today's environment.

The final assembly stage has been recognized to be a key area which has the potential to offer substantial returns as well as play a major role in any change management process within the organisation.

Assembly tooling, jigs and fixtures, are required to support and maintain positional accuracy of components during assembly. Traditional jigs and fixtures make up for the short comings at the product design and manufacturing phases and add significantly to the final product costs and reduce flexibility in the production process.

Jig-Less Assembly Concept (JAC) has been defined and researched with the aim to integrate and optimize various tools and techniques with which to reduce or eliminate the assembly tooling currently in use.

The outcome of the research presents a comprehensive critique of the processes involved in and pertaining to the assembly of typical airframe assemblies.

The thesis forms a platform from which to move forward towards the embodiment of the concept of jig-less assembly. Particular attention is drawn from the research to the need for appropriate organisational and management strategies as well as technical innovation in the adoption of a jig-less approach to airframe assembly.

Together with BAe Airbus and Military this collaborative research seeks to define the scope of JAC by identifying and evaluating the issues and constraints, to enable the development of supportive techniques in unison with best practice engineering within a robust and sustainable manufacturing system.

This commercially focused R & D required liaison and working at all levels within a variety of industrial sites using live case studies at Filton and Chester.

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# Chapter 1

# Introduction

## 1.1 Background

In recent times aerospace manufacturing methodology has been recognized as being a technical and commercial bottleneck within the business operation. Its inability to respond to the demands made upon it from increasing customer requirements and a changing business environment has become evident. Ref (1).

Due to the high investment required to develop new aircraft, work sharing between companies on large complex projects has become commonplace within the industry. Additional demands have come from ever increasing customer requirements: improved quality, custom product range, cost effective ownership and reduced lead times have brought about dramatic changes in the aerospace industry in recent years.
Consequently this has led to co-production between different companies and production sites throughout the world presenting them with the task to manufacture complex components, sub-assemblies and final assemblies which require ever increasing compatibility and interchangability together with improved quality.

Under these circumstances a response within the manufacturing system is required leading to a fundamental review of tooling practices. The final assembly stage has been recognized to be a key area in which substantial gains maybe attained plus the potential of becoming a catalyst for a change management process within the whole organization itself.

Current aerospace tooling is expensive to produce and maintain, requiring substantial working and storage space. They are also inflexible to changes from product and capacity demands. The origins of existing assembly tooling and practices can be traced back to the earliest period of aircraft production and have replicated the physical growth of today's product but have not developed in their own right. Today's large aerostructures: cockpit, wings and fuselage require suitably large tooling systems and are showing signs of not being able to deliver to specification demonstrated by the high degree of direct technical labour input to achieve satisfactory results.

Assembly tooling, jigs and fixtures are required to support and maintain positional accuracy of components during assembly. Designed at the final product design stage they have become product specific leading to a lack of integration within the manufacturing process.

Minimizing or eliminating product specific assembly tooling using a holistic approach to the design and manufacturing process is the philosophy behind 'Jig-Less Assembly'. This concept is being researched and developed to assist the next generation of aerospace manufacture thereby making these products and their companies commercially as well as technically viable. Ref (2).

Together with EPSRC, BAe Airbus and Military this collaborative research seeks to evaluate the scope of Jig-Less Assembly Concept (JAC) by identifying and evaluating the issues and constraints associated with aerospace assembly; and to identify enabling supportive practices and techniques which can take their place within a robust and sustainable manufacturing system.

## 1.2 Project Drivers and Motivation

To remain a player within the increasing competitive aircraft market successful companies will be those which are able to drastically reduce their costs and cycle times and to be flexible to the market needs, whilst meeting ever higher customer requirements.
These issues seem to conflict 'how can one have one without the other' ?
To go some way in meeting these goals a new approach is required incorporating an holistic approach being driven via manufacturing and focusing upon final assembly.

In line with a concurrent engineering philosophy 'time-to-market' is paramount.
Aircraft manufacture requires a high cost up front investment, typically two to four years development phase, ten years plus for the payback period. Reducing these lead times and costs will improve margins but provide a strategy for the survival of such a venture.

Jig-less assembly is one option within an array of possibilities which need to be investigated and developed and thus considered for inclusion within a change management process.

A large proportion of the cost of an aircraft is generated by the assembly process. These costs can typically contribute to more than one third to Non Recurring Costs (NRC), see fig. 1.2.1.

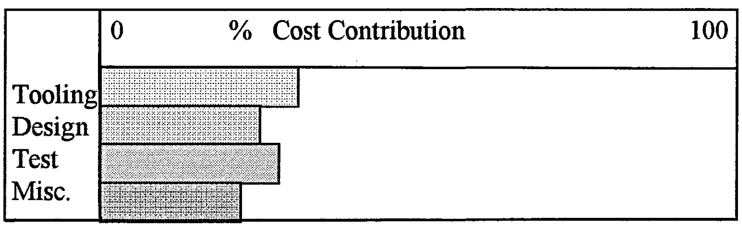


**Figure 1.2.1 Non Recurrent Cost - Civil Aircraft**

The need for change has required every area of the business to be made more competitive. In the case of the final assembly tooling and practices, this may be possible either by improving current assembly tooling design and subsequent manufacturing processes or together with a complete review and change of manufacturing philosophy.

This has been recognized not only by the manufacturers but by governments and research bodies who have a vested interest. Ref (3). A collective body of research councils, EPSRC, ESRC, and bbsrc together with members of the aerospace industry, supported by many university partnerships, have embarked upon an initiative to build a framework of research to address the issues to meet set business targets.

The Integrated Aerospace Programme, Innovative Manufacturing Initiative (IMI), aims to harness the research strengths of academia towards enhancing the competitiveness of the UK's aerospace industry. A strategic research framework has been developed which places special emphasis upon integrating product and manufacturing technologies with the business process which will be able to accommodate industrial requirements and academic research capabilities as they evolve.
During the consultation process companies were asked to specify time and cost reduction targets over a five year period for a set of business drivers and then to assign priorities to technology and business process research topics in relation to attaining the set targets. Ref (4).

During the survey all companies consulted have acknowledged that in order to become more competitive they must meet the following business targets; see figure 1.2.2.
These targets are extremely challenging and highlight the dramatic changes in cost and lead time performance which the industry is attempting to achieve.

| **Target Real Cost and Time Reductions - 5 year period** | **Air-Frame** | **Power** | **Equipment** |
|---|---|---|---|
| Manufacturing Cost | 35% | 33% | 28% |
| Manufacturing Lead Time | 44% | 50% | 27% |
| Time to Market | 43% | 55% | 31% |
| Product Introduction Cost | 50% | 56% | 26% |
| Cost of Ownership | 23% | 40% | 18% |
| Cost of Design Change | 51% | 48% | 36% |

**Figure 1.2.2 Business Targets - (Source IMI Survey 1995)**

Comparing figures 1.2.1 & 1.2.2 gives an appreciation that of how the business targets can be achieved by tackling one of the largest contributors to the cost (NRC) and meet customer requirements.

This particular research project interests itself within the areas of product development and manufacturing technologies; Jig-Less Assembly is seen as major contributor and catalyst to any change management programme.

A fundamental understanding of the assembly and associated processes is of critical importance. By addressing the issues and identifying the constraints involved one can move towards an holistic approach (Concurrent Engineering) to the manufacturing system.

Current practices do have substantial advantages which are proven, therefore any step change in technical terms will undoubtedly require an increase in resources, with this investment carrying a considerable risk. Reducing or eliminating product specific assembly tooling by means of a flexible reconfigurable tooling system means that any change must be able to be supported and integrated within the company, but be able to interface as required with external companies. Ref. (5).

A Jig-Less assembly is about as far away from the old way of doing things as we can get. Therefore, this will require a radical change in design and manufacturing philosophies.

The challenge and associated risk facing the industry to remain competitive is high, and to survive, Jig-Less Assembly and like minded initiatives must be considered and fully investigated. Ref. (6).

## 1.3 Definitions; Tooling & Concepts

Assembly tooling, jig and fixture design and operation is an extensive subject and each industry prides itself on its own expertise. Strict definitions of jigs and fixtures have been blurred by the change in technology mainly from the use of CNC machines.
Jig-Less assembly and its derivatives by its nature is difficult to quantify; its scope and boundaries have no precise limits and will be in a constant state of flux especially during the research stage. Any descriptions will therefore be open to interpretation, although definitions may be used to describe and clarify the fundamental elements and their environment in which they operate.

- **Generic Tooling**

The lowest mechanism in the production rank is the tool. This implement is used to hold, cut, shape, or form the unfinished product. Common hand tools include the, hammer, screwdriver, file, saw and grindstone. Basically, machines are mechanized versions of such hand tools. Most tools are for cutting, used in milling, turning and grinding operations whilst non cutting tools for forming include extrusion dies, moulds and measuring devices.
Tools also include workholders, jigs and fixtures. These tools and cutting tools are generally referred to as the *tooling,* which is usually considered separate from machine tools.

- **Assembly Tooling**

This describes workholding devices, namely jigs and fixtures, used in the assembly process. They are devices which hold (locate) the work (components) and determine the relationship between each of the components with respect to the chosen machining or joining operation, thus providing an aid to achieve an accurate and repeatable finished product. Their primary function as production tooling is to instill dimensional authority, in physical form, to which a workpiece must conform within specified design limits.

- **Jig**

In addition to holding a part, or being held on a part, a jig is a special workholding device that, through built-in features, determines location dimensions relative to the part that are produced by machining or fastening operations. The key requirements of a jig is that it determines a location dimension.

- **Assembly Jig**

In establishing location dimensions, jigs, guide tools, (as with drill jigs for as in fastening assembly operations), and welding jigs, component parts (locate) in a desired relationship with respect to each other while an unguided tool accomplishes the joining operation.

- **Fixture**

A fixture is a special workholding device that holds work during machining or assembly operations and establishes size dimensions. The key characteristic is that it is a special workholding device, designed and constructed for a particular part or shape. Thus a fixture has as its specific objective the facilitating of setup, or making the part holding easier.

- **Assembly Fixture**

Because assembly fixtures must usually allows for the introduction of several component parts and the use of some type of fastening equipment , such as riveting or welding, they commonly are of the open-frame type. Such fixtures are used in the aircraft and automobile industries and are normally of a very heavy construction.

- **Jig-Less Assembly**

The term Jig-Less Assembly may be misleading, in that it implies that the removal of all assembly tooling is possible and desirable. A more accurate and realistic definition would be to describe Jig-Less Assembly as a philosophy which aims to reduce the existing product specific assembly tooling to the minimum by means of the co-ordinated deployment of an amalgamation of supportive technologies and methodologies.
Jig-Less Assembly must provide a co-ordinated transfer of existing tooling functions together with increased flexibility which can integrate and therefore sustain a robust designed, concurrent, manufacturing system. A means of holding and transporting the assemblies will always be a requirement, and therefore fixtures of some description will exist even if in the most simplest of forms.

- **Jig-Less Assembly Concept**

Jig-less Assembly Concept (JAC) gives its name to a collection of ideas whose objective is to provide the means in which a jig-less assembly philosophy can become a workable reality.
The contents of JAC will develop, encompassing new and mature ideas, embracing management strategies, design tools, flyaway tooling, manufacturing processes, inspection techniques and assembly processes so they all come together to form a viable strategic jig-less assembly alternative.

- **Rationalization of Assembly**

Rationalization of assembly implies the efforts and investments to improve assembled product's quality and reduce their costs. Rationalization can be accomplished by a variety of engineering and management methods, including development of new materials, time-and -motion studies, methods analysis and improvement, new manufacturing and joining techniques, product development and design, mechanization and automation. Other approaches include design, planning and control models, and organizational and management systems. Jig-less assembly can therefore be seen as a vehicle in which to achieve rationalization of the assembly process.

- **Part-to-Part Technology**

Part-to-Part or Hole-to-Hole technology is the extensive use of digital modelling through CAD & CAM processes to enhance the accuracy and repeatability of detail part manufacture, thereby enabling greater efficiency and automation in the sub and final assembly process.

## 1.4 Project Methodology

The research plan was formulated broadly into five parts which were implicit within the practical tasks carried out.

- Determine project aims and objectives - Chapter 1, Introduction
- Identify subject areas of interest - Chapter 2, JAC. Chapter 3, Assembly Process. Chapter 4, Literature Review.
- Identify suitable case study as demonstrator - Chapter 6, Case study.
- Collate and review appropriate data - Chapter 4. Chapter 5, DFJA. Chapter 6 Case Study.
- Analyse data to formulate meaningful information - Chapter 5. Chapter 7, Conclusions & Recommendations.
- Reflect and integrate the analysis output - Chapter 5. Chapter 7.

Practical tasks to implement the research plan were carried out thus:

- Literature survey
    - use of library and associated databases to research areas of interest.
    - familiarization of associated subject areas.
- Industrial visits (see appendix A)
    - BAe sites at Filton, Chester, Samlesbury, England and Toulouse, France.
    - GKN Westlands, Isle of Wight and Short Brothers of Belfast, Northern Ireland.
- General training and courses
    - complementary training for generic research techniques.
    - conferences related to product design and tolerancing.
    - short courses on machine design and software packages.
- Preliminary research.
    - establish current practices via company visits, database searches and interviews.
    - familiarization with current manufacturing and company practices.
    - identify and confirm suitability of a case study demonstrator.
    - gain an understanding of Design for X and appropriate enabling technologies.

- Identify and analysis of the case study demonstrator.
  - develop an understanding of the case study form, function and assembly sequence.
  - gain an understanding of assembly issues and constraints including errors causes & effects.
- Identification of the issues and constraints involved.
- Theorise and discuss ideas and findings.
- Make recommendations towards a jig-less assembly strategy.

The essence of this research is very much practical and organic in nature with close working relationships between the research establishments and industrialists key to the success of the project. It was considered to be of paramount importance to gain trust with the working industrial personnel thus resulting in the capture of relative data and allow for a grasp of the real issues at play within the chosen working environment.

The background literature survey was carried out at the Cranfield University library in parallel with generic research training and appropriate short courses in machine design and CAD software. Complementary conferences were attended at various venues on the subjects of product design and tolerancing.

This research programme under the name of 'Cranfly' was in partnership with Salford University whose research area was the kinematics study of tooling design and handling.
Industrial visits were made to the:-

- BAe Airbus Filton site which covered wing design and sub-assembly manufacture.
- BAe Airbus Chester site for manufacturing design, quality assurance and final wing assembly.
- BAe Military, Samlesbury, for Eurofighter manufacture together with innovative manufacturing techniques.
- Airbus final aircraft assembly at Toulouse which was responsible for final product acceptance.
- GKN Westlands and Short Brothers were visited for exposure to a external view other than BAe operations.

Progress meetings and presentations took place, every three months, with BAe, Cranfield and Salford to present work to date, discuss ideas and plan the future work schedule.

After each industrial visit new ideas and views were fed back into the programme and these helped to develop the research thinking.

Once the demonstrator case study had been identified and studied the real issues and constraints became apparent.

Many contacts at all levels within the organizations visited were made, which not only aided this particular research but research programmes which followed (see appendix A).

Manufacturing and product designers were interviewed, and manufacturing systems personnel together with strategic management were consulted. Working on the shopfloor at BAe Filton brought valuable day-to-day insight into the research subject area. Any identified issues, recommendations and proposals was supported by the industrial experiences, building a framework towards an industrially robust jig-less assembly strategy.

## 1.5 Aims

The aims of this research project were to investigate the aerospace industry in terms of its manufacturing capability especially assembly, identifying the issues and constraints with the idea to introduce suitably matched techniques and procedures with which to support the implementation of a jig-less assembly strategy. This in turn should reduce assembly costs, increase flexibility to the product and tooling development, and aid an overall more sustainable robust manufacturing system.

## 1.6 Objectives

Achieving the aims by focusing upon :

- Identifying the issues and constraints together with assessing the necessary requirements as applied in the current manufacturing and design environment.
- Discovering current practice at BAe sites with regards to their design and manufacturing capabilities.
- Gain an understanding of the company history and culture in terms of aircraft manufacture.
- Gain an understanding of the underlying fundamentals of the design and assembly process, generic and specific.
- Identify potential and enabling technologies and supportive techniques to underpin a jig-less assembly capability.
- Using a test case study to demonstrate the potential of using appropriate jig-less assembly technologies on/or techniques.

# Chapter 2

# JIG-LESS ASSEMBLY CONCEPT, JAC

## 2.1 Introduction

The idea or concept of a jig-less assembly is not new, being implicit within mankind's efforts to build assemblies in the pre-industrial revolution, handmade products, and large assemblies throughout history. Buildings bridges and ships all demonstrate a common theme in that their structures require support, via fixtures, during their assembly, but do not use aids or location jigs for components. This is due to economic, physical and technical restrictions. These large custom-built individual assemblies rely mainly upon the experience and skill of the workforce, craftsmen, to provide the required assembly tolerances and meet the acceptable build quality. The aircraft manufacturing industry today still refers to the assembly personnel as fitters as this describes their function in the process to make components fit together in the assembly thereby making up for the components variability, non-conformance, to design specification.

## 2.2 The Jig-Less Assembly Concept (JAC)

As mentioned in section 1.3 Jig-less Assembly Concept (JAC) gives its name to a collection of ideas whose objective is to rationalize the assembly process via a coordinated transfer of the tooling functions into the component design and manufacturing processes together with increased flexibility which is able to integrate and sustain a robust manufacturing system.

At this stage of the project, the contents and boundaries of jig-less assembly are not clearly defined. It is envisaged that a Jig-less Assembly Concept (JAC) will develop in its own right to embrace established design and manufacturing tools such as DFMA, QFD, FMEA, SPC, CAE and be sympathetic with a concurrent engineering philosophy. Many technologies and techniques are being tried and tested to measure their effectiveness to support a jig-less assembly environment. These can be roughly categorized into 'mature', established ideas which could be used now and 'developing' techniques which required further proving or greater adaptation to be of use. Finally the 'blue-sky' category, which includes ideas which may be a little far fetched, require greater research and development and therefore have less chance of being used. All of these techniques and ideas have potential for aiding the Jig-Less Assembly Concept, figure 2.2.1. The 'House-of-JAC', see fig. 2.2.1, shows some of the elements identified and their relationship to the underlying fundamentals, together with the system disturbances, noise, and the required deliverable, for a cost effective rationalized flexible assembly system.

As with the shipbuilding and automobile industries the aerospace industry has the unenviable position in manufacturing engineering with its requirement to produce a product in which the external form is a matter of functional importance as distinct from visual appeal. Manufacturing requirements for aircraft surface accuracy in terms of shape, steps and gaps are increasing as a result of customer requirements. The continual effort being made by designers to meet customer and market needs via superior performance at reduced cost imposes demands upon the aerospace manufacturing engineer in the attainment of accurate external profiles, and this remains together with mass and cost reduction the key design and production drivers. Ref. (7).

Fundamental understanding of the underlying science of the processes at play, deterministic, cause-and-effect analysis, were required when trying to remove or anticipate sources of error within the manufacturing/assembly system, in order to obtain a higher precision assembly. The functions of components and assemblies, together with their physical behaviour during the assembly process also needed, to be addressed. Present tooling and methods can often be seen as a 'crutch', for the manufacturing organization, in terms of product definition and engineering. Ref (8).

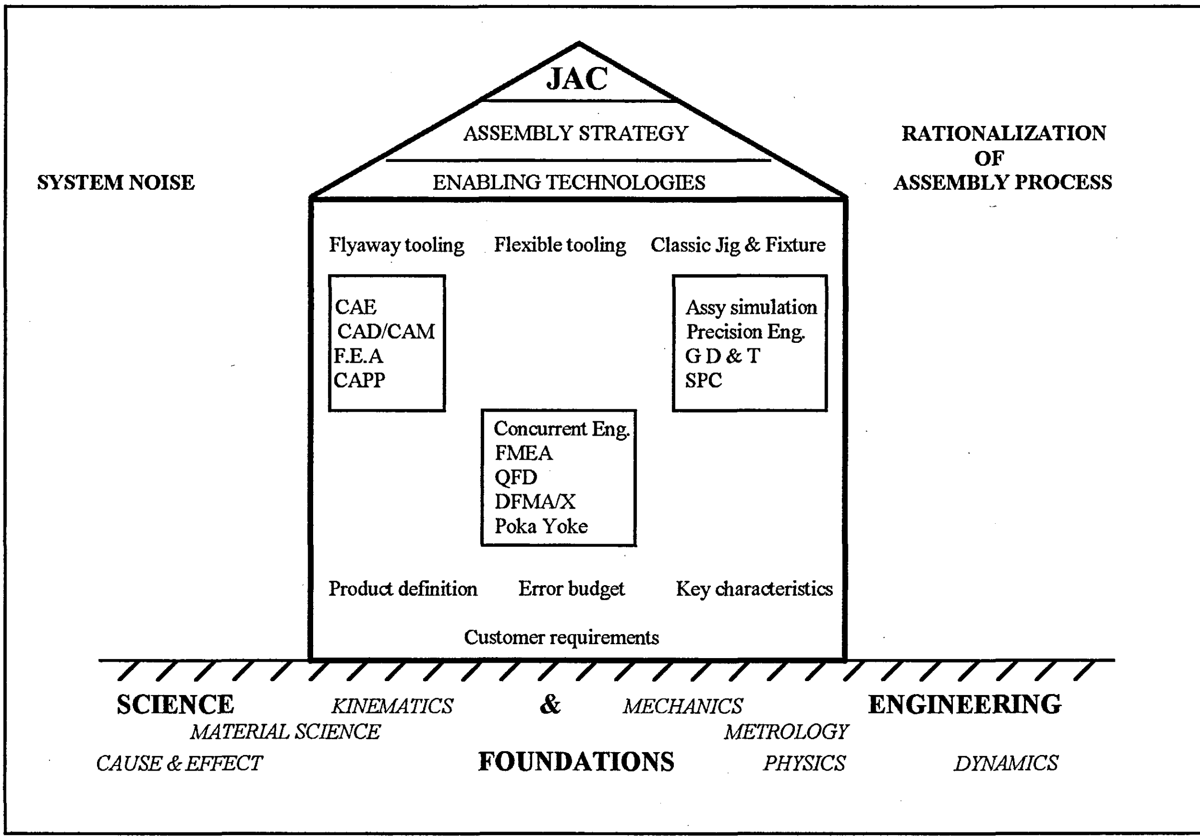


**Figure 2.2.1** **'House-of-JAC'**

Rationalization of assembly implies that the efforts and investments are needed to improve assembled products quality and reduce their cost. Rationalization can be accomplished through a variety of engineering and management methods, including the development of new materials, undertaking time-and-motion studies, methods analysis and improvement, new manufacturing and joining techniques, product development and design, mechanization and automation. All of these and more will need to come together with the ultimate aim to provide components within an assembly features for their own location to each other. A greater understanding and appreciation of the working environment also needed to take into account the environment in which the jig-less concept may operate.

This design philosophy selects the materials to be used and hence dictates the manufacturing process/technologies to be adopted. These traditionally have had little consideration for manufacturing, especially final assembly and maintenance. To meet the key customer requirements, life-cycle cost, and cost of ownership there must be a balance of the drivers, taking into account performance, affordability and product specific quality requirements.

These customer requirements have to be met by adopting a more integrated approach for which a prime area on which to focus is the final assembly stage. JAC can therefore be seen as an important catalysis for change management and technical cohesion in order to meet such a challenge.

The contents of JAC will develop, encompassing new and mature ideas, embracing management strategies, design tools, manufacturing processes, inspection techniques, assembly processes, reconfigurable/flexible tooling and assembly modeling , all under the umbrella of JAC, to form a viable strategic rationalization assembly alternative.

## 2.3 Jig-Less Assembly, current practice

Engineering good practice should always endeavour to optimize and improve existing systems and be part of the manufacturing engineers' remit. Although no formal integrated robust Jig-Less Assembly systems are being used at present, the principles of a rationalized assembly which has the by-product of a reduction of assembly tooling can be seen in many examples. Many of the elements discussed within the Jig-less Assembly Concept, are being practiced today and some from the past.

A small selection of case studies are discussed below, which demonstrate various forms of the Jig-less Concepts, at work from the past and present.

2.3.1 The de Havilland Mosquito aircraft of 1939, see appendix B, demonstrates the use of minimum tooling requirements and a simplified assembly process, using cold mouldings on male concrete formers.This production process complimented the product design of a split fuselage very well and was made possible due to choice of the construction material, wood, the production requirements the available skilled labour and the prevailing political circumstances of WWII. The assembly process was relatively straightforward using little in the way of main assembly tooling, utilizing the internal bulkheads as a means to aid alignment of the two fuselage halves. This form of Fly-Away Tooling was used in 1939 ! The use of skilled labour was the key to ensuring a good quality product. Ref. (9).

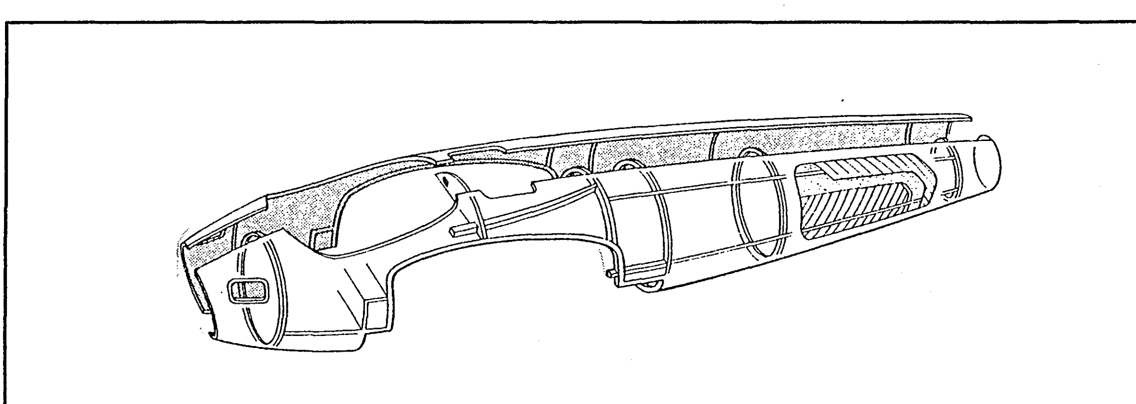

**Figure 2.3.1 De Havilland Mosquito, Split Fuselage Design**

Today's manufacturers using glass/carbon composites, in their construction, utilize similar ideas and construction methods from the past. Manufacturers of low volume sports car manufacturers such as Lotus and TVR and specialized aircraft home build designs rely heavily upon skilled labour during the assembly stage of their products although together with the adaptable construction methods and materials this allows for greater flexibility in product changes, lead times and batch quantities.

2.3.2 Coming up to-date within aerospace, Eurofighter, Ref (10), is being developed with the aim of utilizing many of the JAC Concept techniques, see section 4.10 and appendix A(ii).

2.3.3 Construction of the Boeing 777 including sub-contractors from Japan, Kawasaki Heavy Industries, see 4.16.3, was a landmark product in many ways because of its design and construction methodology. The 777 was the first product in its class to use 100% digital product definitions (DPD). DPD means that all of the geometric definitions of parts and tools are incorporated in a digital format dataset and then becomes the sole primary datum definition stored as a database. This allows for digital pre-assembly, the elimination of physical mock-ups and allows for parallel design by all design functions working on the digital model. Component 'clash' errors are thus eliminated during the detail design process. This has led to Hardware Variability Control (HVC), which emphasizes variation reduction of key areas of parts and assemblies to improve product primary functions through the use of product Key Characteristics (KC). Ref (11).

Using DPD, precision components may be manufactured using hole-to-hole technology for the assembly of large structural parts like the fuselage. So accurate are the mating parts, that assembly can take place without the addition of final assembly tooling. Temporary fasteners are used to keep fuselage sections together before being finally auto-riveted together.

Change, error and rework were reduced by 60%. Assembly quality was improved dramatically over previous models. In addition manufacturing systems integration through design-build teams has been raised to a new level making Concurrent Engineering a reality.

2.3.4 Short Brothers of Belfast, using Part-to-Part technology, have succeeded in eliminating much of the tooling required for the cabin door of the Bombardier Global Express aircraft. Again like the Boeing System, a digitized design (via CAD, CAM and CNC) facility is used in unison to produce complex components and mechanization which locate and reference themselves off each other. Ref (12).

2.3.5 On the Learjet 45 and Canadair Regional Jet project 'Jomach', a multipurpose Fuselage Panel Machining Fixture is used to CNC machine all the fuselage panels, drill location holes, allowing accurate pre-assembly before transfer to the 'Gemcar Automatic drilling and riveting machine. Final assembly takes place in 'Hovair' trolleys which are used to transport the fuselage sections and mate sections together, thus eliminating cranage and providing a constant datum. Ref (13).

Shorts Brother's use of Design Build Teams (DBT) to develop a CE environment, maximize Part-to-Part manufacturing opportunities, reduce overall tool Register and introduce optimal efficiencies in detail part and assembly tooling.

2.3.6 Flat pack furniture designs provide for the home D.I.Y self-assembly units sold by companies such as MFI and IKEA. These have demonstrated that through good and thoughtful design, products can be mass produced and the responsibility of final assembly can be eliminated from the manufacturer and passed on to the end user who requires only the minimum of fitting tools and skill to complete the build with no assembly tooling necessary, see appendix C.

Locating and fastening features have been identified and designed to have multi-role function. These features are accurately produced together with a shared datum for parts. Semi-Kinematic design principles are utilized when appropriate, keeping in mind the environment and assembly skill to be used.

The 1506 Bed, manufactured by Ikea, is a good example of Jig-less assembly, Fig. 2.3.2 . Tapers and draft angles are used to the best effect and the use of 'mis-alignment' captive nuts allows movement within the assembly until the 'draw' bolts are fully tightened.

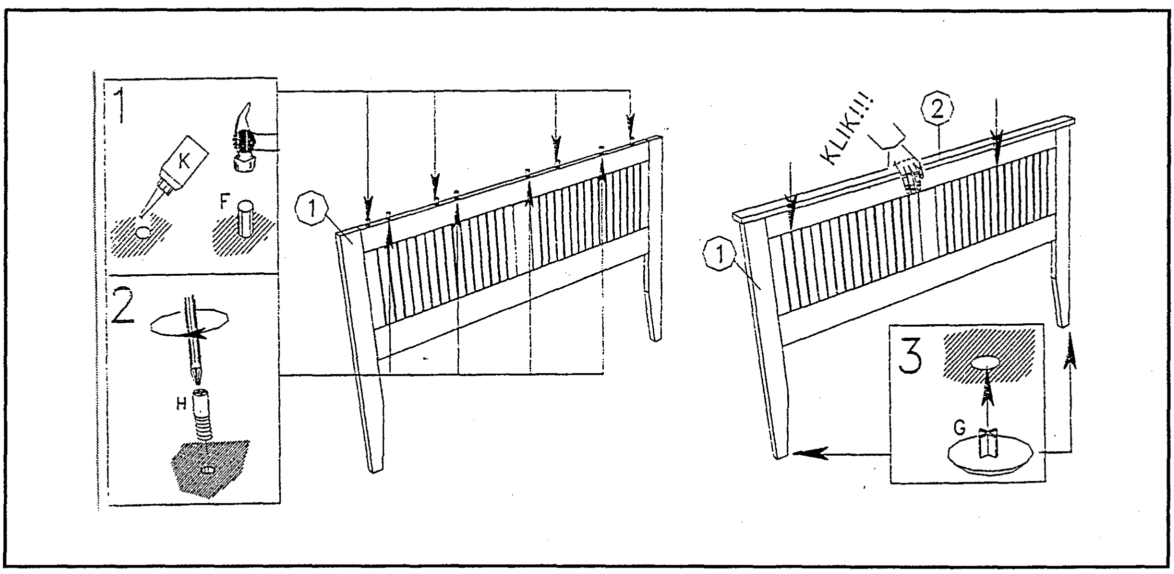


**Figure 2.3.2 Ikea 1506 Self-Assembly Bed**

Looking at the detail of the bed head and tail board a wooden strip requires to be fixed to the top of each. This has been designed so that no fasteners require assembly tools. See appendix C.

The four dowels are fitted into the headboard together with four 'fixing' shorter metal pins. In the top strip four plain holes receive the wooden dowels and are complemented by four holes which receive barbed plastic plugs. The wooden dowels align the top strip with the headboard along its length, the metal pins being shorter then mate with the plastic plug, the metal pins and plug combination reduce any side force subjected to the locating wooden dowels allowing the wooden strip to remain secure whilst the glue on the wooden dowels cures. The assembler has only to roughly line up the dowels and push down with minimum force until the top strip is flush with the headboard top surface. Again these design features are multi-functional, aiding assembly, and also with provide the means of securing the components together.

These examples demonstrate the diversity of the applications and industries in which Jig-less Assembly ideas can and are being used.

## 2.4 Developments in Jig-less Assembly

In response to a more competitive global market within the aerospace industries, together with the increased rising investments required to meet ever demanding customer requirements, the focus on industrial assembly over recent years has become paramount.

Partnerships and Collaborative enterprises have become commonplace to share resources and spread the cost together with associated technical commercial risk.

Research programmes and initiatives whose main objectives are to deliver a Jig-less Assembly package are confined to just a few. Although in line with the general interest in generic rationalization of the assembly process many industrial and academic developments have occurred. Technologies and methodologies which this project has identified, to support a Jig-less Assembly Concept, have made major advancements in their own right and demonstrate potential to make JAC a workable reality. Examples include the following:-

(i) The United Kingdom's Innovative Manufacturing Initiative (IMI) programme have supported a Jig-less Aerospace Manufacturing (JAM) research project, to investigate the significant scientific, technological and economic issues of Jig-less Assembly in an aerospace manufacturing environment. The project involves the collaborative efforts of four divisions of British Aerospace, Short Brothers, four universities and the National Physical Laboratory all of whom are working towards the long term goal of eliminating product specific tooling for the assembly of large aerostructures. Ref (14).

(ii) Individual aerospace companies have also been pursuing their own Jig-less initiatives. For example, BAe Airbus with advanced design and manufacturing processes like the Low Voltage Electromagnetic Riveting (LVER) machine, digital assembly modeling for developing the large commercial aircraft A3XX. BAe Military are also developing numerous technologies and methods for the Eurofighter production. Ref (15).

(iii) Boeing have been involved with the Accurate Fuselage Assembly (AFA)/Fuselage for the 747 and major improvement for production and assembly of the 777-200 airplane. Ref (16)

(iv) Short Brothers, Belfast, UK have made advancements with the Learjet 45 fuselage and assembly systems for individual contract work. Ref (17).

(v) Lockheed Martin Aeronautical Systems (LMAS) have been responsible for producing the F-22 fighter and their engineering and manufacturing development (EMD) effort. Also involved jointly with Boeing, LMAS with the Joint Strike Fighter (JSF) program, concept demonstrators X-32 and X-35 aircraft. Ref (18)

Massachusetts Institute of Technology (MIT) are heavily involved with generic assembly theory and application. Dr Daniel Whitney and associates work has provided a great source of data to the JAC effort. Joint Programmes include:-

- Agile Manufacturing Project.
- Lean Aircraft Initiative.
- The Lean Aircraft Production Research Programme.
- Lean Enterprise, Lockheed Martin.

These programmes have a common theme in that the Lean programmes aim to eliminate non-value-added cost as opposed to the Agile programmes which try to develop manufacturing systems which are flexible to satisfy rapidly changing conditions, responsive to market conditions. Ref (19).

Within the generic assembly field several initiatives are on-going, for example, the Holonic Manufacturing Systems Project, part of the intelligent Manufacturing Systems (IMS) Programme, a Consortium of industry, university and government laboratories from Australia, Canada, Europe, Japan and U.S.A.. The objective of this project is to develop, demonstrate and evaluate Holonic Technologies to improve flexibility, robustness and reconfigurability of Holonic handling systems in assembly. Ref (20).

Dr. Gary A. Gabriele as principle research investigator leads a team on the Integral Fastening Program (IFP), at the Rensselaer Polytechnic Institute. This programme is to develop the necessary technology to allow the design of integral attachment features (e.g. Snapfits) to advance from an art to an engineering science. Ref (21).

In the automotive fields one example which again demonstrates the global interest and participation to assembly and its associated disciplines is the International Motor Vehicle Program (IMVP) at MIT. A multi-discipline progamme involving many industries and research teams. Ref (22).

The IMVP is but one of the many research programmes under the umbrella of the Centre for Technology, Policy and Industrial Development (CTPID). The Centre is concerned with best practice techniques in manufacturing and product development as well as supply chain management and bench marking. Ref (23).

Several common themes run through each of these programmes and initiatives. The desire to gain an underlying knowledge base and develop a science to assembly within the whole of the manufacturing system by utilizing a lean, rationalized, manufacturing and product development methodologies. Functional systems which appear to be gaining favor are product development in terms of tailoring designs for manufacture and assembly systems (DFM/A) plus the use of feature based analysis like key characteristic (KC'S) methodology together with assembly process analysis and modeling.

The output of these programmes and others at some level will have an impact upon the Jig-less Assembly becoming a working concept. The identification and choice how these various enabling technologies may be integrated and managed to produce a desired and robust Jig-less Assembly Concept.

## 2.5 JAC, potential deliverables

The potential deliverables for the successful implementation of a Jig-Less Assembly Concept are envisaged to be wide ranging throughout a manufacturing business.

Jig-Less Assembly Concept used as a catalyst for change management process thereby aiding and supporting a concurrent engineering approach, integrating the customer, product, design and manufacturing phases.

Whatever enabling techniques are employed major advancements can be achieved in tooling design and manufacturing processes just through the attention and subsequent development that they receive. Reduction in tooling together with optimized product design for assembly would aid automation, improving consistency of build and quality. This is already evident at BAeAirbus, Chester, with the introduction of the Low Voltage Electromagnet Riveting (LVER) machine, Ref. (24), removing manual assembly of wing stringers to skins.

Some of the specific benefits to the business are:

- Reduced volume of component concessions
- Greater environmental control at the manufacturing phase
- Early detection of component defects
- Reduction in design and tooling lead-times
- Reduction in tooling modifications
- Increase in assembly efficiency
- Improved product quality
- Reduction of factory space, due to tooling storage
- Meeting customer requirements first time
- Increase of by-products, quantifiable data, use to aid model of total manufacturing process.
- Receptive to product modifications, marketing & design increase confidence in design changes in mid life-cycle.
- Long term tooling cost reduction
- Optimized assembly, capacity increased, via bottleneck identification
- Manufacturing system noise detection and elimination improved
- Preventative maintenance planning optimized through increased system control
- Business change catalyst for further company integration supportive of Concurrent Engineering philosophy

Reducing inflexible product specific tooling with adaptable flexible tooling system will allow the business to respond more effectively to the prevailing market forces, reducing lead times, improving the meeting of customer requirements and providing greater customer service hopefully leading to larger market share. Ref (25).

Efficiency in the assembly process and upstream activities will allow reduced design and development times or allow more time for further iterations to the current designs. Reductions in the life-cycle costs resulting from savings made, will benefit both the supplier and end user.

Although the British aerospace industry will be the main beneficiary of this work, initially, in time the transfer of the technology to other industries and manufacturers of structures could also provide them with ways in which to overcome technical and cost barriers. For example, ship builders, civil engineering projects, bridges and tunnels, and automotive industry, all have products and systems which should be receptive to JAC.

# Chapter 3

## THE ASSEMBLY PROCESS : AS - IS

### 3.1 Introduction

Assembly is one of the most important manufacturing processes. Assembly constitutes a production bottleneck in many fields especially within the aerospace industry, Ref.(26). The best way to eliminate the problem is to remove all the assembly operations from product production. That is the so-called "the best assembly is no assembly" method Ref.(27). This is obviously not possible with such a complex product as an aircraft. When planning the total assembly process, the planner should "outline the nature and the succession of operations necessary to assemble the product", Ref (28). These operations describe all the information needed in the assembly process; including the sequence of operations, the fixturing method, etc. Assembly planning is an integrated consideration of the product process and production system.

Gaining an insight and understanding of the underlying principles and issues regarding the generic assembly process is a fundamental requirement to progress towards a jig-less environment.

The economic significance of assembly within manufactured goods cannot be ignored. Assembly of manufactured goods accounts for over 50% of total production time, figure 3.1.1 and 20% of the total unit production cost figure 3.1.2. Typically, about one-third of a manufacturing company's labour is involved in assembly tasks.

Observations have been made from recent statistical surveys, such as OECD 1988-94, Ref.(29), as indicated below:-

- Countries with a relatively larger production volume tend also to have a relatively higher percentage of assembly.

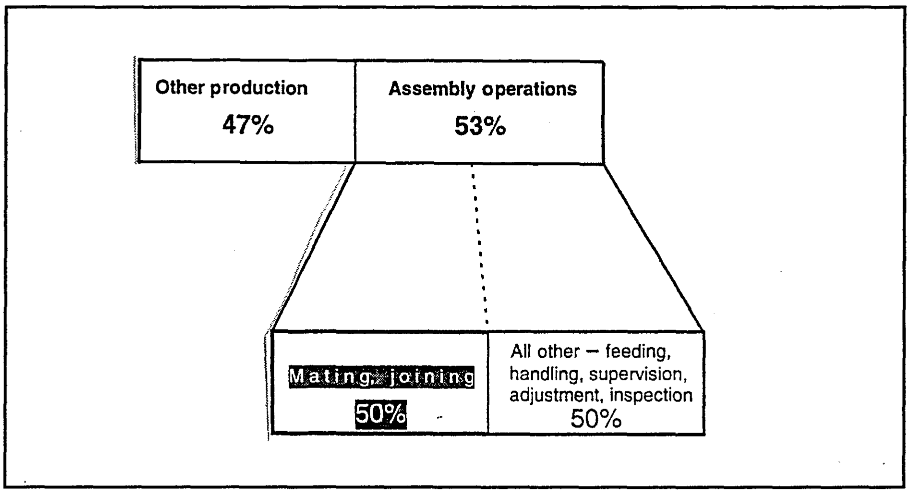


**Figure 3.1.1 Total time in production**

- The percentage of assembly in total value-added is higher than the percentage of total production, indicating a higher relative value-added by sectors with assembled products.

- The share of employment in assembly is consistently, similar to the percentage of value-added by assembly industries.

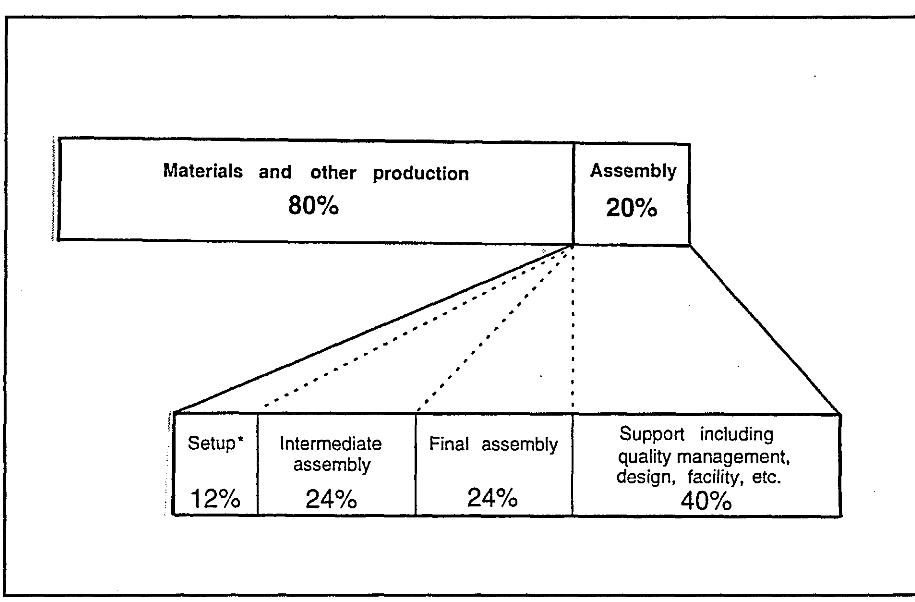


**Figure 3.1.2 Total unit production cost**

These facts indicate the relative importance of assembly in terms of time and cost of assembled products. They also point to the potential savings that can be generated by efforts to understand and improve assembly technologies and systems.

Since assembly, especially final assembly, within an industrial context of the manufacturing system is the result of an accumulation of all that precedes it. Therefore, every aspect of the assembly process will be determined and affected by the customer requirement to marketing strategy, product design, primary and secondary manufacturing processes employed on components, finishing techniques through to assembly system process control.

Jig-less tooling concepts will need to be addressed by each element in the manufacturing system at some point. The manufacturing system requires to consistently be rationalized and to be robust in its operation, because of the individual characteristics associated with each product within its manufacturing system. The work undertaken in this research project has required:-

(i) Scoping the issues, constraints and behaviour of an assembly its components and processes employed, provided a greater understanding of the fundamentals at play. Individual assembly scenarios have demonstrated their own particular concepts and characteristics.

(ii) Using this knowledge appropriate strategies supported by enabling techniques were identified to achieve the required result within a jig-less environment.

## 3.2 Assembly

- Definition of a generic industrial assembly:

through design, a minimum number of selected components are mated to form a geometric entity which possess a functional synergy to address a specific need or task which cannot be achieved by any other means within a defined quality and economic framework.

Peter Snelling, 2000.

- Definition of the assembly process:

the aggregation of all appropriate processes by which various parts and sub-assemblies are built together to form a complete, geometrically designed assembly or product either by an individual, batch or a continuous process.

Shimon Y. Nof, 1997, Ref.(30).

With the above fundamentals in mind the relationship of the product, materials, components, manufacturing processes, assembly process and associated tooling must be examined and understood.

Assembly consists of more than simply joining parts together. Many activities must occur to support part mating. In addition, assembly itself may be hierarchical, in which assemblies are joined to assemblies, Ref.(31).

The main activities of generic assembly are:-

- Marshalling parts in the correct quantity and sequence.
- Transporting parts and partially assembled items.
- Presenting parts or assemblies to the assembly work area.
- Mating parts or assemblies to other assemblies.
- Inspecting to confirm correct assembly.
- Testing to confirm correct function.
- Documentation of the process operation.

Assembly is part of the production system. Industrially produced final products consist mainly of several individual parts and sub-assemblies that have mostly been manufactured at different times, possibly in separate locations.

Assembly tasks thus result from the requirement to build together certain individual part sub-assemblies and substances such as lubricants and adhesives into final assemblies of higher complexity in a given quantity and within a given time period. Assembly represents a diverse cross-section of the problems encountered within the whole of the manufacturing system, with different assembly activities and processes being performed in various branches of industry.

The assembly or assemblies must achieve the designed functional and aesthetic criteria via the assemblies' constitutive parts, with respect to the set boundaries of quality and cost. Thus the assembly is required to function to the desired effect as designed, and any deviation of the assembly compared to the design specification will compromise the intended performance of the product. The majority of industrial products consist of an assembly in which very few are one piece or monolithic in nature.

An example of a complex assembly would be a gearbox, consisting of a casing usually produced from the primary manufacturing process of casting, with secondary manufacture by being machined as appropriate. Rotating internal gears fixed to spindles mesh to provide a mechanical system which modifies input speed and torque accordingly.

An aircraft will consist of the cockpit, fuselage, the central body, wings and tail assembly. Each assembly can be broken down into sub-assemblies which can be further broken down into the individual components and materials.

Industrial assembly is distinguished from non-industrial assembly, i.e., DIY, hobbies etc, due to their economic demands. Its goals of efficiency, productivity and cost-effectiveness will be paramount to add value to any commercial enterprise.

Industrial assembly can be taken to mean repetitive assembly in either one off (similar product), batch (small quantity) or mass production (high volume). Parts and assembly actions can be optimized, because of their nature of repetition. The areas of method study and time study came about from the mechanized growth of industry where the rationalization of a process brought that particular manufacturing system closer to its optimum in that given time period. Ref. (32).

Industrial assembly takes an integrated approach to the:-

- Selection and design of the appropriate assembly method.
- Design and planning of products for assembly.
- Assembly techniques.
- Assembly system planning and operation.

As opposed to a construction site, ship building and facility construction which have their own particular issues and constraints, the aerospace industry (airplane construction) is developing more flexible and automated production methods. These industries span both ends of the manufacturing volume spectrum. Lessons can be learnt and ideas taken from all industries to aid in the quest for improving any one particular product or manufacturing system.

By contrast with primary and secondary manufacturing processes, assembly is relatively poorly understood. This is mainly due to the assembly tasks being traditionally carried out by human operation. The human operator being extremely flexible and efficient overall in his/her capacity to successfully complete complex assembly tasks. With experience able to impart quality checks via in-process inspection and adjustments as required, Ref (33).

A process model for assembly needs to describe how parts mate, what requirements for successful assembly are, how many parts are damaged by assembly and to take into account the internal and external disturbances, noise, appropriate to the assembly system. Beyond models of individual part mates lie models of groups of parts, including assembly sequence options, jigging and fixturing methods, tolerancing of assemblies, and implications for quality control. Ref. (34).

To achieve a substantial reduction in assembly tooling and replace existing tooling with automation and/or with jig-less techniques one cannot proceed by simply mimicking what people do, because since current assembly tooling design and operation is a 'black-art' and successful implementation is achieved via experience and try-and-error. Therefore, a model of the task can be invaluable in understanding the complex environment of the assembly process, Ref.(35).

To analyze and thus gain an understanding of the function of the assembly process together with the assembly tooling the use of system control theory to model the process can give an insight to the mechanisms at play.

- using a holistic approach to design, manufacture and assembly process.
- the use of a deterministic and/or stochastic approach to determine cause and effect.
- identification of the parameters and variables involved.
- determination of the complex behaviour of the assembly system.
- identification of areas and subsets of linear, non-linear behaviour, static and dynamic behaviour within the assembly and the process methodology.

System noise, internal and external disturbances, see figure 3.2.2, result in producing errors, steady-state error, within the final assembly.

This system noise forces the assembly process and thus the final product to deviate from its designed specification. To ensure that the final assembly is to specification and thus the assembly process is in control a closed loop system is required and the feedback loop is provided by the experience of an assembly fitter, operator and/or the use of physical jigs and fixtures.

Therefore, implicit within the existing tooling is the feedback loop within the assembly system, figure 3.2.2, used as a comparator to the design specification, to off-set system noise and provide a steady-state to the assembly process.

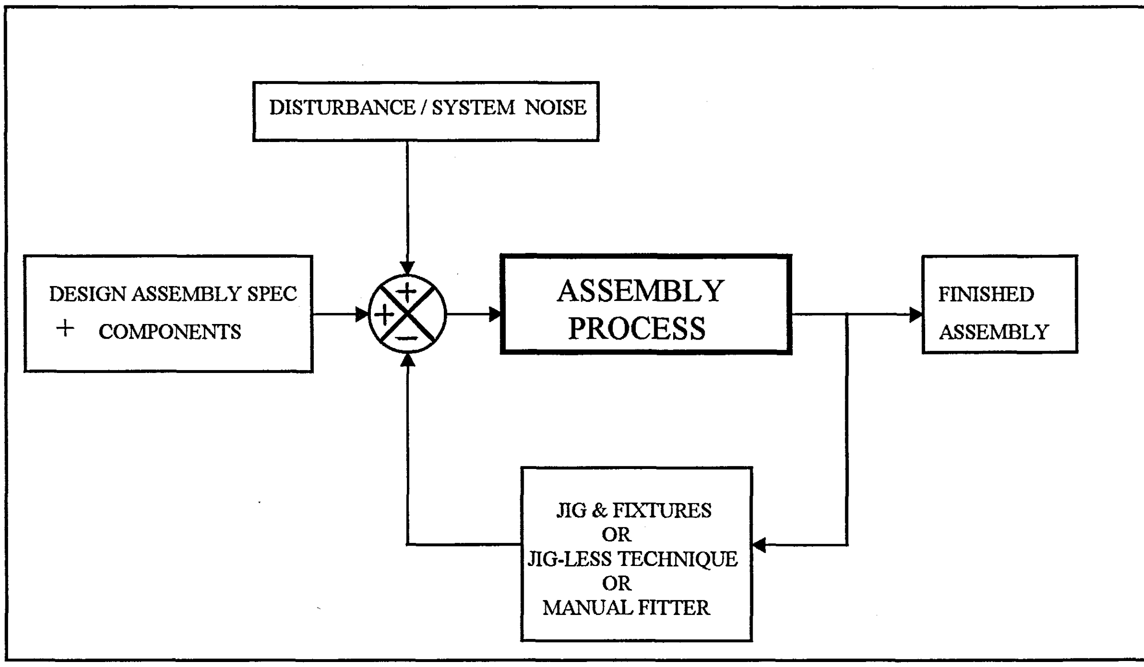


**Figure 3.2.2 Generic Assembly System - Implicit Closed Loop via Tooling/Fitter**

Removal of the assembly tooling and the feedback loop is lost, resulting in an open loop assembly system which can only be brought under control by the intervention of adjustment, via an increase of skilled labour. Therefore the steady-state error, assembly quality, of the assembly process is determined by the performance of the tooling and operation of the assembly process. Any Jig-Less tooling technique must provide the feedback loop in the system and be robust in the presence of system noise at the transient response state, assembly process, taking appropriate action, reactive when required.

### 3.2.1 Interchangability

Components which may be assembled in the field fall under two distinct classifications: those which are replaceable and those which are interchangeable. Compliance with interchangeability or replaceability requirements is normally contractually guaranteed to the customer by the prime contractor.

Interchangeability is a term used to describe a functional characteristic applied to a component or sub-assembly whilst in its working environment which allows it to be disassembled and replaced or exchanged for another random production copy of itself without requiring to be specially fitted, modifications to itself or its mating components, without compromising the performance of the assembly or component. Ref. (36).

Replaceable subassemblies and components permit a minimum of drilling, trimming, and fitting in the field. Interchangeable items must fit within the tolerance specified without further alteration of any kind. Commercial and Military customer requirements are ever increasing the I.C.Y component requirement.

Five common assembly strategies that provide varying degrees of interchangability are, Ref. (37);

1. Interchangable assembly

2. Unit assembly

3. Selective assembly

4. Adjustment at assembly

5. Manufacture to suit

With higher quality required from the product this will place higher demands upon the manufacturing processes and the Jig-Less assembly process.

### 3.2.2 Assembly Variability

A typical assembly process is composed of many steps and parts, each of which can contribute to the total variation in the final product. Sources of variation are varied and can interact, resulting in complex analysis problems. Sources of variation can be attributed to system noise, disturbances and can take many forms internal and external to the manufacturing process and assembled product, Ref. (38).

The source of most rejection and rework in the assembly of aircraft is variation. Variation in nominal design, in the fabricated detail parts, in the assembly tooling, in an uncontrolled working environment and in assembly procedures all lead to parts that do not fit on assembly, Ref.(39).

Figure 3.2.2.1 shows a summary of these major causes of assembly problems in the aerospace industry, Ref.(40).

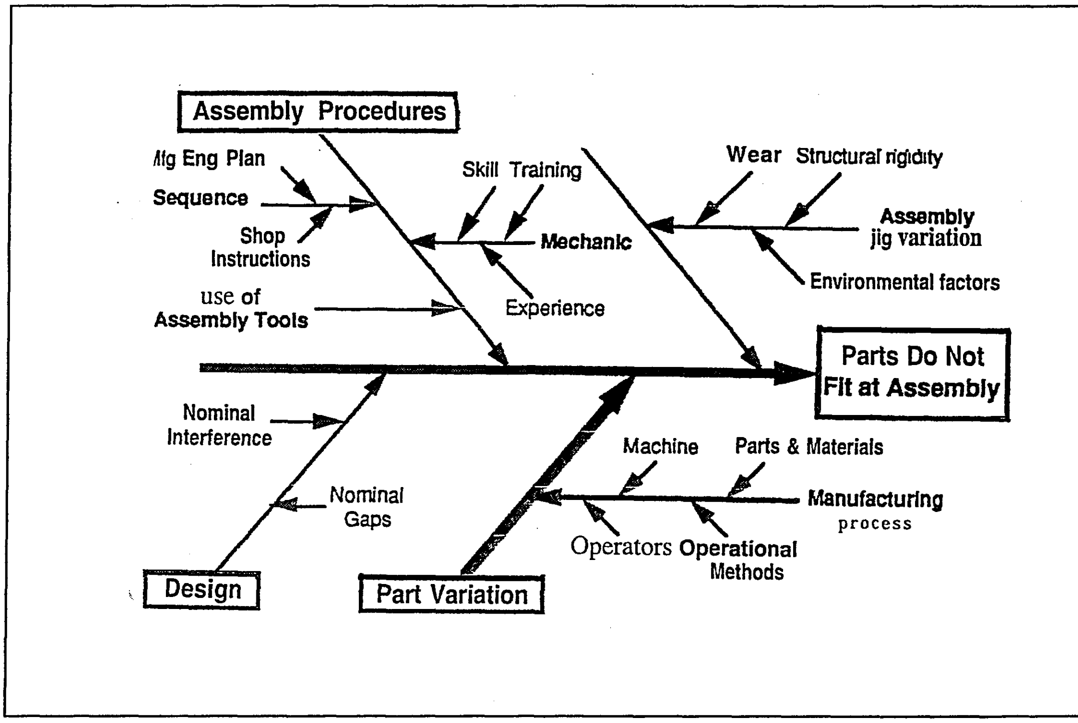


**Figure 3.2.2.1 Source of assembly errors** - Shalon, 1992, Ref. (40).

Among the many sources of assembly errors, thermal deformation and geometric errors are traditionally known as key contributors. Geometric errors are caused by the inaccuracy of machined parts, misalignment of parts and improper assembly.

Temperature control within the assembly process environment will become a major factor in the quality of the finished assembly. The source of the manufactured components will vary and, therefore, not uniformly controlled, if no allowance is made for thermal expansion and contraction. Key features, especially if using hole-to-hole assembly methodology will result in major assembly difficulties when the components are brought together at the assembly site. Today's aircraft construction uses different materials, carbon fibre composite, aluminium alloys, titanium alloys, steels, in numerous sections and shapes, all with different coefficients of expansion.

Approximate calculations can be made for linear expansion but for complex components and assemblies these calculations would require extensive finite element analysis, F.E.A., to predict the expansions. As well move to higher precision component assemblies the consequences of these thermal induced errors at the component manufacture stage and the assembly stage needs to be understood and addressed before jig-less assembly can be contemplated.

Typical assembly problems:-

- tolerance stack-up - all parts are within allocated tolerance but the stack-up causes the assembly to be out of tolerance; in this case tolerances are allocated incorrectly.
- design problem - part geometric definition is incorrect; e.g., parts inadvertently overlap, features do not align, tolerance allocation is incorrect.
- part quality problem - a part is manufactured out of allocated tolerance.
- assembly process problem - the part sequence or one step in the process causes a problem; e.g., environmental effects like heat, vibration, etc., or parts are located incorrectly in fixtures.
- tooling or fixture problem - the locating feature of the tool is out of position or worn, the fixture is malfunctioning, or the fixture was designed incorrectly.

Variation causes rework. Parts that do not fit on assembly must be hand-formed by skilled assembly mechanics into the correct configuration required by the assembly tools.

Typical forms of rework include: shimming (addition of material to compensate for gaps), grinding (elimination of material to compensate for interference), trimming and over-sizing fasteners (compensating for misaligned or poorly-drilled holes). The effects of variation require assembly mechanics to spend non-value-added time clamping (using everything from finger pressure to hydraulic clamps), strapping, hammering, filing, and hand forming parts into their designed configuration. Ref.(41).

Rework has may adverse effects:-

- Added assembly cost. In-process modification to parts to fit assembly structure, to highly skilled expensive labour required. Variation in sub-assemblies must be accommodated at the assembly level. Interchangability of parts and sub-assemblies is compromised.
- Added administrative costs.
- Increase part inventory.
- Increase tool inventory.
- Variable assembly times.
- Variable process flows.

- Reduced product quality, the variable manner in which aerospace structures are assembled ensures that the product will not meet design specification, with incorrect steps and gaps.

- Residual stresses. Restraining detail parts prior to fastening introduces stresses into the structure which degrade fatigue life. Structures assembled with such clamping techniques, tend to randomly 'move' in unwanted configurations once released from the assembly tools, creating downstream assembly process problems.

To reduce variation, analytical techniques have been extensively used in a wide range of problems, Ref.(42). Simulating assembly processes involving flexible and rigid parts, combining elastic and statistical analysis, to minimize total variation involving design and manufacturing processes, Ref.(43).

Importantly, variation in detail parts is the primary cause of variation in assembly procedures and in assembly tools. Variation in assembly procedures are only required if detail parts do not fit and the fitter must adjust and rectify as required the assembly process. Variations from preferred assembly processes are caused by inconsistent variable parts.

Assembly tooling must accommodate detail part variation within a certain range. If parts of the assembly are 'perfect' the necessity of complex assembly tooling would be drastically reduced. Ref. (44).

Assembly tooling itself cannot impart quality into the assembly process if inaccurate components are used. The components assembly process capabilities must be matched accordingly.

Therefore, any Jig-Less assembly process must take into account detail part variation to keep control of the assembly process.

## 3.3 Assembly Tooling Systems

Assembly tooling follows the chosen assembly process and takes account of the quantities involved. Therefore, it can be divided into automated or manual systems. Manual assembly differs widely from automatic assembly due to the differences in ability between human operators and the mechanical methods used for assembly. An operation that is easy for an operator to perform might be impossible for a special-purpose workhead or robot. Ref. (45).

In manual assembly, the tools required are generally simpler and less expensive than those employed on automatic assembly machines. Manual assembly systems also have considerable flexibility and adaptability. Sometimes it will be economical to provide the assembly operator with mechanical assistance in order to reduce the assembly time.

Assembly tooling for manual operations will require careful consideration of ergonomics, problems with repetitive operations causing poor assembly performance, reduced product quality, and injuries must be taken into account. The selection and choice of assembly system, normally lies with economics, quantity, period of production, pay-back period, break-even point, etc.. Special cases due to extreme working environments and physical size of the product require a different approach.

In the early stages of tooling the design product, planned assembly process should be well thought out calling upon all resident production experience. Product design, quality, shop supervision, safety and other elements should provide an input to the decision making process.

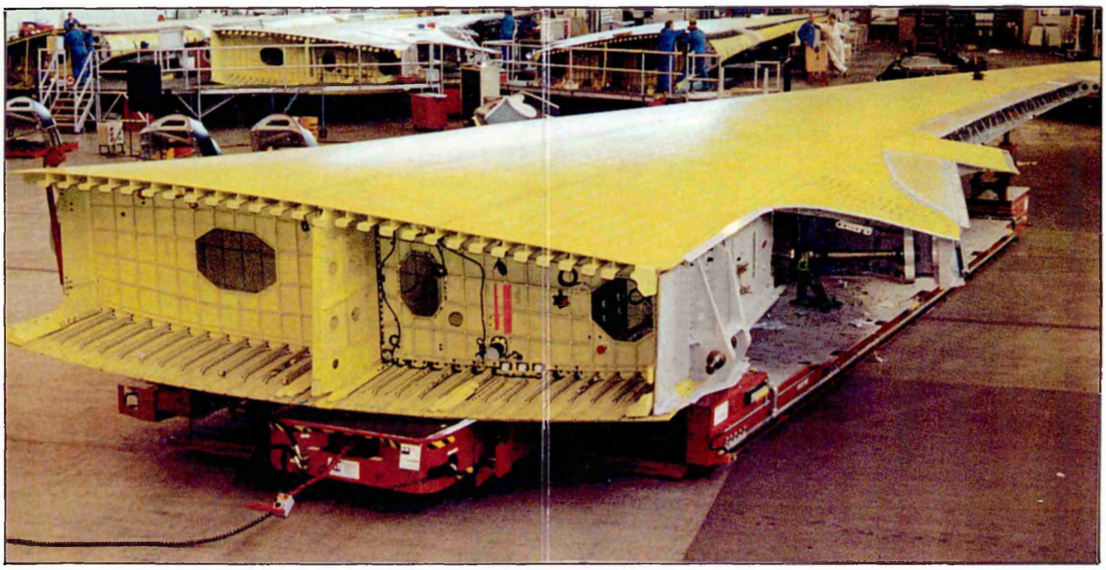

**Figure 3.3.1 BAe Airbus Wing-Box**

Between traditional manual assembly tooling and automated assembly, is robotic assembly which requires the designing of workholding device to be more flexible (i.e., able to accommodate more than one part or able to be quickly changed). Flexible workholders are a critical element in the efficient changing of manufacturing processes, cells, both manned and unmanned. For the cell to be flexible, workholding devices should be able to accommodate all the parts within the 'family of parts'. This design requirement has added significantly to the complexity of conventional jig and fixture design. Design studies and systems for the generation of jig and fixture configuration design help to alleviate these problems, Ref.(46).

BAe Airbus, Chester and Filton, currently manufacture the wings for the Airbus family of aircraft, see figure 3.3.1, and various sub-assembly and final assembly tooling systems are in use. A series of sub-assembly jigs which provide component assemblies such as leading edge, trailing edge and fixed rod inner leading edge; these go together as a final assembly with the wing box assembly.

### 3.3.1 Function and Classification

In the conventional method of fixture design, tool designers rely on their experience and intuition to design single-purpose fixtures for specific machining operations, often using a trial-and-error method until the workholders perform satisfactorily. Of course, these designers should calculate the clamping forces or stress distributions in the fixturing elements to determine the loads that will deform the fixtures or the workpieces elastically or plastically. In the design of the workholding devices, two primary functions must be considered: locating and clamping. Locating refers to orienting and positioning the part in the machine tool with respect to the cutting tools to achieve the required specifications. Clamping refers to holding and maintaining the part in that location during the operations. Ref.(47).

Dimensions are of two types: size and location. Size dimensions denote the size of geometrical shapes - holes, cubes, slots, of which objects are composed. Location dimensions, on the other hand, determine the position or location of these geometrical shapes with respect to each other. Thus jigs accomplish the layout automatically.

Design criteria for generic assembly tooling meet the functions of a fixture, locating, holding and clamping. Meeting all the design criteria for workholders is impossible and compromise is inevitable. Some 'ideal' functional requirements for jigs and fixtures are given below:-

- Positive Location

A fixture must, above all else, hold the workpiece precisely in space to suppress each of 6 degrees of freedom; e.g., linear movement along the X, Y, and Z axes and rotational movement about each axis.

- Repeatability

Identical workpieces should be placed by the workholder in precisely the location on repeated loading and unloading cycles. It should be impossible to load the workpiece incorrectly. This is called "fool proofing" the jig or fixture.

- Adequate Clamping Forces

The workholder must hold the workpiece against the forces of gravity, centrifugal forces, inertial forces, and cutting forces. Milling and broaching operations, in particular, tend to pull the workpiece out of the fixture, and the designer must calculate these machining forces against the fixture's holding capacity. The device must be rigid.

- Reliability

The clamping forces must be maintained during machine operation every time the device is used. The mechanism must be easy to maintain and lubricate.

- Ruggedness

Workholders usually receive more punishment during the loading and unloading cycle than during the machining operation. The device must resist impact and abrasion for at least the life of the job. Elements of a device that are subject to damage and wear should be easily replaceable.

- Design and Construction Ease

Workholders should use standard elements as much as possible to allow the engineer to concentrate on function rather than on construction details. Modular fixtures epitomize this design rule as the entire workholder can be made from standard elements, permitting a bolt-together approach for substantial time and cost savings over custom workholders.

- Low Profile

Worksholder elements must be clear of the cutting tool path. Designing lugs on the part for clamping can simplify the fixture and allow for proper tool clearance.

- Workpiece Accommodation

Surface contours of castings or forging vary from one part to the next. The device should tolerate these variations without sacrificing positive location or other design objectives.

- Ergonomics and Safety

Clamps should be selected and positioned to eliminate pinch points and facilitate ease of operation. The workholder elements should not obstruct the loading or unloading of work pieces. In manual operations, the operator should not have to reach past the tool to load or unload parts. A rule sometimes used is that the operator can repeatedly exert a force of 30 to 40lb to open or close a clamp but greater forces than this can cause ergonomic problems.

- Freedom from Part Distortion

Parts being machined can be distorted by gravity, the machining forces, or the clamping forces. Once clamped into the device, the part must be unstressed or, at least, undistorted. Otherwise, the newly machined surfaces take on any distortions caused by the clamping forces.

- Flexibility

The workholding device should be designed so that it can be quickly exchanged and/or so that it can locate and restrain more than one type (design) of part. Many different schemes are being proposed to provide workholder flexibility: Modular vice fixturing, programmable clamps using air-activated plungers, part encapsulation with a low-melting-point alloy, and NC-controlled clamping machines are some of the more recently developed systems. Despite their flexibility these clamping systems have some significant drawbacks. They are expensive, and the individual systems may not integrate well into individual machine tools. Ref.(48).

In generic terms fixturing hardware can be classified in several generic ways, figure 3.3.1.1 illustrates.

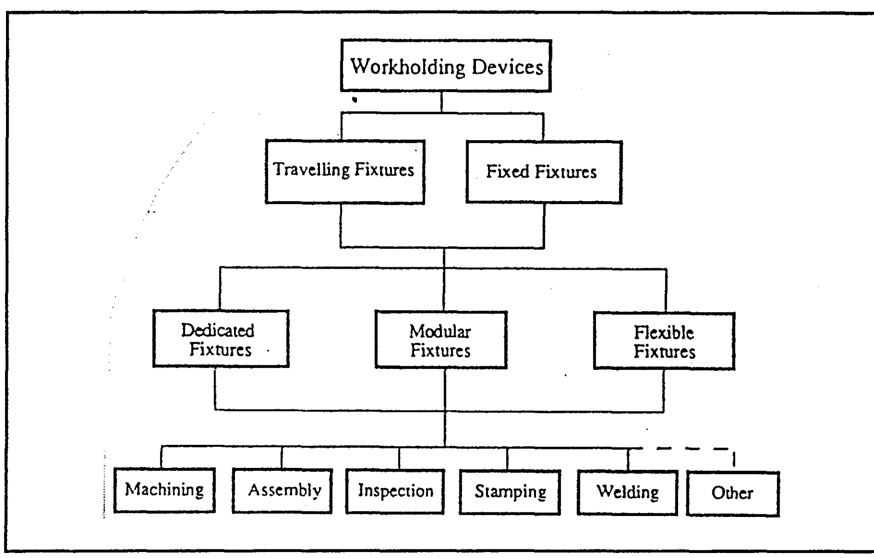


**Figure 3.3.1.1 Fixture Classification**

Fixturing hardware can be classified in several ways such as (1) the fixture may travel or remain with the workstation, (2) the fixture may be reused and may conform to workpieces with complex geometry; and (3) the fixture may vary with specific applications.

Mobility of the fixture can be divided into fixed or travelling. A pallet is a travelling fixture that is transferred, manually or automatically, from one workstation to another while the part is permanently held against the fixture. Many flexible machining systems use this approach. These pallets can be expensive to design and keep in service once they are designed. If the part is transferred manually or automatically from one workstation to another, but the fixture is permanently mounted on the workstation table, this is called a fixed fixture. This is usually the approach taken with manual machining and a number of transfer line systems.

In addition to their mobility, fixtures can be classified based on their adaptability to different parts. While the design goal is the ability to conform to any geometry and be able to handle lot sizes from one to several million units, the three classifications discussed below are more common.

- Dedicated fixtures
- Modular fixtures
- Flexible fixtures

Fixtures, particularly dedicated ones, have traditionally been classified by application, as the bottom tier. But it should serve as a reminder that when it is possible to use the same fixture, or at least the same fixture design methodology, much time, effort, and cost can be saved by trying to develop a unified approach to these important manufacturing design problems, Ref. (49).

Assembly jigs and fixtures usually must allow for the introduction of several component parts and the use of some type of fastening equipment, such as reveting or welding. Such jig and fixtures are used in the aircraft and automobile industries.

Long experience in airframe manufacture has brought about the standardization of certain types or classes of assembly fixtures. Airframe size and shape will vary, but for production, every airframe must be divided into small segments which can be conveniently fabricated. The segments or subassemblies are in turn divided into detail parts. The assembly fixture positions, locates, and clamps the individual parts or subassemblies while they are being fastened together. The first problem is the accurate and convenient positioning of the parts. The second problem is positioning them in a manner that will permit the fitters to fasten them together. The required shape of the subassembly determines the position of the detail parts and thereby influences the type of assembly fixture selected, Ref. (50).

Five general classes or types of assembly fixtures are common to all airframe manufacture. They are (1) table-type fixtures, (2) picture-frame-type fixtures, (3) double picture-frame or box-type fixtures, (4) the large rectangular box-type structures that encompass large sections for final assembly, and (5) nest-type fixtures. Fixtures of the first three classes are constructed in accordance with standards except for the detail tooling unique to the airframe to be built. Fixtures of the last two classes do not generally have a degree of similarity that will permit complete standardization. Standards will usually, however, prescribe the tool material, the structural section, the joining method, and all purchased components. Ref.(51).

Many fixtures have characteristics of more than one of the above types. The case study, see section 6.3.3, the 'Bathtub' stage (1) shows an assembly requiring precise fixturing in two planes, using box-type fixture together with nesting characteristics.

A final-assembly tool or fixture positions, locates, and clamps individual workpieces, subassemblies, and major assemblies while they are being joined to form the final product. Final-assembly tooling may by convention be extended to include all fixtures and tooling in a designated final-assembly area. In this broad connotation it may also include the large rectangular box-type fuselage mating fixtures described as subassembly tooling.

With a low production volume, the segmentation of the aircraft will not be carried to the extreme lengths justified by mass production. Although the same number of detail parts will be assembled into the end product, a greater number of parts will be joined in any one assembly fixture. Fewer subassemblies will exist as entities, and consequently fewer fixtures will be required. In these circumstances, the final-assembly area may well include tools, fixtures, and production sequences which would clearly be defined as subassembly tooling in the same or another plant which was building the same end product at a high production rate. Ref.(52).

### 3.3.2 Strengths, weaknesses & capability

Traditionally the manufacture of complete aircraft and aerostructure components, both in civil and military programmes relies on the use of fixed tooling. The tooling is designed and manufactured specifically for individual product types and is commonly known as product specific tooling. Ref (53).

The functions performed by jigs include simply holding parts to retain their shape, locating parts for drilling and controlling tolerances in the build of structures. It is not economic to machine components to such tight tolerances that they fit together exactly. Jigs and fixtures are inadvertently used as comparator devices, gauging the quality of the components during the assembly process in a qualitatively way, GO and NO-GO gauging. This lends itself to a rough-cut means of quality control but cannot provide quantitative data for future analysis and feedback, Ref. (54).

This approach has advantages in terms of product consistency, necessary for interchangeability (ICY) requirements for spares applications, for the possibility to design retrofit modifications subsequent to aircraft delivery and it also produces a high quality product.

However the associated disadvantages include the following:-

- High non-recurring costs at the start of a programme. Tooling spend is made far in advance of any revenue subsequently generated by the project and this has an important effect on cash flow and interest charges for the business.

- Long lead times.

- Inflexible to major developments to an existing product type.

- Cannot respond rapidly to increases in production rates.

Currently if there is a need to increase production over and above the capacity of the existing tooling capabilities the answer is to introduce rate tooling, i.e., multiple tools, another set of tools. Because of the uncertainty in present day markets and long lead times to acquire a new set of tools this can be a risky and expensive venture. There are examples in the industry where tooling has been ordered to meet a need for increased production 2-3 years in advance and when, due to world economic factors (outside the control of aircraft companies), orders and options have been cancelled. What remains is expensive surplus scrap metal which either has to be stored or disposed of. Ref. (55).

Previous studies and observations have been made at BAe Airbus, Ref.(56), Chester with regards to the strengths and weaknesses of the current wing build philosophy. The Wing-box, Stage 01 jigs , see figure 3.3.2.1, at Chester have a major influence over the assembly quality of the finished wing box and have highlighted the following strong areas in the tooling design:-

(i) Strengths

- The design of wing jigs have been subject to much slower rates of development than for the aircraft assemblies produced within them. This has resulted in jig technology being mature and well tested.

- The robust nature of the jig structure has made possible long wing assembly production runs, indeed the first Airbus wing assembly fixtures for the A300 Airbus were commissioned in 1970 and are still in use.

- It has been possible to manufacture more than one type of wing box in the same assembly fixtures, e.g. the wing boxes for the A330 and the A340 are produced in the same assembly fixtures, as are the wing boxes for the A320 and A321. It must be pointed out that the overall dimensional sizes of these wing boxes are essentially common, however, the lack of commonality of detail parts and assemblies has required the provision of extensive fool-proofing facilities.

- The ability to manufacture a complete wing box within the Stage 01 jig has resulted in the ability to link the build quality of the sub-assembly jigs to a common standard.

- The ability to access both sides of the wing box simultaneously has proved to be a major asset in reducing wing build cycle time.

- On nearing completion of the product life cycle, it has proved possible to utilize the major components of the Stage 01 jigs to manufacture a new Airbus variant; all but two of the wing assembly fixtures used to produce the A320 were previously A300 or A310 assembly fixtures.

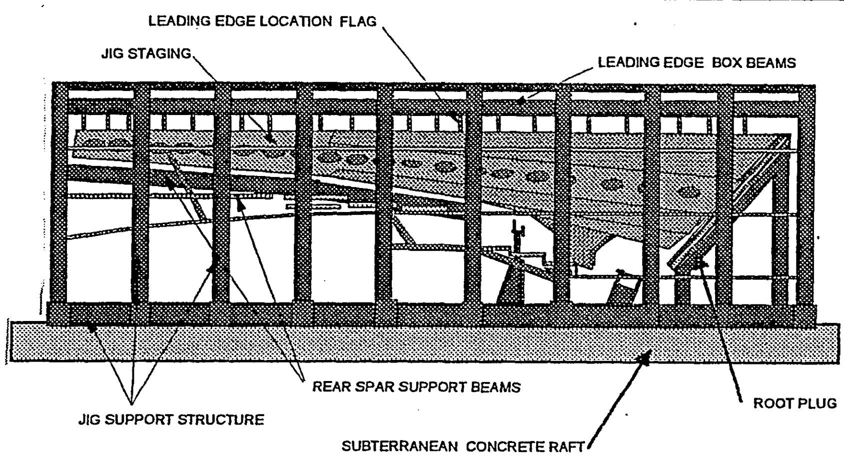


**Figure 3.3.2.1 Stage 01 Jig & Wing-Box Assembly**

The assembly fixtures do have some major drawbacks which must be addressed by the jig-less tooling concept these include:-

(ii) Weaknesses

- The wing assembly fixtures are a massive capital investment, with long pay back periods.

- The assembly fixtures are dedicated to one or two major aircraft variants, it being too expensive to continually convert the fixtures for multiple variant build. Thus when an aircraft program contracts, it is likely that the assembly fixtures will be under-utilized, extending the pay back period.

- The fixtures in use at present have been used for long production runs, they would prove to be too expensive for use on short production runs, as happened for the Concorde programme.

- The tight build tolerance used on aircraft assemblies requires the frequent calibration of tooling to ensure the required accuracy. This recertification process is proving difficult and costly, as it was not fully appreciated as a requirement during the design process.

- The use of aluminium tooling slabs to control thermal expansion has proved unsuccessful for the following reasons:-

a) The thermal expansion rate of the aluminium used in the expansion slabs, although closer to that of the aircraft components is still not exactly the same.

b) The aluminium slabs connect to the steel support structure, which acts as a very effective heat sink. This results in a time lag between the expansion of the aircraft components and the tooling. This time lag has been measured to be in the order of hours rather than minutes.

c) The glass roof fitted to the factory allows sunlight to heat front spar assemblies in the afternoon. Whilst the leading edge is expanding, the trailing edge is shaded by the staging around the jig, resulting in differential expansion between front and rear spars. When the sun is low in the sky, it is possible, for example, for a Port wing jig to provide shade for its associated Starboard jig, resulting in different thermal expansions for a given ambient temperature rise.

- The design of the jig does not facilitate measurement of the wing within the assembly jig. The use of slips to position assembly components, requires them to be simply "go" gauges, i.e. at the lowest production tolerance, however, frequently slips are manufactured to the nominal component requirements, which results in misplacement of components which are at the maximum production tolerance. Thus the slip cannot provide a measurement of the actual location of the component, only the information that the component lies within a certain positional range.

- Optical measurement within the jig is proving to be almost impossible, since many of the datum pads and sight lines used during the assembly of the wing jig are later obscured by the wing jig staging. The staging itself is also not stable enough to support the theodolites required for optical measurement, resulting in corruption of the datum plan.

- The use of sensors mounted on the jig for measurement purposes is proving difficult, since the unpredictability of the differential expansion occurring between the jig on to which the sensors are mounted and the components result in lack of confidence in the output readings from the sensors.

- The practice of modifying existing jigs to build a new aircraft variant has resulted in several design standards for each aircraft variant, for the A320 Stage 01 jigs, there are three completely different versions of assembly jig design. This makes modification to the tooling very difficult since the designer must asses the impact of the design change on each particular variant and it is all too easy for the designer to miss a particular standard, since all of the different designs have the same tool number.

- The practice of separate jig assembly and optic, line-of-sight, drawings results in poor cross-referencing between each drawing. It is, therefore, possible for the designer to delete or modify components which destroy the optical integrity of the jig, without changing the optical drawing standard. This will only become apparent when optical recertification of the jig is attempted, with consequent need for urgent, expensive design modifications.

- The limitations of measuring the wing box within the assembly fixture result in measurement of the wing being delayed until it is located in the horizontal plane in the Stage 03 area. The wing box is structurally complete by the time it reaches Stage 03, making it very expensive and impracticable to correct any defects highlighted by measurements of the wing box.

- Wing boxes produced in the Stage 01 jig frequently require concession action to correct assembly problems created within jig. The problems of unacceptable wing twist, incorrectly located engine pylon pick-ups and spoiler hinge line problems result in complaints from both the other European partners and the final customer.

Product designers in the past have concentrated their efforts on meeting the primary functions of the product and past downstream the way in which the product would be manufactured and assembled to the production engineers. This has led to a reliance and faith in the assembly process and its tooling to make up for the short comings in product design for manufacture and assembly.

Removal of the present physical tooling exposes the assembly and manufacturing processes to its strengths and weaknesses. Jig-Less assembly must fulfill these inherent characteristics plus the addition roles to justify the investment.

### 3.3.3 Kinematic considerations

Kinematic design is generally applied, as far as practicable, to machine tools, jigs and fixtures.

The basic concept of kinematics states that the ability of a body to move freely in all modes and directions may be resolved into components of three translation axes, together with a rotation about each of these axes, and six and not more than six constraints in the correct positions are necessary to define fully the position of the rigid body with respect to a fixed frame of reference. Pure kinematic design demands that these constraints should be points of contact. The important aspect of fixturing is the process of locating and supporting a part in three-dimensional space. As figure 3.3.3.1 shows , a part, prismatic or rotational, has 12 degrees of freedom, six of which are translational, and six which are rotational. Ref. (57). In practice, point contact is impossible with heavily loaded structures. In these circumstances, if kinematic principles are to be applied, recourse is frequently made to 'semi-kinematic' design in which point contacts are substituted for 'area' contacts. Care must also be taken to provide a force to maintain the parts in contact. This force is known as a closure. Closure may very occasionally take the form of the component, assembly or jig due to it's weight. Ideally this closure should be applied through one point but in practice this is not always possible.

With kinematic design, each constraint is a simple point contact which takes away one degree of freedom. High accuracy of function can be obtained with the minimum of tooling and without specially skilled workmanship or close dimensional limits. Where a design departs from kinematic principles and redundant constraints are applied, the constraints are known as fitted constraints. To employ such methods, location of such features require great accuracy in the manufacture and deployment of tight working tolerances to achieve a successful outcome.

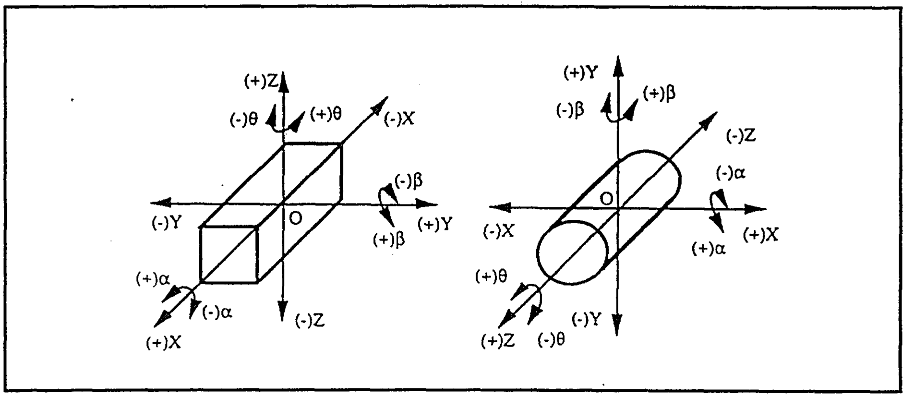


**Figure 3.3.3.1 Degrees of Freedom for Prismatic & Cylindrical Part**

Good fixture design adopts kinematic design principles as far as possible. If a component is secured on a fixture which includes a redundant constraint, the position of the component cannot be fully defined unless the fixture and the component are geometrically very accurate on all their respective location surfaces. If inaccuracy exists unwanted movement will occur. For this reason fixtures which adhere strictly to kinematic design theory are frequently used to locate inaccurate components or assemblies such as rough castings for machining operations. The support points (constraints) are usually in the form of hemisperically tipped support studs and closure is applied to hold to component/assembly in place. To prevent damage via point contact on finished surfaces location would, therefore, employ either semi-kinematic or fitted constraints, by location applied on surfaces of a substantial area, rather than on points. Ref. (58).

Kinematic design is of great importance in the design of a new generation of tooling and assembly of components which will be required to provide flexible and cost effective solutions for the minimum required assembly tooling used with JAC.

This is shown in latest research being carried out at Salford University by Kerr and O'Reilly, Ref.(59). With regards to developing restraint theory using screw theory, Ref. (60), an exact analysis is used to calculate whether a component is properly restrained, and the quality of the restraint, together with Extraction Cone Analysis, (ECA), to ascertain whether a component can be extracted from, or enter its fixturing scheme. Hopefully this will lead to, where possible, design knowledge to provide assembly phase with unique location of components with the correct kinematic restraint and allow assembly entry paths and access for component parts.

### 3.3.4 Master tooling

A master tool is the dimensional authority, in physical form, to which production tooling must conform within certain specified limits. Production tooling, in turn, is the dimensional authority, in physical form, to which a workpiece must conform, again within specified limits.

A master tool is the dimensional authority for the construction and control of production tools, thereby establishing the relationship between holes, surfaces, and/or contours of a specified part, mating part, or assembly, or sub-assembly. Ref. (61).

Master tools are used:-

(i) To ensure interchangeability between airframe parts and/or assemblies where the required tolerances are such that they cannot be achieved under ordinary manufacturing practices.

(ii) To fabricate and check aircraft production and inspection tools, particularly where duplicate tools are required.

(iii) To define hole patterns, contours, surfaces, and critical attachment points. In general, they simulate one or more of the production parts of the assembly being controlled.

(iv) To coordinate the mastering of adjacent and/or mating structures.

Master tools are almost mandatory when acquiring the tooling for interchangeable items. The increasingly rare exception, as noted above, is when the tolerances governing a mating condition are very liberal, while the tolerances governing fabrication of the components are relatively tight. Master tool control is normally the only practical method to coordinate tooling and ensure interchangeability. Ref. (62).

Replaceable items are by nature less critical and may or may not require master tool control. The problems of duplicate tooling for high production must also be considered.

Jig-Less assembly if fully implemented will make the need of master reference tooling and the static site in which it operates obsolete.

# Chapter 4

## LITERATURE REVIEW

### 4.1 Introduction

This chapter reviews subject matter which has been identified to have relevance to the investigation into the Jig-less Assembly Concept. The list is by no means exhaustive but as JAC is developed its contents will include additions in recognition of their contribution.

The main thrust of academic and industrial research is associated within areas which attempt to gain an understanding of elements within the assembly process. This include peg-to-hole analysis, Ref. (63), assembly process modeling, Ref. (64) and design for assembly, Ref. (65), part reduction, Ref. (66), which are examples of initiatives which are implicit within a modern good practice engineering environment development. They stand alone with no specific integration for a concise Jig-less methodology.

Therefore, the identification and understanding of subject areas which may lead and/or aid in the realization of a Jig-less Assembly Concept is of the most importance. Additionally it is important to identify how each of these elements, such as assembly itself, has an effect upon the system in a holistic way and how the individual elements interface.

Behind each of the subject areas mentioned in this chapter lies a whole science, or body of work, in its own right. Realistically only a brief insight into each of the identified areas could be achieved, highlighting how it may play its part within a Jig-less assembly concept.

## 4.2 Concurrent Engineering, CE

Integrated manufacturing systems such as Concurrent Engineering (CE) are being developed within the aerospace and other complex product manufacturing industries. True CE implementation has been difficult and usually it can be found that only parts at any one time of a CE system operate as designed.

Concurrent Engineering is a philosophy which takes a systematic approach to the integrated concurrent design and development of products and their related processes, including marketing, manufacturing and support. From the outset it encourages all elements of the product life cycle to be considered - from conception through to in-service support and disposal - including quality cost, schedule and customer requirements. Ref. (67)

One recent example which has been evident in the aerospace industry demonstrating the effectiveness of CE is at Short Brothers of Belfast. Concurrent Engineering philosophy was adopted with the objective of attaining maximum manufacturing efficiencies whilst reducing initial engineering lead-times and, therefore, contributing to an overall reduction in aircraft 'time-to-market' and recurring manufacturing cost. Projects, utilized digital product feature models throughout the Aircraft and Tool Design process, together with DFMA tools, implemented by cross-functional personnel in the form of Design Build Teams. Results, very encouraging, producing every increasing CAD to CAM integration together with meeting the majority targets set. Ref. (68).

BAe Airbus and BAe Military are also engaged in producing a CE environment, implementing cross-functional matrix organization digital product model Integrated Product Development (IPD), process and Product Diagram. Ref. (69).

The Company Culture of any particular industry has a major influence upon the way a manufacturing business operates, making change difficult and use of technologies and methods difficult to introduce and operate effectively. Ref. (70).

Tools to aid the design process have gained much interest in recent years and have come along way in providing a means to communicate the product requirements through the system, marketing to design through to manufacturing. These being Design for Manufacturing and Assembly (DFMA), and Quality Function Deployment (QFD) and Tagachi Methods, to mention just two. Again their effectiveness in a robust industrial environment is in question. Ref. (71).

The 'hard' technologies like new or improved primary and secondary manufacturing processes and together with changes in material developments have led to major improvements in how products are manufactured.

### 4.2.1 Product, product design & design tools

The nature of a product and its subsequent manufacturing process and development are entwined. The product and its working environment will influence the choice and direction of its design processes and determine the nature of the manufacturing system and company organization. Likewise, the organization behaviour will influence the product produced, since the organization in question, through experience and tradition, develop particular behaviour working methodologies. Ref.(72).

What tools and techniques can contribute to the success of CE ? The list extends from CAD/CAM, CAPP and DFM (Design for Manufacture) to the less familiar LCC (Life Cycle Cost) modelling and QFD (Quality Function Deployment).

Even when operating concurrently, there are distinct sequential stages in every manufacturing programme: requirement specification, preliminary concept definition, full concept definition, product realization, manufacturing and in-service support.

A key objective of CE is to match designs to their manufacturing processes. Tools have immense potential in the expression of process capability and the derivation of design rules or production criteria that can be applied automatically to emergent designs before their release for manufacture. The same approach can generate process-verification data aimed at controlling the process instead of inspecting quality into the product.

Many aids to manufacture demand persistent effort before they yield advantages. The exceptions are 'team building' and formal Design for Manufacture which, properly done, is a special form of team building with a clear intellectual objective. Solid modelling and associated behavioural analysis are important and effective, both for risk mitigation and physical design. 'Traceable requirements' and 'product definitions' are emerging as needs. Ref. (73).

Jig-less Assembly is about as far away from the traditional way of doing things as one could imagine. Therefore, product development process must adapt so products produced will satisfy not only customer requirements but also the business objectives. The manufacturing system in turn must deliver the company and customer requirements which are inherent within the product specification. An understanding at the beginning of product definition, see example of how different the new product is from the old and, therefore, how the product design process must change to suit modern manufacturing techniques. Ref. (74).

The manufacturing system including the primary and secondary manufacturing processes and the process capability of enabling technologies employed for Jig-less Assembly must be fed into the product definition and subsequent product design process.

Product definition, including how product characteristics, mass, shape, speed etc., are translated into component features, material, quality (tolerances) and finish, with Jig-less Assembly mean that an additional view must be incorporated. These must all be considered together with the additional requirements in process and final product design features in the product to facilitate a workable Jig-less Assembly process.

The assembly tooling, especially final assembly, is used by the design process as a 'crutch' permitting many short cuts to be made in areas of product definition, product design and subsequent manufacturing processes. The idea that any problems downstream can be overcome by other sectors of the sequential manufacturing process, can be engineered in at a later phase, does not support the philosophy of a jig-less assembly concept.

The removal of the traditional assembly tooling will have a far reaching affect upon product definition and design. These processes must, therefore, adapt to take account of the changes in manufacture and final assembly due to JAC being adopted.

No one designer in a large modern multi-partner manufacturing organization, producing such a complex product as an aircraft, can be expected to understand all the issues and constraints relating to product definition and design.

The following classical areas have been identified when trying to meet and satisfy the customer requirements and achieve the elements within the products life cycle costs, Ref. (75) :-

- Specification
- Designs
- Manufacture
- Installation
- Commission
- Operate
- Maintenance
- Dispose

Introducing a radical change at the manufacturing process stage will require the designers and the design process to develop design tools and methodologies to incorporate such a change.

Undoubtedly an aerospace business will have a number of highly skilled, very experienced designers who have been grouped together into functional specialization areas. Consequently, the end result is aerodynamics specialists, structural load designers, detail designers, and manufacturing design engineers. Each function performs an important role in the definition of the product, and each function has a database of information in historical terms relating to previous designs, optimum features designers rules, codes of practice.

Radical change is difficult to introduce and the introduction of design tools, such as FMEA, DFM, DFX and aids, into the organization culture via its product development process must be adaptable and robust in order to be used in the design of new concepts and product introduction to meet customers' requirements and lead times.

If a new concept like Jig-less Assembly is placed into an existing mature product development process it would most likely result in delivering a new product which reflected the earlier versions. Company culture and therefore organisation behaviour determine the way people think and work. Ref.(76).

Due to the company's experience of what works and what does not work, previous capital investment, technical and commercial risk, together with lean work force have little time to indulge in new concepts. This being the situation, producing a real change management culture is difficult, resulting in companies preferring to specialize in what they are comfortable with and concentrate on what they do best.

The design phase of the product development process is considered to be the singularly most important area of influence in terms of meeting the customer requirements and thereby business objectives.

For example, Syan, Ref. (77), indicates that 'studies considering' the costs associated to a product during its entire life-cycle have demonstrated that from 60% to 95% of these costs are determined during the design phase. Corbett, Ref. (78), shows results from a study carried out at Rolls-Royce which reveal that the design phase accounts for 80% of the final production cost.

Design has also been shown to be important for incorporating quality into a product. Ref. (79). In addition, design has been shown to have a great influence when time to market is considered. Ref. (80).

In the last years of the 1980s product developers began to turn their attention toward a new competitive dimension. No longer would product cost or development cost dominate the planning of new products. This new focus on product development cycle times was brought about by a number of factors. Average product life cycles decreased, while global competition increased, leading to an increase in customer alternatives. At the same time, industry consolidation became rampant, causing less competitive companies to be swallowed up. In this new environment, market share was often won by early visibility within a market segment. In simple terms the company that reached the finish line first wins.

Therefore, design has a great influence upon the products life-cycle costs (inception through to disposal), affecting 'non-price' factors, product quality and product image. Over the past years a number of tools and techniques have been introduced that promise to decrease design cycle time. These include CAD, Design for Manufacturing, Quality Function Deployment, and the use of cross-functional teams. Taken in isolation, as 'turn-key' solutions, none of these will deliver a new understanding of how to manage product development, beginning with an analysis of the factors which drive product development times. Ref. (81).

Successful managers should ask, what are these factors? how can they be measured? and how can they be leveraged to produce competitive advantage?

### 4.2.2 Product definition

The design process must begin with a clear understanding of what the customer needs and/or expects from the product that is to be designed. It should not be assumed that those designing the product already know the customers' requirements. The designers must know what is expected in all areas of the product, including its role, physical characteristics, and performance specifications. Customer requirements identified in this step are later translated into product characteristics. Ref. (82).

Not all of the characteristics are equally important to the customer. The key to understanding is acknowledging that the customer's view of what is important is in fact the correct view. Realizing the relative importance of each requirement is critical.

The design team should receive support from any group that has direct interface with the potential customers. Traditionally this support comes from the marketing department in the form of customer survey results and demographic information.

The purpose of translating customer requirements into product characteristics is to convert the customer requirements communicating in the previous step into the actual characteristics of the product. For example, if the customers of a telephone manufacturer say that one of their requirements is that the buttons are easy to push, the designers must be able to convert this requirement (information) into specific product characteristics such as key pad size, individual key size and shape, and spring stiffness. It is important to remember that the list of customer requirements resulting from direct customer input (surveys, interviews, etc.) may not contain all the requirements which must be considered in the development of the product. Stated a little differently, not all customer requirements are explicitly stated. The design team must ensure that all the requirements (stated or not) are translated into product characteristics. Ref. (83).

The designers then must determine the critical part characteristics and the level which best satisfies the corresponding requirements.

The introduction of Jig-less assembly to the manufacturing process will place new demands upon the engineering requirements of the product. Product definition phase will highlight the engineering changes required by the downstream use of Jig-less assembly techniques.

Product definition will take into account the customer requirements, engineering design and the key feature characteristics of the design. Ref. (84).

- Customer requirements, comprehensive list of customer needs and desires to which the product must provide and conform. Typical customer requirements for the Bathtub structure case study, see 6.1, of an aircraft would cover areas such as geometry and strength, part interchangeability or replaceability, ease of maintenance.

- Design for Jig-less assembly should have little or no impact upon the choice of customer product requirements. The customer may be internal or external to the organization. External customer may be the end-user or a maintenance company. Internal customers can be any function or department, assembly process, finishing process or example.

- Engineering design. Product defined in a digital format, 3D

- Key characteristics of the design

### 4.2.3 Product Development Process, PDP

The complexity and performance of products such as aircraft is increasing whilst the customer demands a bespoke, 'customized, product at higher quality, faster delivery at a lower life-cycle costs.

The aerospace industry has been forced to address each stage of its operation, both in business and the technical side.

Advanced complex products are intolerant for getting the product wrong and must be closely tailored to their specific product definition. Simultaneously the design process involves applications of technology for the cost effective transformation of resources to create a product that will satisfy the customer requirements as well as the product performing its function in the most efficient and economic manner.

The design and manufacturing system which produces it must also be efficient and economic in its operation within the various constraints that are imposed.

The tooling is a by-product of the company philosophy and strategy which has been involved into the conceptual and detail design stages. Due to traditional aerospace and engineering practices 'over-the-wall' practices between operational stages have produced a rigidly defined product which fulfills its primary function, but does not consider downstream manufacture, assembly and inspection. As a consequence, tooling design, jig and fixtures are designed to the final product design and not catered for at the detail product design stage.

This is evident at BAe, for the tooling philosophy publications which the tooling design office use have not been up-dated and do not take into account technical and design advancements relying upon the past experience.

Most research for product development process is focused on design process. Pahl and Beitz, Ref. (85), have divided the design process into the following four distinct phases: (1) clarification of the task and development of the design specification: (2) conceptual design: (3) embodiment design; (4) detail design.

Actual product development processes involve many people from diverse disciplines, several iterations, and many trade-off's and decisions to reach the goal of the effort. The product design is only part of a process that starts with recognition of a market opportunity and selecting a strategy, development of system requirements, generation and assessment of concepts, development of a manufacturing system, and production of the product. For best results to be achieved, many of these tasks must occur concurrently. Ref. (86). For complex, highly engineered products such as aircraft, this process takes several years and involves hundreds to thousands of people.

As global competition has increased, manufacturing firms have been forced to improve the efficiency of the development process, in addition to improving the product itself, in order to remain viable and seize market opportunities ahead of competitors.

They have done so through the establishment of multi-disciplinary product development teams (e.g. Integrated Product Teams - IPTs) and implementation of Integrated Product and Process Design (IPD).

BAe Military have addressed the Integrated Product Development with the establishment of an initiative via the Operational Efficiency Improvement (O.E.I.) group. Breaking down the product and process using cross-functional matrices flowing one into the other. Ref. (87).

The introduction of Quality Product Management (QPM) takes an approach to view the product as an object which is made of many smaller objects which the organization as a whole is responsible for. This fundamentally differs from organizational focus on functions and the tasks which they perform.

QPM consists of a series of tools; Quality Matrices, Product Diagrams, Engineering Analysis and Engineering Investigation. These are used to gather, formulate, analyse and communicate information throughout the different phases. This is important in any Concurrent Engineering philosophy and Jig-less assembly design requires these tools to communicate its requirements from design to physical assembly stage.

### 4.2.4 Quality Functional Deployment, QFD.

Quality Function Deployment (QFD) is an important tool to aid multi-functional planning and communication in a concurrent engineering product development environment and aid in the transfer of the Jig-less assembly requirements to the product and processes. QFD is a process which allows a systematic conversion of the requirements of a customer, be it an internal function or external end user, into weighted elements of a matrix. Ref. (88).

QFD is a structured planning tool which can be used to influence the incorporation of product attributes which are in agreement with the customer expectations and organisational needs. This is done by mapping out these requirements into specific design attributes through one or more matrices. The matrix or matrices are then used to define the required features of the product, identify areas of trade studies, and provide a source of documentation of a product design evolution.

QFD can be applied during each stage of the IPD phases to identify and prioritise the customer requirements and translate them into product design requirements. Hence, QFD can be used to encourage dialogue between a mixed disciplined design team.

The QFD approach used by Lucas, Ref. (89), is done by four stages, each stage output cascades into the next stage as an input:-

Stage 1: Match customer requirements against the product characteristics.

Stage 2: Match the key product characteristics against the component characteristics.

Stage 3: Matching the key component characteristics against the manufacturing system characteristics.

Stage 4: Matching the key manufacturing system characteristics against the operational control characteristics.

The product development process is often so detailed and complicated that no one individual can comprehend it all. Thus, the inexperience or lack of suitable tools to guide the team can lead to the inadequate establishment of product attributes and misunderstanding of customer requirements during the construction of a QFD matrix.

This therefore suggests jig-less assembly design rules and procedures must be proven and robust in use.

### 4.2.5 Poka Yoke

Known as a fool-proof device, Poka Yoke is an analysis method that is primarily focused on the effectiveness of processes. The aim is to maximize the probability that customer requirements will be satisfied each time the process is performed. Poka Yoke is used to achieve zero defects by analysis of the mechanisms (causes) determining the actual root (causes) so that preventive mechanisms can be tailored effectively. Jig-less assembly requires the process to be bench marked against more traditional methods of assembly. Ref. (90).

Processes should be measured to answer two important questions:-

- Is the process doing its job?
- Is the process improving?

Three types of Poka Yoka may be identified, Ref. (91).

(1) Contact type : This uses shape, dimensions or other physical properties of products to detect the contact or non-contact of particular feature and hence prevent the manufacture of defects.

(2) Constant number type : This detects errors if fixed number of movements have not been made.

(3) Performance sequence type : This defects errors if the fixed steps in sequence have not been performed or alternatively, prevents incorrect operations from being performed, thus eliminating any defects.

### 4.2.6 Failure Mode Effects Analysis, FMEA.

The FMEA is a reliability technique that documents all possible failures in a product design and determines the effect of each failure on the operation of the product design. Classification of each potential failure mode is made according to its severity, and critical single point failures are identified. QFD and FMEA are complementary as the first is targeted at satisfying customer expectations, the second at preventing failure to satisfy. FMEA is used to analyze both products and processes, hence the introduction of the terms Process FMEA and Product/Design FMEA. Therefore, the FMEA helps to prevent failures and defects in product design through a systematic approach in which causes and effects of failures are studied at the design stage. FMEA is also used in hierarchical manner particularly for the complex system which many components, where a "bottom-up" approach would be too time consuming and costly. Ref. (92).

### 4.2.7 Design for X-ability, DFX and DFMA

Design for X (DFX) represents a suite of contemporary product development techniques. They can be effectively applied in product development to achieve concurrent improvement in quality, costs, cycle times. DFX allows not only the rationalization of the products, but also the associated processes and systems. Ref. (93).

Design for X has undergone tremendous developments. One of the recent developments is the search for a basic DFX pattern, which can be used to explain how DFX works. Ref. (94).

A DFX-shell is a framework which can be extended or tailored to develop a blue print for a variety of DFX tools. The cycle starts with the first step of investigating customer requirements and establishing DFX development specifications moving on to product modelling via key product characteristics. It is envisage a Design for Jig-less Assembly (DFJA) will in time emerge and develop from this framework.

Well known DFX tools, such as Boothroyd - Dewhurst Design for Assembly (DFA), Ref. (95), Lucas Design for Assembly DFD, Ref. (96). Hitachi Assemability Evaluation Method (AEM) Ref. (97), and Design for Manufacture (DFM) Ref. (98) are well developed and proven.

Design for Manufacturing and Assembly (DFMA) is a design philosophy used when a reduction in part count, reduction in assembly time, or a simplification of subassemblies is desired. It can be used regardless of the complexity of the part or the environment, and is especially favoured when manufacturing costs are a concern. DFMA encourages concurrent engineering during product design so that the product qualities reside with both the designers and other members of the developing team.

This synergy can be understood by reviewing the advanced manufacturing processes that increase the effectiveness of DFMA. The availability of statistical process capabilities plays a key role in the DFMA process for determining the manufacturing technology to be used. Ref. (99).

With the application of DFMA, complex assemblies are converted into simple part assemblies, reducing parts count and simplifying the assembly process. The tooling design and manufacturing process can also benefit with the ultilisation of such design tools.

Design for X tools and techniques can be regarded as critical vehicles used extensively within a CE environment by IPD teams. A DFX tool blueprint for Jig-less assembly will be a requirement for a successful Jig-less assembly implementation and because of the diverse nature of jig-less assembly it will require input from many sources. Researchers and engineers have found that DFX tool implementation is not an easy task. Ref. (100). It takes the correct attitude to use it successfully and overcome all barriers created by people familiar with work under a different approach.

### 4.2.8 Key Characteristics, Datum Flow Chain and Feature Design.

In a complex product it is not economically or logistically feasible to control and/or monitor thousands of tolerances and processes. To identify what tolerances and processes to control many organisations are using a method called Key Characteristics (KC) also termed Critical Parameters and Special Characteristics. KC methods are used to identify and communicate to manufacturing where excessive variations will occur and most significantly effect product quality.

The method of Key Characteristics (KCs) is intended to focus designers on a small number of high priority aspects of a design that are of prime importance to the customer.

The method appears to have originated in the auto industry and has since spread to the aircraft and other industries. In the ideal case, KCs are defined at the top of the design process as individual characteristics of the product that define performance and function, and assure quality and safety. KCs are then "flowed down" to supporting features, parameters, and dimensions of assemblies and individual parts. This procedure is intended to create a set of defining characteristics each of which can be traced back to a top level customer deliverable. Viewed this way, KCs can be seen as an accompaniment to, or an implementation of, Quality Function Deployment and the House of Quality. Ref. (101).

Three kinds of KCs, are recognized and used for different purposes at appropriate points in the design of complex assemblies:-

- product KCs, called PKCs, define items that are of importance to the customer or to regulatory agencies; these are permanent properties of the design.
- assembly KCs, called AKCs, define important dimensional datum's, assembly mating features, and fixturing features on parts and assemblies; the AKCs are defined in the context of a particular assembly process that is intended to deliver the PKCs, including both nominal dimensions and tolerances.
- manufacturing KCs, called MKCs, are parameters of manufacturing processes that are intended to deliver the AKCs.

In order to rationalize the identification of PKCs, AKCs, MKCs, and their associated dimensions and tolerances, and to embed them in a systematic design process for assemblies, a concept called datum flow chain can be used.

A datum flow chain (DFC) defines the hierarchy of dimensional relationships between parts in an assembly. Ref. (102).

Datum flow chains express the designer's logical intent concerning how the parts are to be related to each other geometrically in order that PKCs will be delivered. Hence the DFC takes notice of the 'mates' in the assembly, which by definition carry dimensional constraint from part to part.

When defining the DFC, the designer must identify the surfaces or reference axes on the mating features which are intended to carry dimensional constraint to the mating part.

The datum flow chain must be evaluated by tolerance analysis methods, Ref. (103), in order to determine if the AKCs and top level PKCs are actually delivered, given process variability data on the MKCs. The DFC provides the input data for the tolerance analysis.

To model and simulate a design for assembly and incorporate jig-less assembly via fly-away tooling designs feature based design is used to define such analysis of a product. Feature based design is now acknowledged as a key technology for many CAD/CAM applications Ref. (104).

Using the object-oriented approach, each level in the assembly hierarchy is defined and interconnected to its associated family of inherited attributes within the structure.

The development of a formal structure for the representation of assembly information is considered to be an essential prerequisite to the generation of CAD/CAM systems that are capable of optimising product design and manufacture. Such representation can form the basis of design improvement techniques (DFA) and manufacturing planning (assembly planning). This work has demonstrated the value of an object-oriented approach which is a natural method of handling the complex relationships between the parts and sub-assemblies of an assembly. The feature representation used is one that has previously been used for process planning and process capability modelling, thus establishing the possibility of using features as an integrating agent across a number of manufacturing applications. Ref. (105).

The development of a 'Feature Library' to enable flyaway tooling has been initiated to achieve the fulfillment of objectives set by the JAM research project at Cranfield University. Ref. (106):-

- The creation of a database describing structurally integral features that will act as tooling elements during assembly.

- The analysis of the tooling features with respect to manufacturability, design effectiveness and cost.

The methodology to select features to satisfy specific assembly requirements is being developed. A primitive classification scheme for features for flyaway tooling has been set out involving, static geometrical features and dynamic, mechanical features. This forms a 'Preliminary Feature Library for Jig-less Assembly'. Ref. (107).

The features for flyaway tooling will be different from features used in Feature Based Modelling Concepts because features for flyaway tooling must be integrated into the complete process in order to design for minimum tooling. This will involve the selection of appropriate features for assembly and inspection facilitating the minimum amount of tooling, whilst incorporating design constraints and manufacturing requirements. The features act as a control role in the methodology to design for minimum tooling. The features also play an important part in the use of Error Budgeting, see 4.8.

## 4.3 Computer Aided Tools and Systems

There is general agreement that IT is the one tool which is essential to a company's survival. It is impossible to undertake CE on today's complex aerospace products without its proper use. Most companies also identify traditional CAE tools as important, typically CAD for mechanical design, structural analysis and numerical control of machine tools. Additionally, there is widespread appreciation of the value of engineering data management systems which interlink with planning and scheduling systems used during manufacture. Ref. (108).

The introduction of CAD systems has eliminated the inaccurate translation processes required previously during the transfer of the design into the manufacturing environment. The 3D digital product definition allows both part and tool designers to work directly from the exact same design information.

More importantly, the 3D solid models allow part and tool designers to visualize in three dimensions the relationship between a given part and all mating parts and/or assembly tools. CAD systems also facilitate a systems engineering perspective by allowing design engineers to rapidly access the designs of other parts of the product which may either affect or be affected by their own designs. The addition of variation modeling packages into the CAD environment will eventually enable designers to verify their designs under both nominal and variable conditions. Finally, the data from the solid models can be down-loaded directly to computer numerically controlled (CNC) machining centres for the consistent, accurate production of detail parts and to computer controlled measuring/monitoring systems.

It must be taken for granted that the jig-less assembly will require the product to be digitally defined in a CAD environment. Computer aided engineering makes a jig-less assembly strategy possible. Ref. (109).

## 4.4 Dimensional Management

Dimensional Management, (DM), is both an engineering methodology and a set of computer software tools that, if implemented correctly, is a proven process to help achieve these goals. Specifically, DM provides the ability to dramatically improve the odds of manufacturing and assembling a product correctly "the first time" to meet customer expectations. Early in the design phase of a product, the Dimensional Management process provides rapid and simultaneous communication of numerous product and process changes to the entire design and build team. The outcome is significant reduction in the impact of assembly and manufacturing variation on the overall product requirements which in turn reduces concept-to-market time, improves quality, and reduces cost. Ref. (110).

Most engineering organizations make an educated guess based on past experience using 1-D tolerance stacks as an aid in their decision. Dimensional Management demands the use of a comprehensive simulation of the product and process build to help determine an optional combination of assembly methods, fixtures, datum features and tolerances to achieve product requirements.

The goal of Dimensional Management is to improve the quality and reduce the cost of a product through development of a robust design. In other words, establish a design and process that allows for the largest amount of variation without having an adverse effect on product requirements and quality.

For a realistic simulation of the product and process build, the simulation must include the geometric effects caused by 3-D geometry, assembly sequence, assembly methods (i.e., bolt to hole clearances, fixtures, clamping variation, etc.), individual part manufacturing variation, and any potential "variation noise" that might also occur during build (i.e., weld distortion, bending, gravity effects, or torque effects.). During the early design phase of a product the simulation model would include 3-D Geometry, proposed Geometric Dimensioning and Tolerancing schemes (GD&T), assembly methods and sequence, and the measurements or product requirements. The simulation model statistically predicts, based on the proposed tolerance, datum, fixture, locating, and assembly method scheme, how much variation will occur for each product's dimensional requirement. A statistical ranking identifying the variation contributors causing the product requirement variation is also an outcome of the analysis. This information provides the engineer with a tool to help optimize the design and process to meet the overall build objectives. Ref.(111).

The benefits of this step in the Dimensional Management process include early confirmation that the design and process as specified meets product requirements, prediction of the amount and causes of the variation, and a decreased need for prototype builds, reducing concept-to-market time and cost. A complete model is now in place to fully comprehend the "design intent" product and process build.

The major 3-D CAD companies are aggressively pursuing the ability to fully define and version control complete product and process models including tolerances linked to functional features, assembly sequence, assembly methods that reflect real life conditions, and links to CMM measurement programs. There are also commercially available variation simulation analysis packages directly embedded with these new product and process modeling systems. However, the software tools in this area are still in their infancy and will continue to be enhanced over the next several years.

## 4.5 In-Process Monitoring & Gaugeless Tooling

A significant element in the pursuit of a jig-less assembly will be the use of in-process monitoring of the assembly process in real time, thus providing feedback loop within the assembly cycle.

Ideally, in-process measurement should involve continuous real-time measurements of part attributes that define part quality. This provides the maximum leeway in making system adjustments to compensate for undesirable product attributes. However, this technique is often difficult to implement due to environmental restrictions and inaccessibility of surfaces. Also, the cost of setting up such systems can be significant since a good deal of customization is usually necessary for each specific application. Sensors are a key component of in-process measuring systems. They are usually involved in three generic types of monitoring applications. Ref. (112).

(i) Production monitoring, where sensors determine the status of operation on the production floor. Information pertaining to work-in-progress, rejection rates, machine productivity, etc., is gathered by means of sensors, both for component accuracy and rates of progress.

(ii) Machine monitoring, where sensors provide data relating to the status of the process leading to process adjustments or maintenance. In this role, sensors are employed to increase the quality performance of production.

(iii) Environmental monitoring, where information concerning the condition of an area is recorded by the sensors.

In general, sensors are used to detect the presence/absence position condition or identity of an object. Position sensors are utilized to measure the dimensional characteristics of an object. Typical quality applications involving position sensors include measurement of workpiece shape, size and provide location feedback information for machine control systems. Some commonly used position sensors include rotary encoders, linear scales, interferometers, linear variable differential transformers (LVDTs), ultrasonic and pneumatic sensors and touch-trigger probes. Condition sensors are used to gather information about the status of an operation and are often used for real-time monitoring of machines. Vibration sensors, accelerometers, load sensors temperature sensors are all examples of condition sensors. Ref. (113).

Amongst the other methodologies available to consider are the non-contact types developed within the aerospace industry to eliminate the master tooling used for the variation of production tooling, such as Laser Interferometry for large scale dimensional measurement.

The building and running costs of the traditional hard tooling systems has been recognized as technically and commercially unsuitable for the production of future projects. Ref. (114).

Technological advances have now provided an alternative to the static site. Using a non-contact measuring system also referred to as Gaugeless Tooling, can provide flexible real time, 3D-data collection capabilities. Which when integrated with the CAD/CAM data set enables manufacturing to build and maintain production tooling. Also there is the possibility of using such ideas and techniques to monitor the assembly process itself: in-process inspection. Although a well-developed strategy would need to be used such inspection can become a ‘bottleneck’ in the manufacturing process.

There are a number of non-contact measuring systems available.

- Photogrammetry
- Theodolites
- Laser Interferometers
- Co-ordinate measuring machines (CMM) (Contact)

These use various measurement techniques and there are a variety of devices available on the market which makes the choice of system for a particular task difficult. The Optical Metrology Centre at City University, London is part of the JAM project, studying measurement systems for Jig-less Assembly. Ref. (115).

## 4.6 Manufacturing Process Selection

Jig-Less assembly will undoubtedly require higher precision initial assembly and therefore associative improvement in component quality. Selecting the appropriate manufacturing process will become increasingly critical with the requirement to use more capable manufacturing processes. The first step in selecting the appropriate processes is to ascertain if current processes are capable of meeting the tolerances required by the assembly in question. Process capability audits will be required on the initial short listed alternatives, statistical analysis carried out, Ref. (116), with an assessment with regards to the associated issues of the product and its specification. The manufacturing engineering organization will have to pay particular attention to factory capacity issues created as detail parts destined for precision assembly processes are shifted from less capable to more capable machines.

If existing manufacturing processes are not capable of meeting the required tolerances, or if the factory does not currently have the required capacity on its most capable machines, the problem becomes a bit more challenging. The manufacturing organization should then perform a trade-off study between alternative courses of action: developing a plan on how to either acquire the required capability, or redefining the jig-less assembly requirement.

## 4.7 Flyaway Tooling

A derivative of Jig-Less Assembly, Flyaway Tooling describes the process of design and construction of structurally integrated features applied to mating components within an assembly. These aids to assembly become part of the component design, eliminating the need for external assembly tooling. As the name implies this tooling remains with the assembly which can also aid dis-assembly as well as re-assembly for rebuild or maintenance requirements. These attachments or feature may take the form of structurally or non- structural elements, main function used as a guide during the assembly process together with the structural elements provide local support within the assembly. Non- structural elements requiring support to the assembly via limited external fixturing. Ref. (117).

To support and aid in the design of integral flyaway tooling attachments, features, the use of feature based design incorporating Product Key Characteristics, PKC`s, Datum Flow Chain and Error Budgeting analysis modelling via a digital 3D format will be required. Ref. (118).

## 4.8 Error Budgeting

Error Budgeting is a technique used for analysis at the design stage to predict the total error of a mechanical system. The error budget is based on the behaviour of individual components of the assembly as well as their interactions with other components. Since no assembly is perfect, an error exists in determination of the location of the components to each other and the specified datum and thus to any tooling present. The error budget is concerned with determining the effect of system variations on the assembly components. Working backwards from the target error for the completed assembly it will be possible to predict the degree of difficulty in achieving the total error budget. The error budget should contain as many of the sources of error as possible. Ref. (119).

To use an error budget, two tasks must be undertaken, namely, to determine the sources of error within the assembly and its environment, and determine how those sources of error combine to effect the assembly overall. The use of the error budget has the potential to provide to the design function:-

- trade-offs at the Concept Stage.
- comparison of configurations at design stage.
- setting limits at the detail design stage.
- identification of sources of error, geometric, thermal, dynamic, static and dimensional.

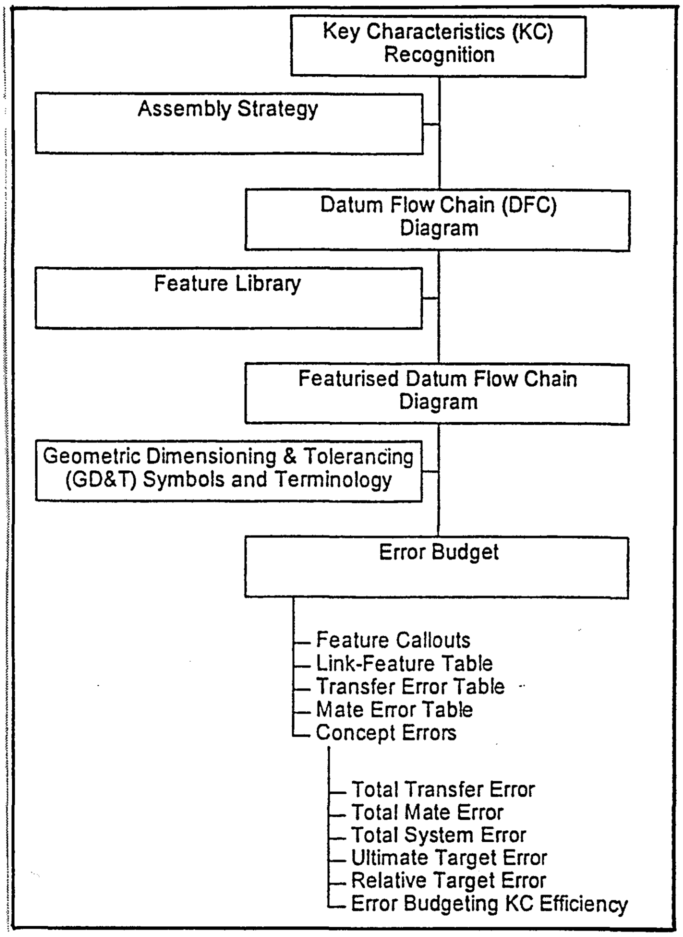


**Figure 4.8.1 Error Budgeting Flow Chart**

The potential for developing error budgeting from a two dimensional tool into three dimensional methodology, volumetric error budgeting is under development and proposed as a useful technique for jig-less manufacture. Ref. (120). Error budgeting is also being considered in partnership with a combined use of Geometric Dimensioning and Tolerancing, (GD&T), Ref. (121), and feature library see Figure 4.8.1.

The challenge for Error Budgeting with regards to its application to jig-less assembly will be with its ability to integrate successfully with its required inputs, KC, DFC and GD&T, and thereby provide, output, a robust design technique to be used by the product and manufacturing design functions.

## 4.9 Aircraft Development and Production

During the early years of aircraft production until about 1930, wing and fuselage structures were made from the composites of the day, woods spruce, balsa, and ash with plywood or fabric covering which provided good weight-to-strength ratio. The development of high tensile steels and aluminum alloys led to more sophisticated designs which could be assembled and accurately located, then welded or riveted, in precision jigs. The first fully-machined aluminum alloy tapered wing spars were made in 1935 for the all-metal short "Empire" and "Sunderland" flying boats.

From 1950, with the availability of jet engines, there were major increases in the speed of aircraft and consequential safety problems resulting from metal fatigue. Due to this, pushing back of the technological boundaries bought about a new era of air travel led by British aerospace industries in the form of the ground breaking de Havilland Comet airliner.

Catastrophic failures consequently provided hard earned lessons in material behaviour and also a reminder of project risk when introducing advanced technology. Loss of confidence in such a high profile venture together with subsequent development led to Boeing aircraft company gaining the initiative and the demise of the British aircraft industry as total single manufacturer of a mass market airliner. The concept of fail-safe designs and fatigue resisting materials led to welding and bonding techniques for the elimination of stress concentrations. Chemical etching was developed for the removal of bulk material in areas where it was not required.

The advent of more computer power and the development of Finite Element Modelling (FEM) techniques brought with them significant improvement in structural optimization capability. In order to take full advantage of these developments a radical change in manufacturing methods was required .

Aircraft designed during the period 1950 to 1970 introduced honeycomb-sandwich construction, machined wing surfaces and other parts from aluminium alloy plate, and the adhesive bonding of stringers to fuselage skins.

Soaring production costs and severe inflation since 1970 have demanded research into better quality materials, improved specifications, product design and production methods sympathetic with each other.

Innovations in machining, shaping, cutting and drilling aided by computer controlled machine tools, together with an extensive use of complex aluminium alloy forgings or castings have eliminated the need for large numbers of rivets and fastenings.

At the same time precision forgings and castings, which are produced by modern equipment, require very little machining and are specified with those tolerances and dimensions near to the final shape. The next phase in commercial aircraft which has already found favor in military applications is the use of carbon fibre composites, their derivatives and hybrid combinations. These materials have yet to be proven within mainstream application in a robust environment together with the cost implications, which have yet to be justified. The next step change generation of commercial aircraft will undoubtedly require the properties of these materials in order to make the designs a reality.

With the final amalgamation of the British aerospace industries in 1970 with additions occurring up to 1981, British Aerospace plc (BAe), was a fragmented organization spread over several sites throughout the world.

British Aerospace as a company includes the Military Aircraft Division (MAD), designing developing, manufacturing and supporting a range of combat and training aircraft such as the Harrier and Tornado. The commercial side of BAe is involved mainly with European airliner business.

BAe has developed due to the rapid and unprecedented change in the demand of today's global markets. It has become a major engineering facility and engineering group, and a clear migration can be seen from low technology products and manufacturing processes towards high-end technology products and manufacturing processes. Although British Aerospace ancestry can be recognized in the wing design of today's BAe Airbus, Filton, the design can be traced back to de Havilland designs at Hatfield, during the 1950's in the Comet airliner. Because of the complexity of modern aircraft, and resulting scale of associated costs and investment required, calibration of design and production has become essential between manufacturers.

BAe is part of the European Consortium, Airbus Industrie, see fig. 4.9.1. In thirty years, Airbus Industrie has grown from zero to take 30% share of the world market for major commercial airliners, with its family of Airbus airliners incorporating ten types, ranging from 120 to over 400 seats. British Aerospace, BAe Airbus, is responsible for design and manufacturer of the wings. Future projects in which ideas and technologies are being developed including Jig-less Assembly for the next generation airliner, Airbus A3XX.


**Figure 4.9.1 Airbus A310**

Another major research and development project in which BAe is associated with is a European consortium to develop the Eurofighter, multi-role tactical military platform for the defense industry. BAe military have taken advantage of the lower commercial risk in terms of public transport requirements and are utilizing the latest technologies in design, and manufacture. Many jig-less ideas and enabling technologies are being tried and tested within the Eurofighter programme.

Two special cases which have been recognised as being significant for the Jig-less tooling for the assembly of modern aircraft, by the author, is the design, development and construction of the WWII de Havilland Mosquito fighter bomber, 1939, Ref. (122), see appendix B, and the principle and application of the Fairey Aviation Envelope Tooling System, 1945, Ref. (123), see appendix E.

These case study examples address two primary aircraft product functions, external profile accuracy and interchangeability.They have a direct influence upon the life cycle costs, aerodynamic profile accuracy, attainment of best-fit of the external contour surfaces which directly influence the performance of the aircraft in flight in terms of drag, thereby effecting the speed and fuel consumption. The attainment of interchangability of the components which make up the surface is required to meet repair and maintenance requirements through the use of in the field spares back up. These two functions tend to be inversely proportional to each other, e.g. with high accuracy in the panel fit reducing steps and gaps with adjacent panels. This consequently produces components with a low interchangeable factor and vice versa.

These two cases together demonstrate that initially determining the primary datum as the function of the external surface, profile, and then adopting a reverse construction process, outside to inside, design specifications are more likely to be achieved.

The second world war, WWII, brought much change and innovation which transposed itself into very short project development cycles.

The de Havilland Mosquito was the first modern aircraft with an all wood construction to go into RAF service. The choice of construction material, wood, because of the prevailing circumstances, surprisingly led to positive effects to the product performance and the manufacturing system. The primary product functions were met and exceeded, with the light-strong construction especially suited to high speeds because all surfaces are smooth, free from rivets. Overlapped plates, steps and gaps between panels and undulations also lends itself to too very rapid initial and subsequent production. The Mosquito's fuselage is made in halves by stretching two skins of birch plywood over concrete moulds remains unique in a mass produced aircraft construction. Echoes of the past can be seen in today's modern aircraft like the Eurofighter, split cockpit construction, Ref. (124), see figure 4.9.2.

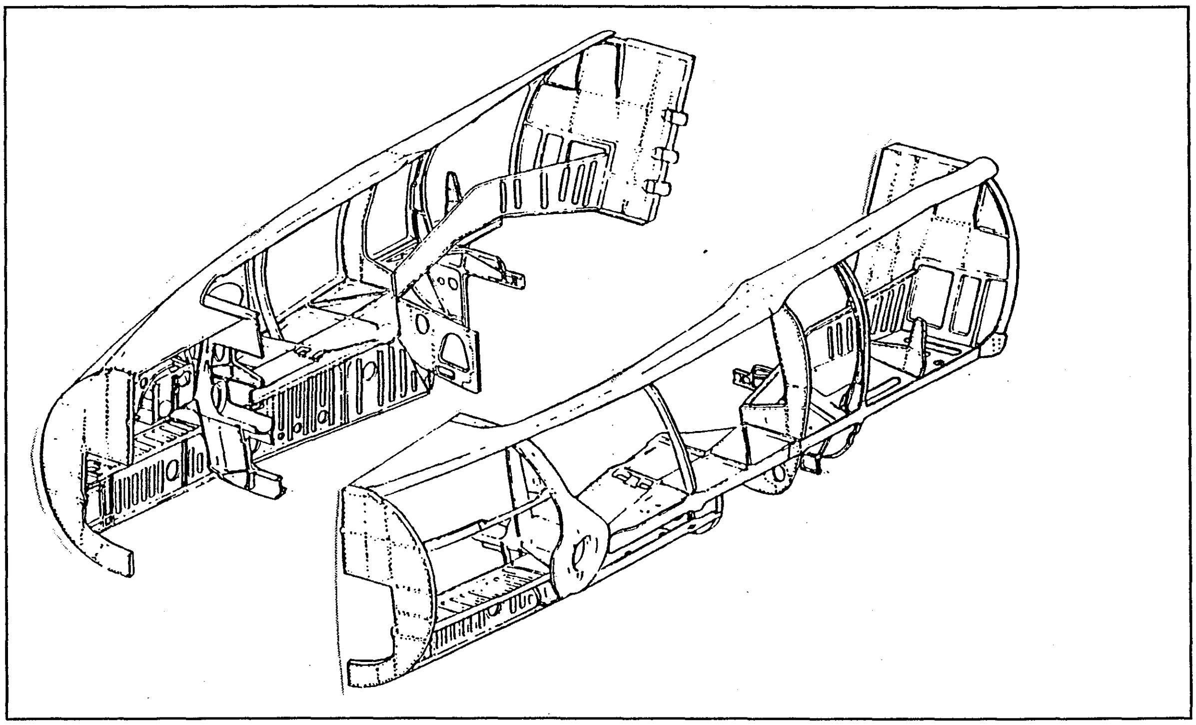

**Figure 4.9.2 Eurofighter 'split' Cockpit Assembly.**

Lessons can be learnt from yesteryear's ideas and techniques, improved upon and integrated into today's enabling methodologies to aid in the development of the Jig-less assembly for modern aircraft manufacture.

Envelope tooling will be used and developed within the enabling techniques for Jig-less tooling.

## 4.10 Aerospace Current Industrial Practice

Commercial demands have forced the major aerospace manufactures to address their costs and quality. Boeing Aircraft Company along with Airbus Industries, Short Bothers and others moved towards using various tools and techniques which will be used within a jig-less assembly environment.

The Boeing 777 commercial transport represents an attempt to produce an evolutionary aircraft. Market demand sized, shaped, and launched the newest member of the Boeing family. In creating the 777, Boeing used fundamentally new approaches to designing and building an airplane. The 777 program established design/build teams (DBTs) to develop each element of the airplane's airframe and systems.

Under this approach, all of the different specialties involved in airplane development - designers, manufacturing representatives, tooling, engineers, finance specialists, suppliers, and customers worked jointly to create the airplane's parts and systems. Collocated team members work concurrently, sharing their knowledge rather than just applying their skills sequentially. Ref. (125).

Since all affected disciplines were involved, problems were resolved early in the process, long before they reached the production phase. Digital mockups and digital preassembly helped design/build teams integrate all systems and components and check for interference's.

The 777 was the first product in its class to use 100% digital product definition (DPD). DPD means that all of the geometric definitions of parts and tools are incorporated in a digital dataset and secured in a database as the sole authority definition.

The use of 100% DPD allowed the 777 program to also use 100% digital preassembly and eliminate the need for physical mockups. The traditional product development approach at Boeing relied on physical mockups to validate design integration and to define parts that were difficult to accurately define on 2D drawings.

The 3D solids that were created for DPD were used in a computer simulation of the assembly of the airplane referred to as digital preassembly (DPA). DPA was used to make sure that the parts and tools fit together and could be assembled before the datasets were released for production. The 3D solids were created in progressively more accurate levels of definition corresponding to the requirements of the design stages.

The CATIA CAD/CAM system along with Boeing-developed software was used to support the requirements of DPD and DPA.

Hardware variability control (HVC) is a process that emphasizes variation reduction of key areas of parts and assemblies to improve airplane-level performance targets for shape, fit, appearance, service life, and safety. HVC begins with the identification of top-level key characteristics, like wing sweep, related to airplane-level performance. The top-level key characteristics are flowed down through the assembly breakdown of the airplane to the detail part level. Ref. (126).

Statistical analysis is conducted to optimize key characteristic tolerance specification considering manufacturing process control capability in support of the airplane-level performance targets. A statistical process control plan is then developed for each of these key detail part and assembly characteristics to continuously improve the quality of the critical airplane performance items.

The combined result of these product definition process initiatives was remarkable. Change, error, and rework were reduced by more than 60% compared with previous best efforts.

Assembly quality was dramatically improved over that of previous models. The body was in alignment within 0.040 inch over a length of 150 feet.

Another example of current practice within aerospace is BAe Military Eurofighter, as one member of the multi-partnership for the European combat aircraft, BAe Military it is responsible for the final assembly of the fighter aircraft.

Eurofighter's production engineering team has put into practice a host of new ideas for the manufacture of the fighter aircraft to reduce assembly tooling and increase flexibility in the manufacturing system, see appendix A(ii). These include:-

- Integrated product teams, its members representing a variety of specialised functions.
- Use of master CAD/CAM digital model throughout the design and manufacture phases.
- DFM/A implemented on components design.
- Extensive use of simulation and analysis in design process, including full clash detection and effects of tolerance accumulation and identification of critical features of the design.
- Highly accurate ICY machining stations, to drill body panels.
- Hole-to-hole techniques, between components and sub-assemblies.
- Flexible assembly area, to accommodate model changes.
- Use of low cost aluminium modular tooling, involves the construction of an aluminium profile frame combined with sets of pick-ups consisting of tubes and aluminium blocks that allow the parts actually holding the aircraft to be moved through six degrees of freedom.
- Modular assembly floor, false floor matrix up from cast plinths, designed to house the assembly equipment serviced from below the floor. Allows dismantling and repositioned in minutes with no need for recalibration.
- Split cockpit design to aid assembly process, see figure 4.9.2.
- Use of accurate one-piece components produced by super-plastic forming (SPF) process, thereby reducing the part count and the requirement for additional machining.

## 4.11 Non-Aerospace Industrial Practice

Outside of the aerospace industry some examples of assembly tool rationalization can be found. The marine industry, ship building and the automobile industry have the same commercial drivers to respond to.

You might have trouble finding a tape measure at the Vosper Thornycroft shipyard. For the company has abandoned using them and chalk to mark up steel plate for work such as the welding on of stiffeners. Now it marks up the plate by carbon dioxide laser. The accuracy of the laser has reduced mistakes and reworking costs substantially.

Vosper Thornycroft can now cut by laser 15mm-thick mild steel plate at 700mm/minute and 8mm-thick stainless steel at 1m/minute. The accuracy and cleanness of laser cuts means ship parts slot together with interference fits that allow high-quality welding. The company also laser cuts rather than drills all circular holes larger than 3mm in diameter and 4mm thick aluminium at 1m/minute. Everything from the CAD system straight on to the laser. Ref.(127). The CAD design is downloaded directly into the CAM system controlling the laser system. The resulting parts can be assembled faster, fixed with smaller welds than alternative methods. The laser system allows the product and build assembly method of easy slot together box construction, see figure 4.11.1. With less costly corrective work the possibility to automate becomes a reality.

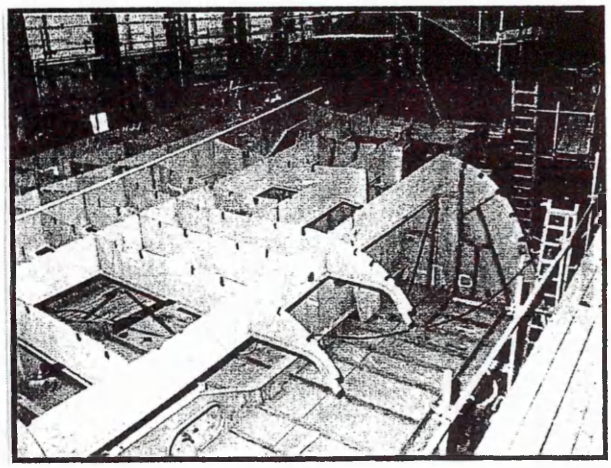

**Figure 4.11.1 Slot and Weld Box Construction**

The Nippondenso Co., Ltd., (NDCL) is Japan's foremost manufacturer of automotive components. It has rationalized the manufacture of its car radiators, by reducing the assembly tooling, see figure 4.11.2.

In a conventional radiator factory, the radiators are carried around in fixtures that hang from an overhead conveyor. The fixtures hold several metal items together, these are the core, two end plates, and two headers. The cores are quite springy and would pop apart if not securely held by the fixtures.

The parts are soldered together in a large oven, through which the conveyor travels. Then the radiators are removed from the fixtures and placed in a crimping machine where the plastic inlet and outlet tanks are crimped securely into place. Typically this is done with a large press die that is shaped to conform to the tank. When a new type radiator is to be made, the factory must switch over.

A lot of time is lost while one kind of fixture and press die is exchanged for another. Possibly hundreds of fixtures are involved in the switch.

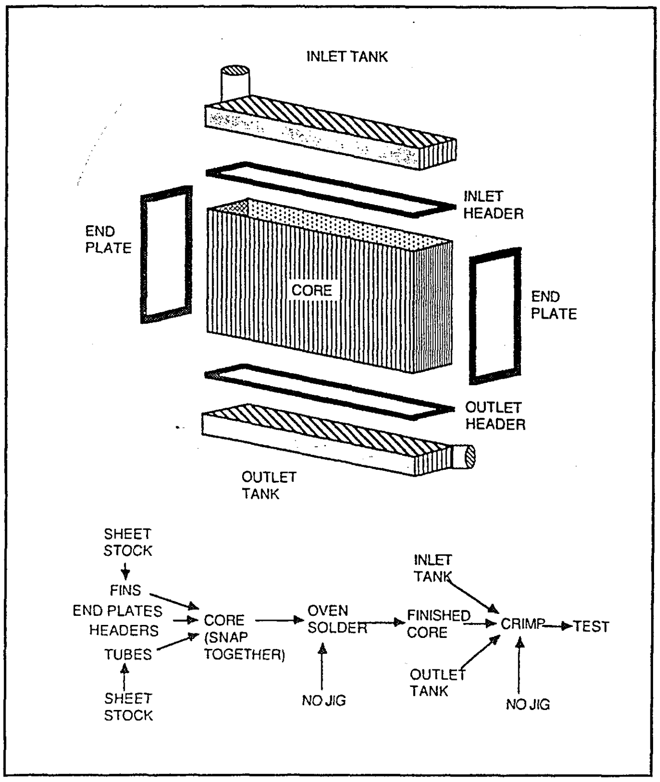


**Figure 4.11.2 Jig-Less Radiator**

The radiator is made by cutting and folding arbitrary lengths of flat brass stock, snapping them together to make a core, and oven-soldering the core into a rigid structure. Top and bottom tanks are added by a self-configuring crimping press. The use of arbitrary stock lengths, the snap-together core design, and the self-configuring press together permit one of a kind production in terms of jig-less assembly there are no fixtures. Ref. (128).

# Chapter 5

## DESIGN FOR JIG-LESS ASSEMBLY, DFJA

### 5.1 Introduction

Jig-Less Assembly Concept (JAC) does not consist of any one technology or technique, but a suit of technologies and tools coordinated and managed in a specific way. Ref.(129).

Any one element within the manufacturing system is as important as the next. Each element within the design philosophy including the use of 'soft' tools such as DFA or Poke Yoke, to the 'hard' tools used in the manufacture and assembly stage such as, component dimension variability and in-process assembly inspection will impact upon each other. Therefore, each phase must be able to dovetail within its system and be robust in operation.

The data and information contained within this chapter was collected as discussed in section 1.4 the sources included a literature survey, industrial visits and general research training and university courses.

Two major hierarchy categories have emerged which form the jig-less assembly system:

- The foundations which contain the fundamental sciences and technologies which require identification understanding and controlling. This is in-line with general good engineering practice through the evolution process.

- The secondary group include specific tools and techniques introduced at a specific stage with the manufacturing system which are able to take on a particular role or task these will normally replace the functions currently carried out by the existing assembly tooling, see 3.3.

For implementation of a jig-less assembly to take place support by enabling technologies and thereby to orchestrate the House-of-JAC, see 2.2, fundamentals need to be addressed and firm foundations laid for these enabling technologies to perform as required.

## 5.2 Foundations for Jig-Less Assembly Implementation.

The main requirement that needs to be in place for a jig-less assembly environment to be sustainable is the construction of a suitable science based foundation to which a environment can develop in which suitably matched enabling techniques can operate. Chapter 4 covers some identified critical elements of jig-less tooling system.

Several definite areas which make up the foundations include:-

- Structural stress analysis
- Dynamics
- Kinematics
- Material science
- Error, cause and effect identification and analysis
- Thermodynamics
- Mechanics
- Computer Science

The 'House-of-JAC', figure 2.2.1, shows the basic foundations which support the building works technologies and techniques, to enable Jig-less assembly to operate.

Understanding of the fundamental behaviour of the system will be required, as the physical classic tooling is removed it is envisaged that the tools and techniques used to replace the original system, will require a step change in their precision and repeatability capabilities.

## 5.3 Enabling Technologies, Potential Jig-less Techniques.

Technology plays the key role in enabling the jig-less assembly process. Enabling Technology is a term used to collectively describe a technique or methodology which may be ultilised individually or in combination to perform a task or activity to realise the Jig-less Assembly Concept.

No one technology or technique can be used in isolation to achieve a suitable jig-less assembly system. Any one technique must be capable and meet the transfer function requirement for the relevant assembly tooling element, see 3.2.

The right choice of technique or process used at the right time in a concurrent engineering manner will provide a key and supportive framework. It can provide a common view of the product and process design to enable parallel design and integrated design of products and processes. Design information can be captured in a manner that more effectively drives downstream manufacturing processes. Design iterations and lead times can be reduced together with enhanced designs through computer-based analysis and simulation rather than physically building and testing prototypes. Product design information can be used more readily to create process design data and drive to downstream production processes. Tooling design can start at an earlier stage and be more adventurous reducing the associated risks at the development phase.

The principle areas of interest and techniques which have been identified which have potential in filling a role and able to make a contribution to the Jig-less assembly system have been listed.. The list is organic in nature, its contents changing constantly as each entry demonstrates its contribution to Jig-Less assembly in a robust environment.

- Development of a stable, good engineering practice, manufacturing environment
- Design philosophy
- Design process and procedures
- Design tools such as DFMA, FEA and QFD.
- Manufacturing process selection
- Manufacturing process capability
- Material selection
- Material primary and secondary process selection
- Assembly process selection and planning
- Assembly analysis
- Computer aided engineering, CAD/CAM
- Metrology - Inspection, In-process measurement.
- Dimensional management
- Joining/fastening technology
- Component and assembly variation analysis

With use and development the potential enabling technologies and techniques which have been listed will prove their worth and the measure of their value to the overall system. Various combinations is thought to be a key outcome of Jig-less assembly for particular industries and products, therefore, a generic system my not be as successful as a tailored system.

The identified potential Jig-less assembly enabling techniques which fall under the hierarchical scheme of science, technologies and techniques have also been categorised into three main groups, plus an example of how a combination of technologies and techniques may be used;

- Mature techniques
- Developing techniques
- 'Blue-sky' techniques
- Combined techniques.

### 5.3.1 Mature and developing techniques

These two groups contain technologies and techniques which are seen as providing the greatest potential to become enabling techniques for a jig-less assembly system.

The mature techniques are those already robust and proven in their role or ones which are used more predominantly in other industries but which could be easily transferred to the jig-less assembly system.

Developing techniques are the ideas and techniques which require proving in a robust environment and also may require further development to be proven as a technique in itself.

Every technology or technique carries a technical and, therefore, cost risk element. Mature and developing techniques respectfully carried appropriate low, medium to high risks. When constructing and manufacturing an assembly strategy, these elements must be taken into account to justify such a programme.

The following ideas, technologies and techniques are listed with no comparative weighting against each other as with only implementation and use can the level of success be judged. The criteria used for the selection of the following was made against those recognised as having made progress, and those having the required potential, to fulfill the role of the feedback loop, see 3.2, in the assembly control system. Also those able to allow the transfer of the assembly tooling functions inherent in the existing tooling and those which will integrate within the Jig-Less Entity Relationship Blueprint, see figure 5.4.1., the proposed design for jig-less assembly, DFJA, implementation system, see 5.4.

| | | |
|---|---|---|
| 5.3.1.1 | Integral Attachment Flyaway Tooling (feature library) - | Ref. (130) |
| 5.3.1.2 | Digital Assembly Modelling - | Ref. (131) |
| 5.3.1.3 | CAE, CAD/CAM Integration - | Ref. (132) |
| 5.3.1.4 | Process Control, SPC - | Ref. (133) |
| 5.3.1.5 | Non-Contact Measurement - | Ref. (134) |
| 5.3.1.6 | Key Characteristic Identification and Selection - | Ref. (135) |
| 5.3.1.7 | Computer Aided Tolerancing - | Ref. (136) |
| 5.3.1.8 | Error Detection and Compensation - | Ref. (137) |

| | | |
|---|---|---|
| 5.3.1.9 | Assembly Strategy Selection, rigid and part - | Ref. (138) |
| 5.3.1.10 | Assembly Strategy Selection, compliant part - | Ref. (139) |
| 5.3.1.11 | Structural Behaviour Analysis - | Ref. (140) |
| 5.3.1.12 | Memory material couplings - | Ref. (141) |
| 5.3.1.13 | Framing assembly techniques - | Ref. (142) |
| 5.3.1.14 | Fastening optimization - | Ref. (143) |
| 5.3.1.15 | Assembly condition monitoring - | Ref. (144) |
| 5.3.1.16 | Optimization of assembly planning - | Ref. (145) |
| 5.3.1.17 | Assembly, real-time, behaviour measurement & Compensation - | Ref. (146) |
| 5.3.1.18 | Dimensional management, tolerancing optimization | Ref. (147) |
| 5.3.1.19 | Rapid tooling, prototyping - | Ref. (148) |
| 5.3.1.20 | Error budgeting, volumetric - | Ref. (149) |
| 5.3.1.21 | Thermal assembly environment controls & compensation - | Ref. (150) |
| 5.3.1.22 | Adhesive fastening - | Ref. (151) |
| 5.3.1.23 | Composite material molding - | Ref. (152) |
| 5.3.1.24 | Advance manufacturing technologies - | Ref. (153) |
| 5.3.1.25 | Advance welding techniques - | Ref. (154) |
| 5.3.1.26 | Concurrent Engineering design tools - | Ref. (155) |
| 5.3.1.27 | Flexible fixture framing system - | Ref. (156) |
| 5.3.1.28 | Compliant fasteners - | Ref. (157) |
| 5.3.1.29 | Reconfigurable tooling system, large scale - | Ref. (158) |
| | small scale - | Ref. (159) |
| 5.3.1.30 | Robotic fixtureless assembly - | Ref. (160) |
| 5.3.1.31 | Kinematic location and restraint analysis - | Ref. (161) |

## 5.3.2 'Blue-Sky' Concepts and Techniques

'Blue-Sky' ideas, concepts and techniques are those which are very much in the future, alternative design and process concepts which are high risk but could provide high returns in providing a rationalized, flexible tooling system. These are discussed below.

### (i) Box, egg-box, design and build.

This concept involves building a wing from a series of stiff boxes that locate to each other in a modular format. During construction, the structure is cantilevered from a wing root plug and the assembly process is similar to that of a sectional road bridge, figure 5.3.2.1. Ref. (162). The components which make up the box can be slotted together, temporary fixed by the use of inter linked male and female draught angles, before the box completion or secondary fastening process, such as welding takes place. Ref. (163).

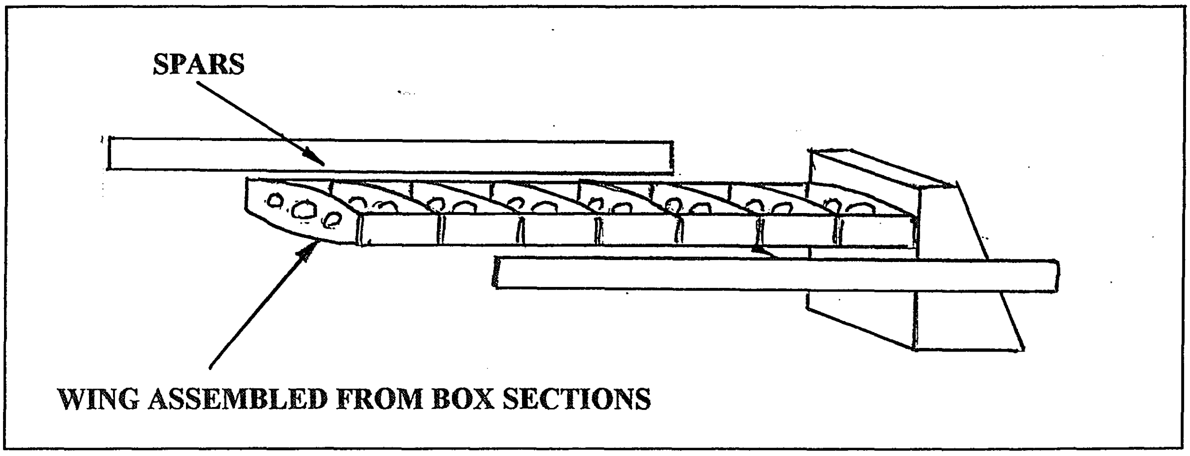


**Figure 5.3.2.1** **Box design**

### (ii) Integrated Tooling - (flyaway derivative) multi-functional design features.

Structures often have features that may be utilized to perform multi-functional tasks. Primary task to carry fuel, as in the fuel pipe runs, secondary function maybe used as an assembly locator. This will provide a common datum and hold the internal components together before the external components are fitted, thereby eliminating specific external assembly tooling, see figure 5.3.2.2., Ref.(164).

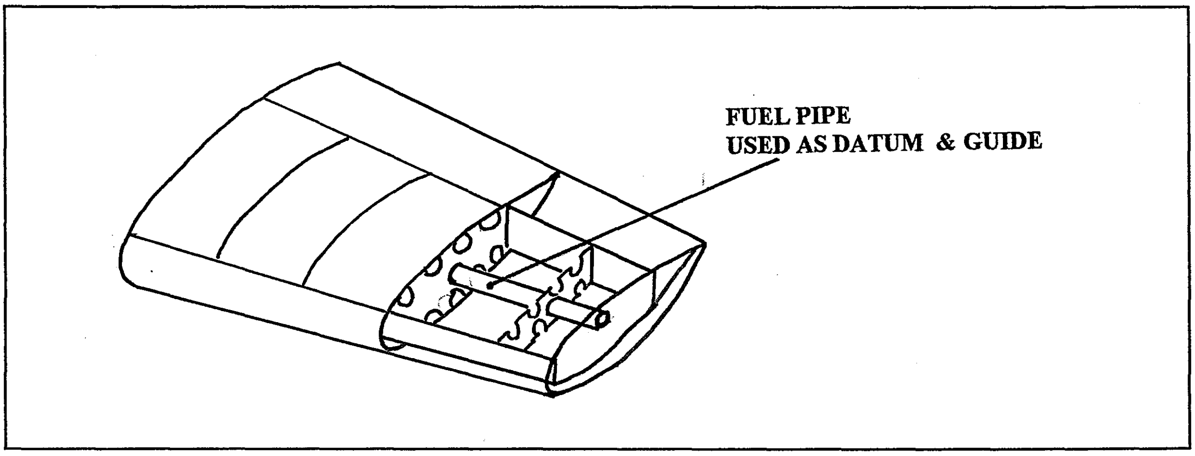


**Figure 5.3.2.2 Integrated Tooling - Wing Box Components**

### (iii) Integral guide springs and 'snap-fits' attachment.

The use of internal compliant 'spring' guides attached to the assembly component these act as guides during the assembly process. Their secondary function is that of a temporary snap-fit fastener giving local support and location before a more permanent fastening system is utilized, see figure 5.3.2.3. Ref.(165).

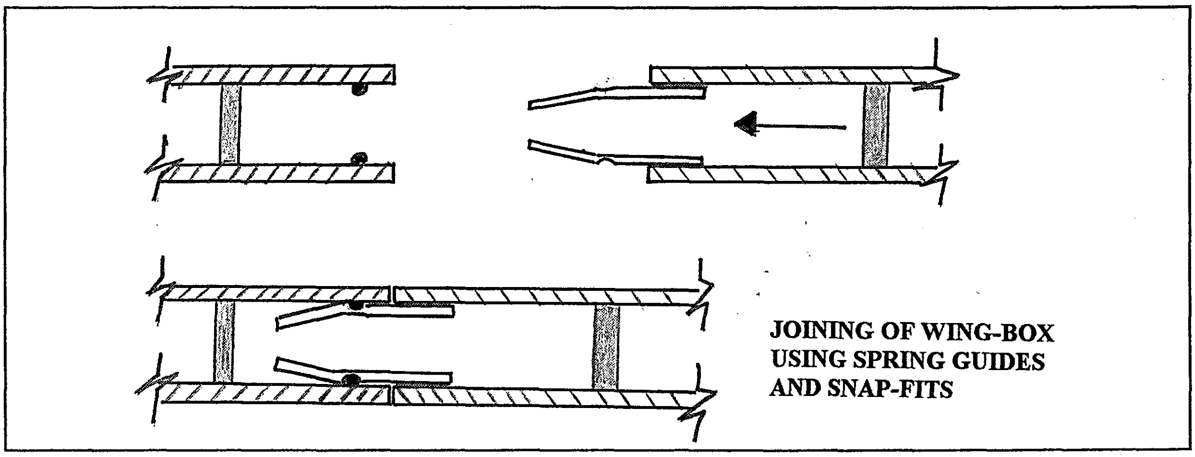


**Figure 5.3.2.3 Guide Spring & Snap-fit Attachment.**

### (iv) All welded construction.

An all welded structure has the advantages of weight saving and part reduction. The fasteners and associated tooling is eliminated. The welding process can be automated, see figure 5.3.2.4, and can compensate for slight miss match between parts with weld material. There can be inherent problems with distortion and residual stresses in the welding process, the technology especially via 'stick' welding where these issues are being overcome. Ref. (166).

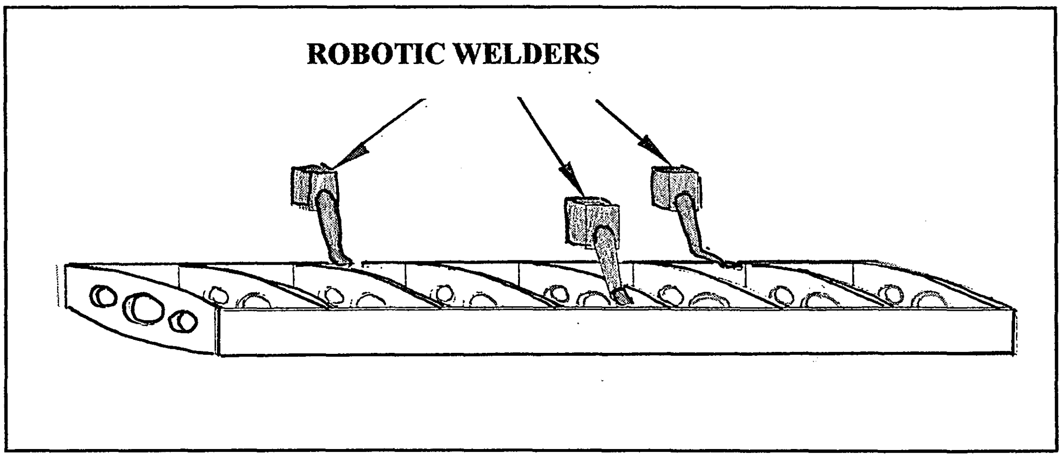


**Figure 5.3.2.4** **All Welded Construction**

## (v) Multi-pin Reconfigurable Tooling

The development of a reconfigurable tooling system for the manufacture of complex aircraft parts. This 'discrete' die system was a series of pins with hemispheric ends that are positioned by computer control. The pins array themselves into the shape of the desired sheet metal component. Changing the configuration of the pins allows quick tool reshaping to build a different part or to correct the part shape. A polymer blanket between the pins and the metal prevents dimpling during sheet-forming operations, see fig. 5.3.2.5. Ref. (167).

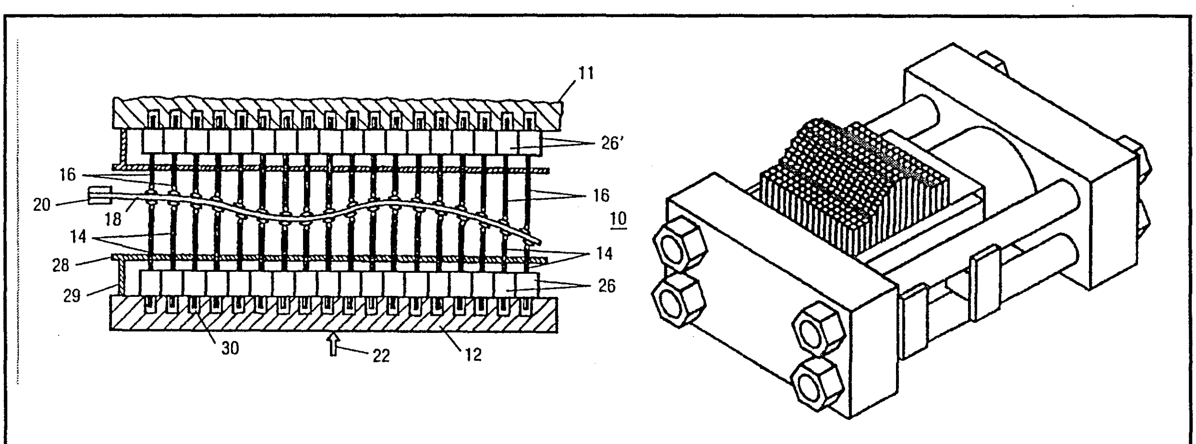


**Figure 5.3.2.5** **Multi-pin Reconfigurable Tooling**

These discrete dies have been developed over some time, Ref. (168) being used for smaller components that require high forces to deform the sheet material.

Expanding this idea larger size for the use in a flexible tool mould the pins are arranged to create any form for moulding, carbon fibre composite lay-up. When the moulding process is complete both the pins and the covering sheet can be reset to form a flat surface, so the mould is not only precise but re-usable.

### (vi) Envelope Tooling.

This application, developed by the Fairey Aviation Co., in the 1950's takes the philosophy of constructing the aircraft from the all important outer profile. Due to the stringent requirements for skin-smoothness, panel steps and gaps, the need to control the assembly of certain airframe components from the outer skin inwards towards the centre, see figure 5.3.2.6 and appendix E.

The name refers to the aerodynamic form or envelope of the aircraft upon which the system is based. Envelope Tooling Systems use a type of jig consisting of a template accurately shaped to the external form of a portion of the aircraft and supported by a series of formers erected at intervals along a rigid base. The airframe unit is built up on the template, drilled through from the outside and also riveted on the jig. Ref. (169).

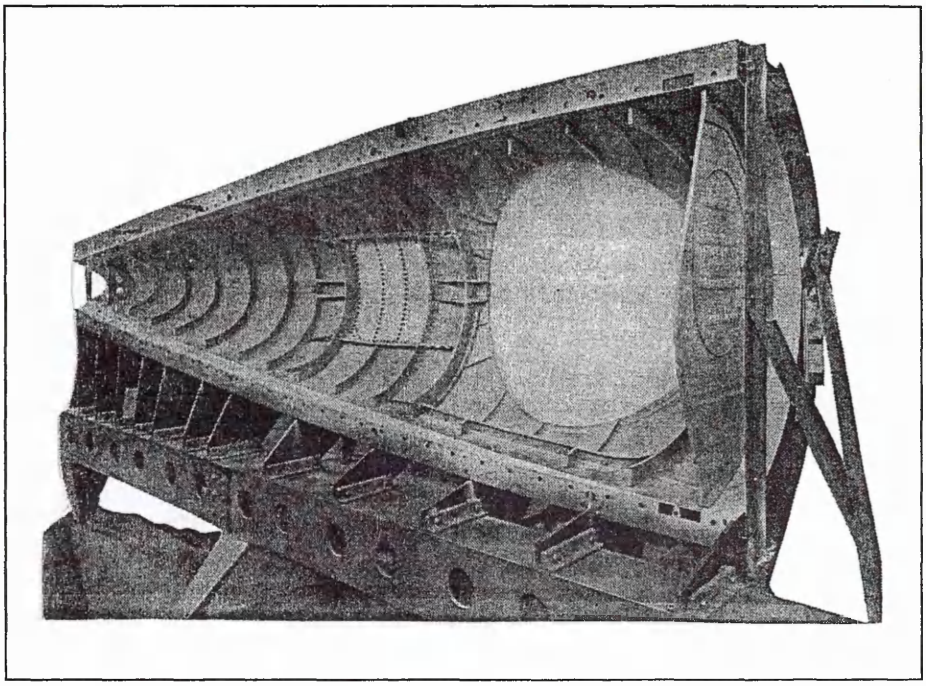

**Figure 5.3.2.6 Envelope Tooling**

In light of greater tolerances and I.C.Y requirements being called for, the adoption of such a build philosophy, used in conjunction with appropriate techniques, can provide a suitable tooling system.

### 5.3.3 Combined Techniques

Updating and bringing together several concepts, philosophies, and techniques can provide existing developments towards enabling technologies which are flexible, rationalize the assembly, product and remove product specific assembly tooling.

An integrated solution by combining past philosophies from the de Havilland Mosquito, see appendix B, aircraft build and Envelope Tooling, see 5.3.2 (vi), concept, and the reconfigurable multi-pin die system, see 5.3.2 (v). A combination of these techniques and philosophies being manipulated and controlled via computer system allowing product design data to be directly fed into the tooling system thereby providing a flexible, reconfigurable enabling process. This will be able to create moulds for carbon fibre composite components, die moulds for shot peening skin section panels, as the 'mould' could be programmed to gradually producing the final shape via infinite stages. As a consequence would reduce excessive induced internal stresses in the material. Subsequent internal assembly operations could be made more flexible by using split section construction used in conjunction with CNC tools, robotic machine tools, fastening systems, drilling and machining all can take place on the same station system thereby increasing product and capacity flexibility.

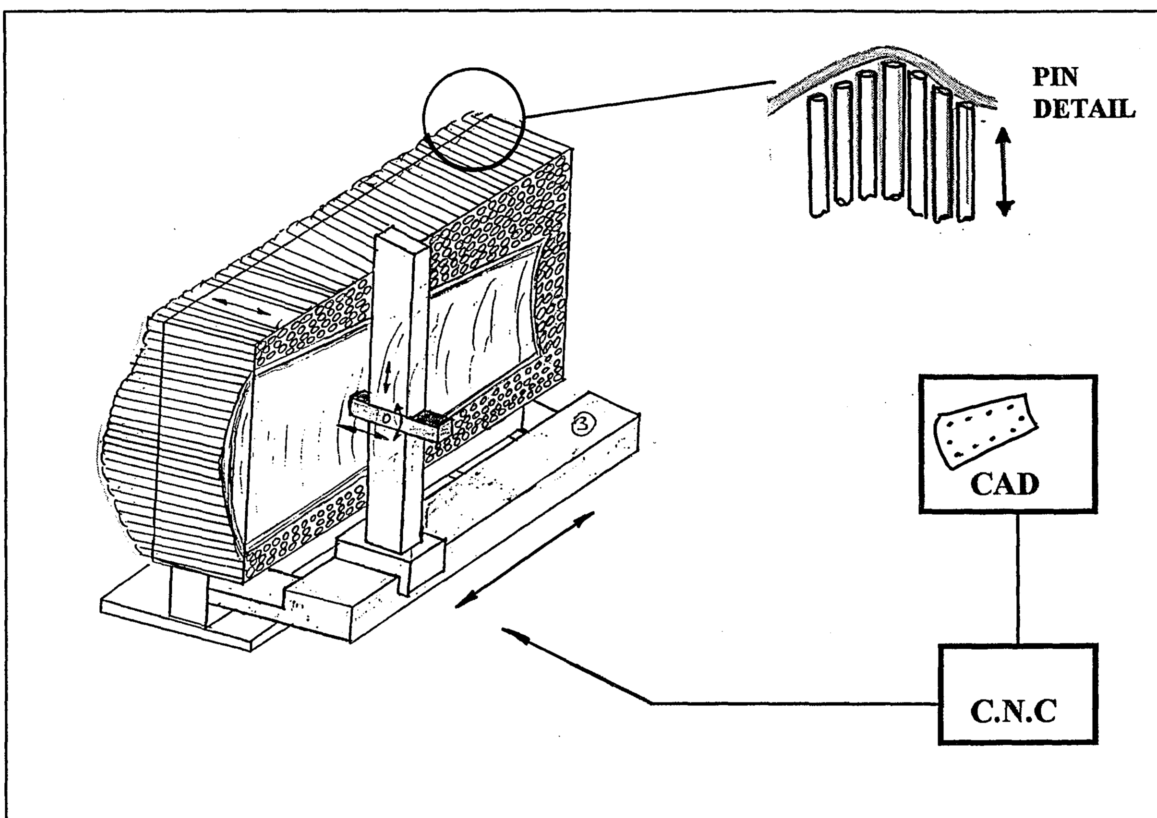


**Figure 5.3.3.1 Reconfigurable Multi-Pin Mould Die**

Figure 5.3.3.1, shows a representation of the concept. The CNC controlled machine tool operates an arm which positions the pin in the matrix cage to the desired position from the CAD data, thus creating the required form.

## 5.4 Implementation Requirements

The technologies and techniques do exist to put together a form of Jig-less assembly but its level of success could be varied with regards to implementation with existing manufacturing system organizations and their existing products.

Requirements for jig-less to succeed are numerous and wide ranging although some major generic areas can be identified.

A proposed design for jig-less assembly, DFJA, implementation system is shown in figure 5.4.1. This shows one version of a proposed working design incorporating the main elements and their relationships and interactions;

- Capture of customer requirements communicated to the engineering design phase.
- Formulate the design in a three dimensional (3D) digital definition of the product. In the aerospace industry, only those products digitally defined in the CAD environment are good candidates for Jig-less assembly. Ref. (170). CAE is the backbone to the system, as most of the analysis tools and production systems are software driven. Pre-assembly simulation can take place by identification of the product, key characteristics.
- Assess the Concurrent Engineering design tools together with tolerance analysis and error budgeting requirements.
- Decide upon the specific product whether to use Flyaway tooling features together with features to aid in-process measuring to be at the earliest stage.
- Short list appropriate enabling JAC techniques which could be used.
- Select the most appropriate manufacturing process plan capable of producing the required quality to interface with the chosen assembly strategy. Planning simulation to optimize assembly process and highlight bottlenecks.
- Decide the assembly strategy to be used, enabling jig-less assembly techniques or mixed with traditional jigs and fixtures.
- Reduction in part count within the product, due to DFA and advancements in manufacturing capabilities has moved traditional aircraft build from multiple piece aluminium alloy fabrication to major components are monolithic; CNC machined from large solid billets and plate. This puts greater requirement for higher precision of these components and the process capability matched accordingly and sufficiently robust. Define the process capability requirements and use these to control the assembly phase, via in-process real time measurement, whichever enabling assembly technique is used it must provide the feedback criteria.

The proposed DFJA implementation system model has been seen to be used in parts throughout the research period with success but as yet the model has not been validated as a complete system.

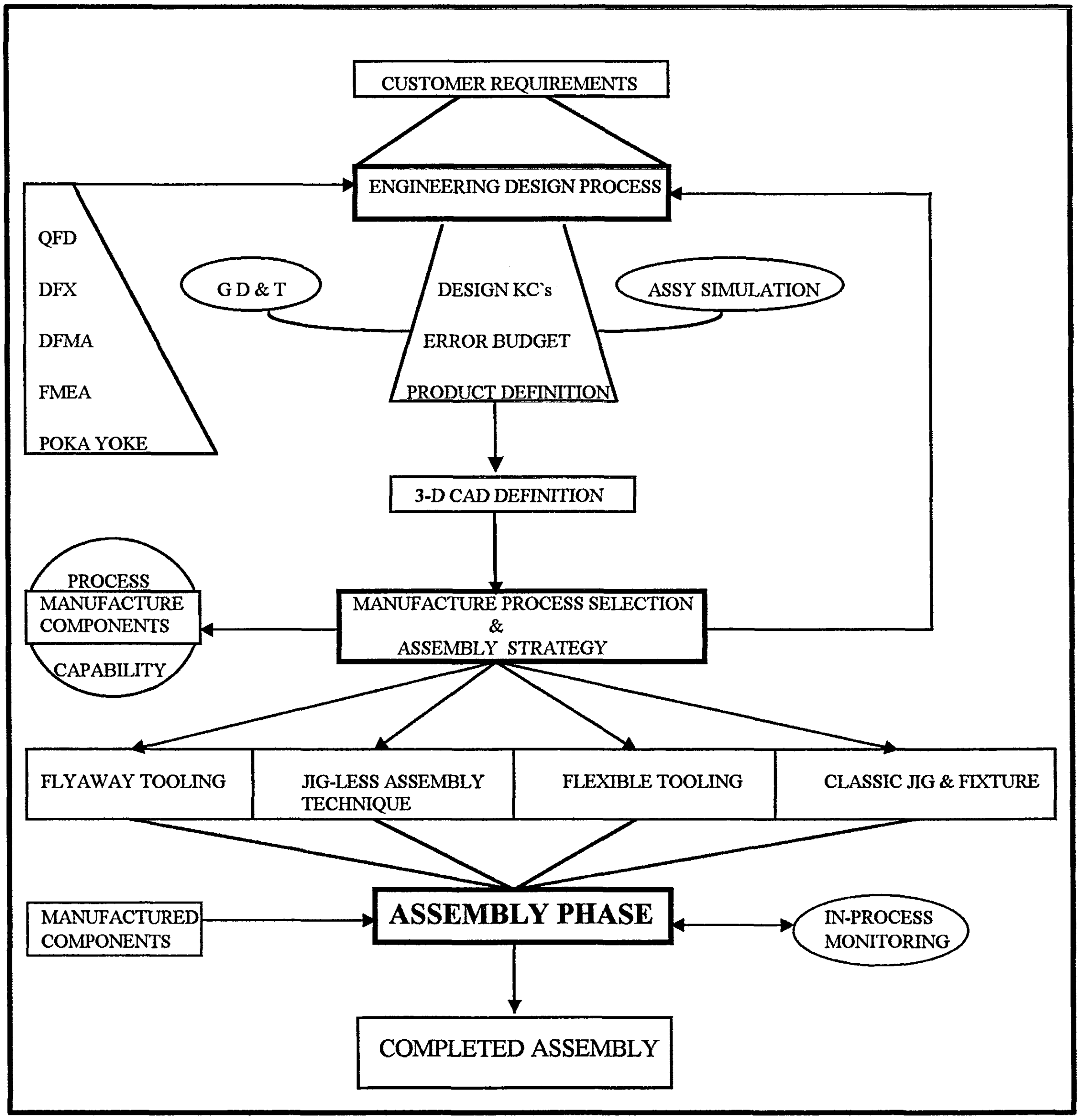


**Figure 5.4.1 Jig-Less Entity Relationship Blueprint**

For the previous mentioned design tools and enabling techniques to operate effectively a culture change in the organization will be required with the training and support to nurture a Concurrent Engineering philosophy. The physical environment is also critical to maintain the precision required by reducing the sources of errors. The need of environmental control or temperature compensation will need to be addressed. Ref.(171).

Although some existing products and practices could be used to facilitate some form of assembly rationalization, with only the minimum of change, but when looking for a major step change in the rationalization process, 'off-the-wall' ideas from lateral thinking can produce alternatives in design and process which potentially produce high returns.

It also must be noted that the risk element and cost implications are proportional to the positive dividends and a cautionary note, like all major change management proposals, must be made to the risk of failure.

Contingency plans may be used by the selection and introduction of particular techniques in the process as back up, gaugeless inspection, as example to reduce the risk to the commercial operation.

Parallel process can be another strategy used. By proving a system off line to the main process, therefore, not affecting manufacturing capacity of product quality. This has been used by BAe in its 'Proof-of-Concept' programme. Ref. (172).

It must be realized that once a product has been designed to facilitate a jig-less assembly tooling system and physical tooling is thus not available it would be very difficult, if not impossible, to return to a traditional tooling system.

# Chapter 6

## CASE STUDY - DEMONSTRATOR

### 6.1 Introduction

A case study was thought appropriate, to be used as an exploratory demonstrator for the jig-less assembly concept to provide a focus to the investigation, and to generate ideas and draw conclusions to the research.

The case study provided access to a real life aerospace, BAe, Filton, environment. The product could, therefore, be studied and the issues and problems experienced within the manufacturing system would come to light and defined if these are specific to the product or generic assembly issues, see appendices A & D.

## 6.2 Case Study - 'BATHTUB'

The chosen case study;

Inboard Fixed Leading Edge, (Root End), Assembly,

commonly referred to as the 'BATHTUB' because of its resemblance to the said sanitary item.

Its position and relationship within the main wing assembly can be seen in figure 6.2.1.

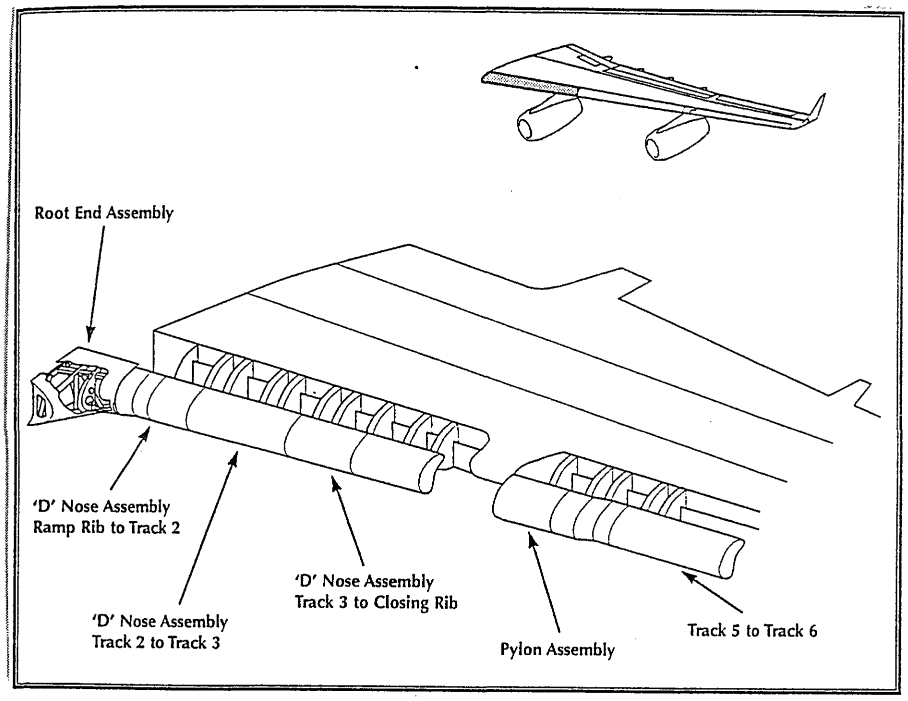


**Figure 6.2.1 Fixed Root End - Bathtub Assembly**

The Bathtub was chosen because of its manageable size as a complete sub-assembly, and its assembly process operates from one area at the BAe site, Filton, Bristol. The site and assembly process was accessible to the demands of the research programme.

The Bathtub as assembly provided a mature product to which its history and development could be traced and investigated.

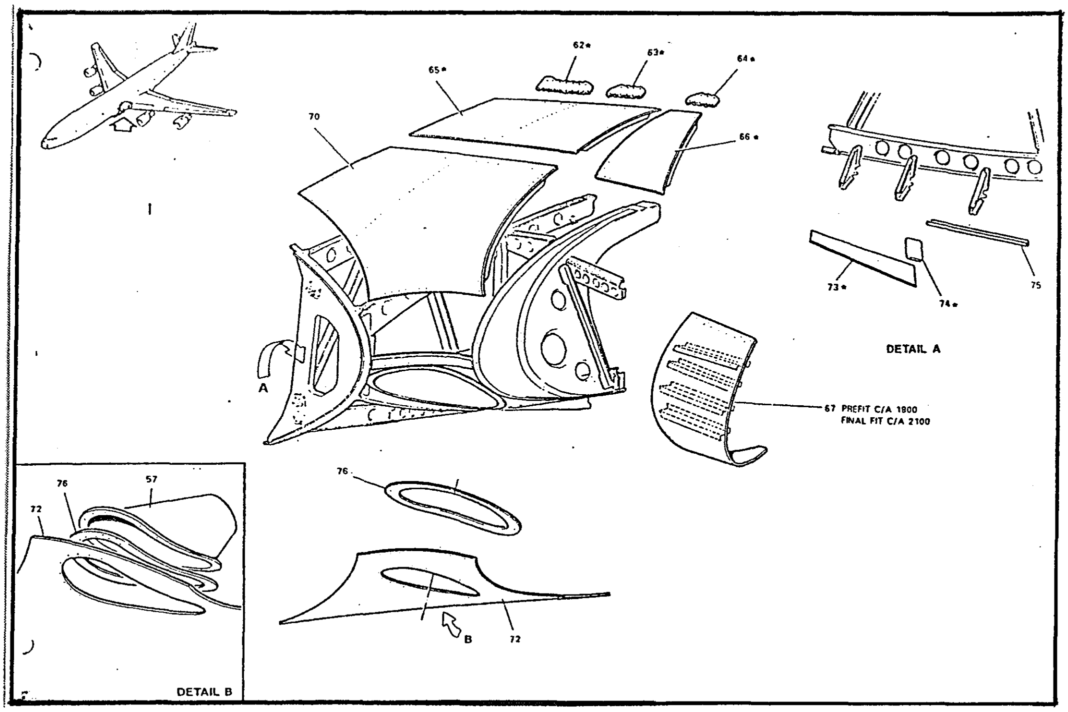


**Figure 6.2.2** **Bathtub Assembly**

From an engineering point of view the Bathtub displayed traits of a complex assembly, constructed of various materials, sections, manufacturing processes together with a high labour intensive assembly content. High precision assembly requiring I.C.Y. components made this an ideal candidate for the jig-less assembly tooling study, see 6.2.2.

## 6.2.1 Function and Key Assembly Characteristics

Main functions of the Bathtub:-

(i) Aerodynamic.

Provide aerodynamics in the fuselage wing root area, a critical position, requiring the surface of the assembly to display a smooth finish with steps and gaps between panels kept to a minimum.

(ii) Landing Light Housing.

Underside of assembly in the working position, required to house a landing light for the aircraft. When operating the lamp it produces high temperatures, to be absorbed by the surrounding assembly.

(iii) Access Panels.

Maintenance access panels underneath the assembly are required to be I.C.Y. controlled, together with aerodynamic requirement, produces tight tolerances and panel dimensions. Panel removal required for landing light and systems maintenance and allow for access to inner leading edge systems.

(iv) Structural.

The Bathtub assembly itself is not a load bearer for the main wing. Its structural strength must be sufficient to keep its integral form under its own static load, under the aerodynamic forces applied in flight, and the thermal stresses from the landing light.

### 6.2.2 Construction and Assembly Plan

The Bathtub comprises a multitude of components produced from a variety of materials and manufacturing processes. This following account briefly describes that of the existing build procedure.

- Rib Assembly:
  One piece machined billet, aluminium alloy
- Slant Rib:
  One piece pressed (7 stage), aluminium alloy
- Beams:
  Stretched formed, aluminium alloy
  One piece machined billet, aluminium
- Panels:
  Carbon/Kevlar composite
  Aluminium alloy, pressed.
- Fixing butt plates and brackets:
  One piece machined aluminium alloy.
  Pressed aluminium plate.
- Fasteners:
  Aluminium alloy rivets
  Stainless steel bolts
- Light Housing:
  Pressed and weld aluminium alloy
  Perspex/glass lens

Assembly plan consists of three main phases and two detail fitting phases. Bathtub assembly is handed, port and starboard for each respective wing.

**(i) Sub-assembly details assembly;**

Detail components such as brackets fitted on bench making up sub-assemblies. Example Landing Light Housing, see figure 6.2.2.1.

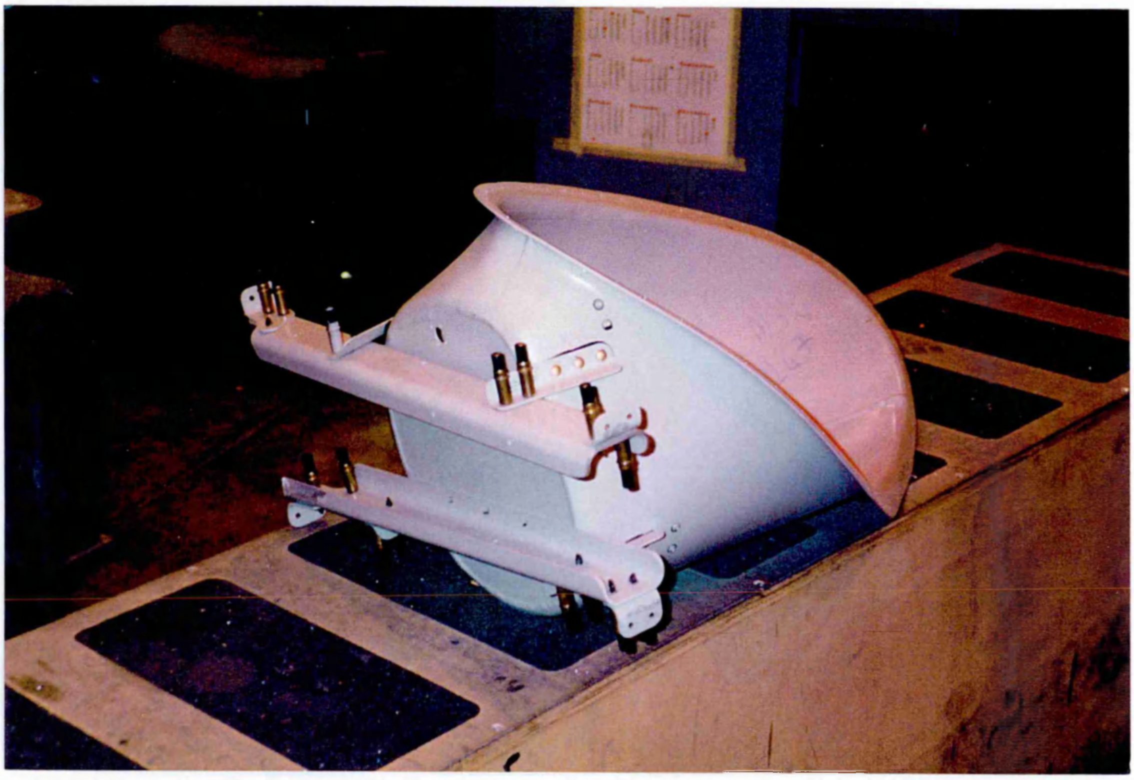

**Figure 6.2.2.1 Landing Light Sub-Assembly**

**(ii) Stage 1, Main Assembly.**

The first main assembly stage consists of assembly the internal Bathtub framework, detail brackets and checking the fit of major panels.

- Bathtub internal framework, consisting of beams, slant rib and forward machine rib, see figure 6.2.2.2.

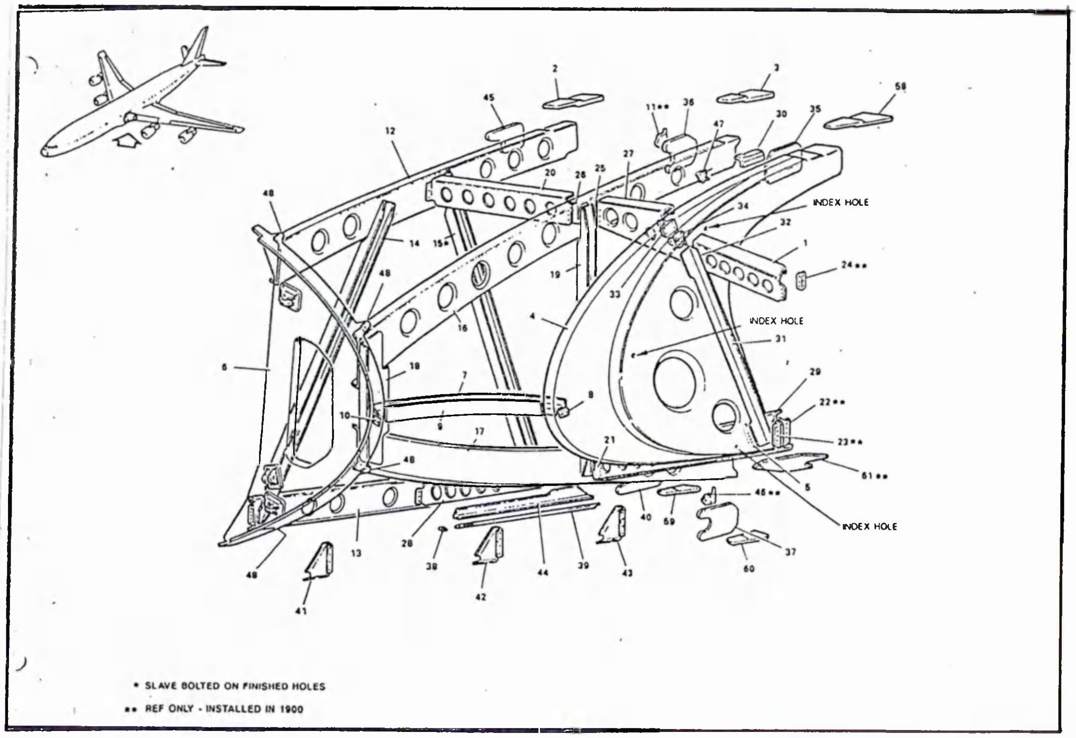


**Figure 6.2.2.2 Bathtub internal framework**

- Components pilot drilled, slave bolted, temporary fasteners, together in main assembly jig, see figure. 6.2.2.3.


**Figure 6.2.2.3 Stage 01 Assembly Jig & Assembly**

• Local 'G' - clamps are used in a ad hoc manner to mate parts as required, see figure 6.2.2.4. Pilot holes are opened up systematically to full size. Removal of parts of the jig allow for access and subsequent removal of Bathtub structure from the jig, drilled holes are then deburred.

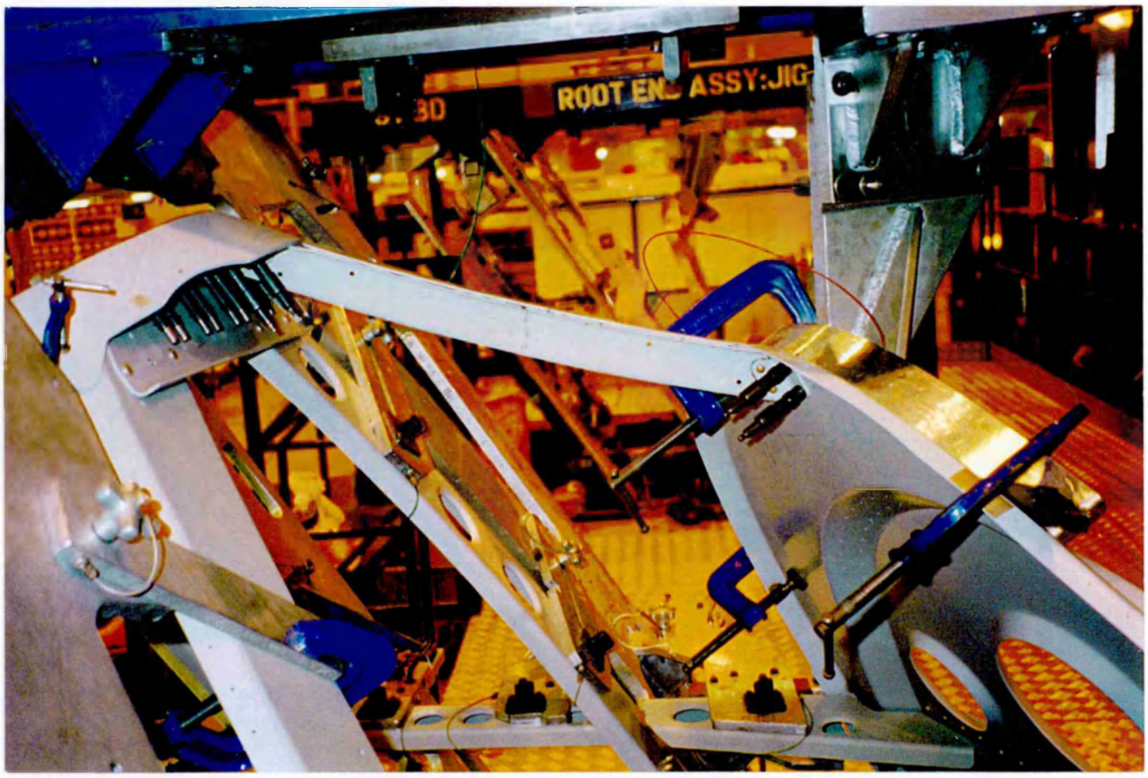


**Figure 6.2.2.4. Local clamping of detail parts**

**(iii) Stage 02 - Panel fixing, using 2nd assembly fixture, see figure 6.2.3.2.**

The disassembled Bathtub framework for stage 01 is transferred to the stage 02 fixture for re-assembly after deburring of holes. Panel fitting and detail parts are then added at this stage.

- Bathtub structure re-assembled in stage 2 assembly fixture, see fig. 6.2.2.5.

**Figure 6.2.2.5. Frame work re-assembly in stage 02 assembly fixture**

- Panels attached to framework via slave bolts, panels come with pre-drilled holes, fig. 6.2.2.6.

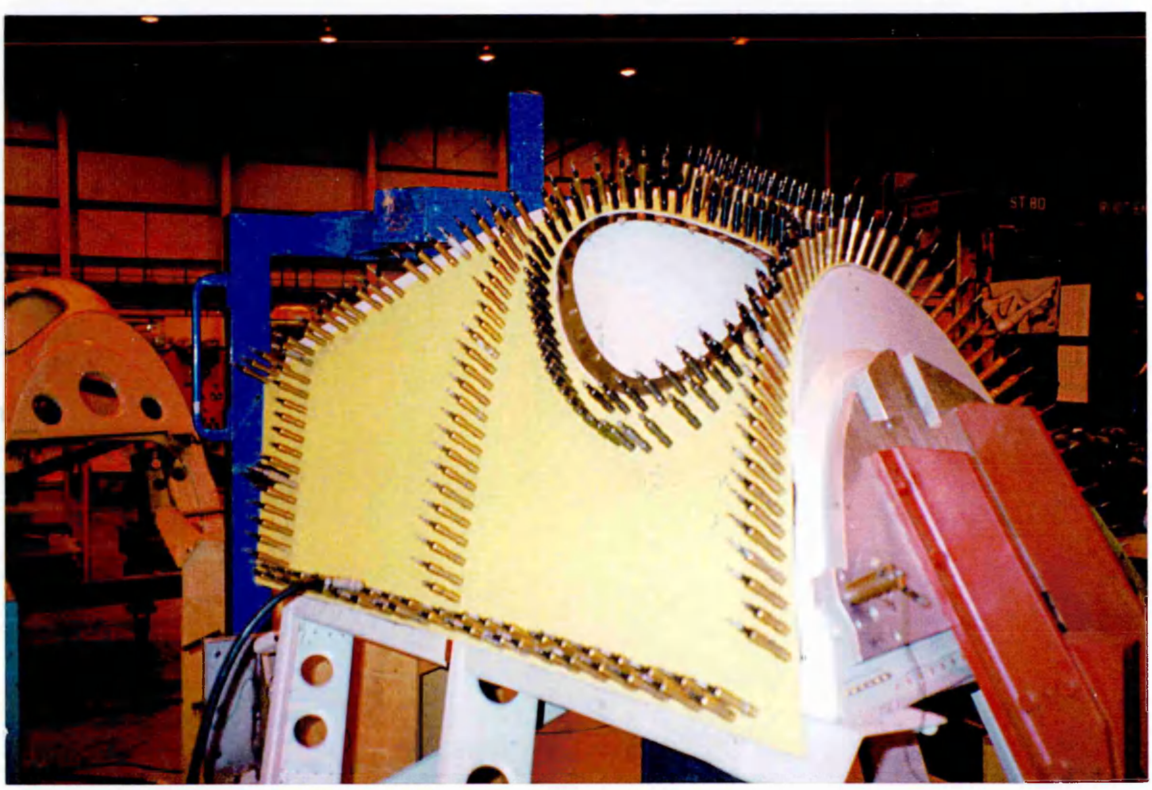

**Figure 6.2.2.6. Panel fixing**

- Panel best fit by fettling from experienced fitters, see figure 6.2.2.7, panels removed to deburr frame members. Reassemble panels using anti-scuff sealant on contact surfaces.

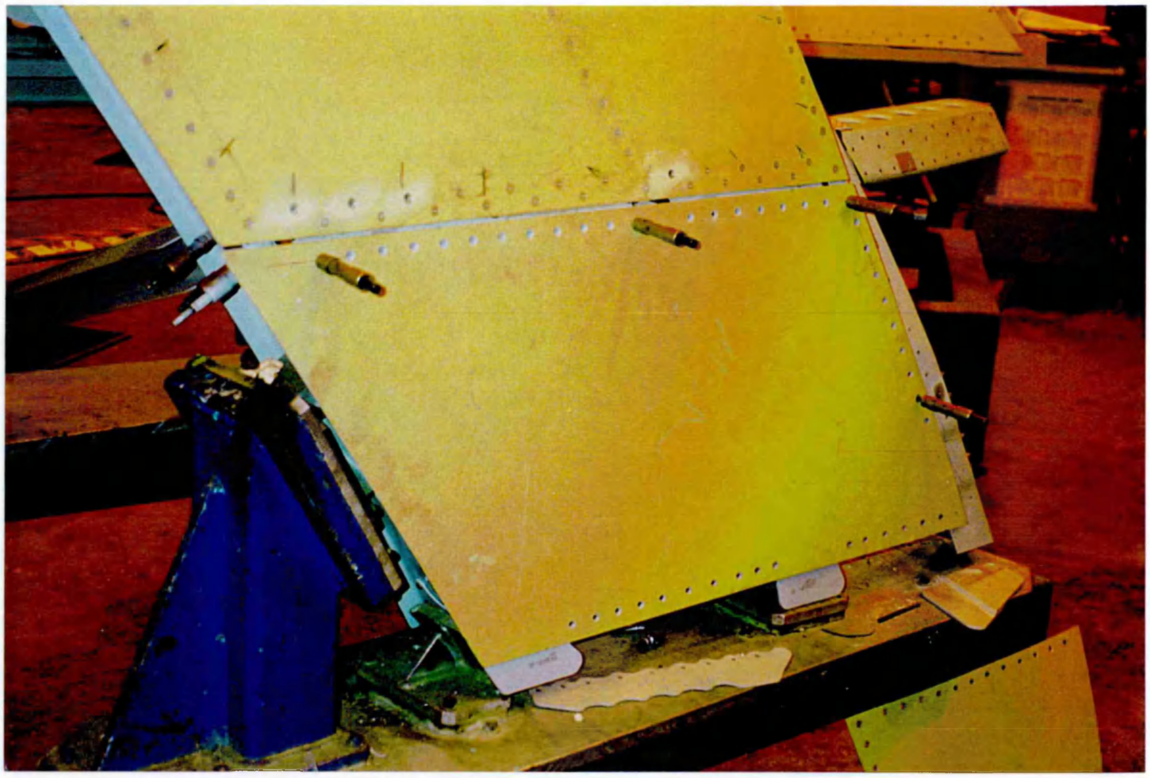

**Figure 6.2.2.7. Panel fettling**

- Bathtub assembly removed as complete assembly to transport fixture, see figure 6.2.2.8.

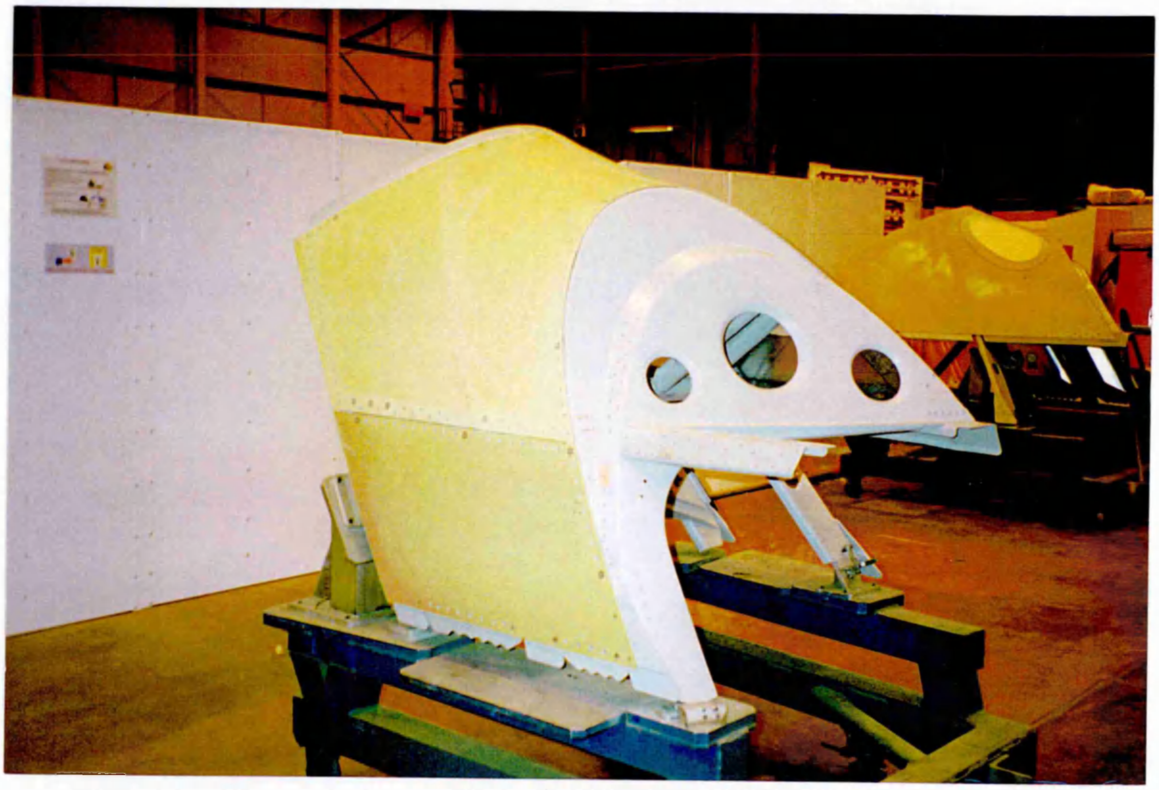

**Figure 6.2.2.8. Bathtub on transport fixture**

**(iv) Stage 3 - Main Wing Leading Edge L/E, Build Door fitting.**

Bathtub is moved via wheeled transport fixture to the Leading Edge (L/E) sub-assembly using an overhead crane. Bathtub is lowered onto the Build Door of main L/E assembly, see Figure 6.2.2.9.

**Figure 6.2.2.9 Stage 03 Build Door - Loading Bathtub assembly**

- The Bathtub is then 'fitted' to the L/E build door, see fig. 6.2.2.10.

**Figure 6.2.2.10 L/E Build & Bathtub fitting**

- Slave bolted until satisfied with quality of fit, adjustments between landing plates, fig. 6.2.2.11.

**Figure 6.2.2.11** **Final adjustments**

- I.C.Y. measurements made and recorded between Bathtub Sloping Rib and L/E 'D' nose, see figure 6.2.2.12 & appendix D.

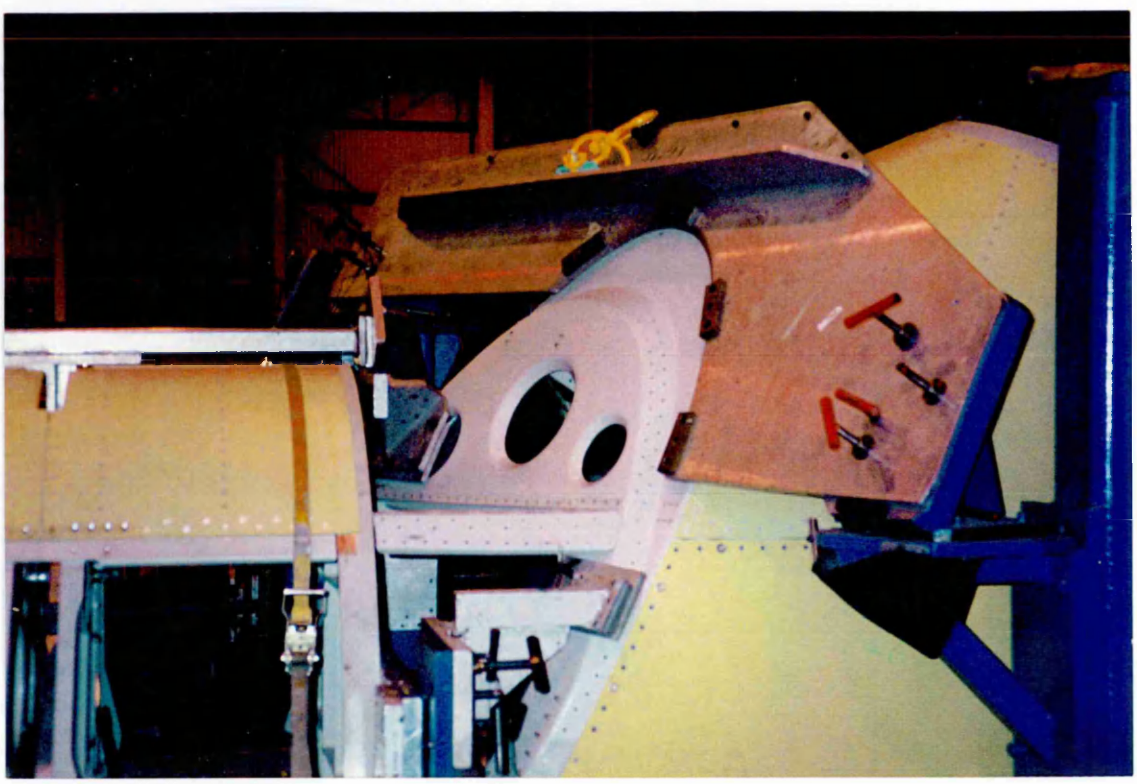

**Figure 6.2.2.12** **I.C.Y Sloping rib measurement**

**(v) Final detail assembly stage.**

- Bathtub is then removed from L/E turned upside down and internal detail items fitted and final finishing, see figure 6.2.2.13.

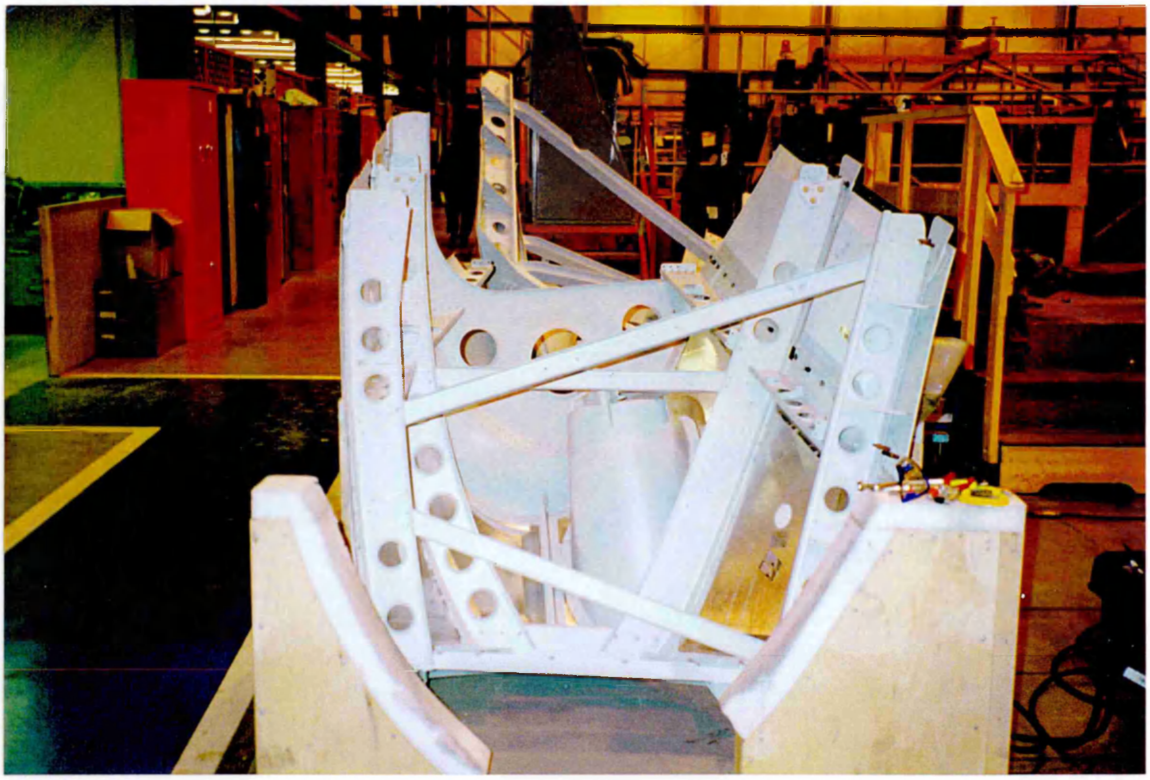

**Figure 6.2.2.13 Final detail and checks**

Matched bolts used whilst fitting are tagged to Bathtub. Bathtub sub-assembly is now one of matched pair with corresponding L/E assembly.

Bathtub is packed and sent from BAeFilton site to BAe Chester site, there it will join its paired L/E assembly and be fitted to their respective main wing. Holes on the Bathtub and L/E will be opened up when fitted to main assembly. Bathtub is removed from main wing assembly and transported separately to France Airbus Industries final assembly site for Bathtub final fitting to aircraft and wing.

## 6.2.3 Assembly Tooling

The Bathtub assembly tooling consists of a set of jigs and fixtures constructed of heavy steel gauge box section with aluminium alloy attachments. These assembly tools are handed for the respective port and starboard sides of the aircraft.

- Stage 1 jig is of a closed box type using datum plates for the respective starting components to which the build will take from. Guide tables, local clamps, toggle peg and hole alignment ensures component fit, working is mainly done inside the assembly tool, see figure 6.2.3.1.

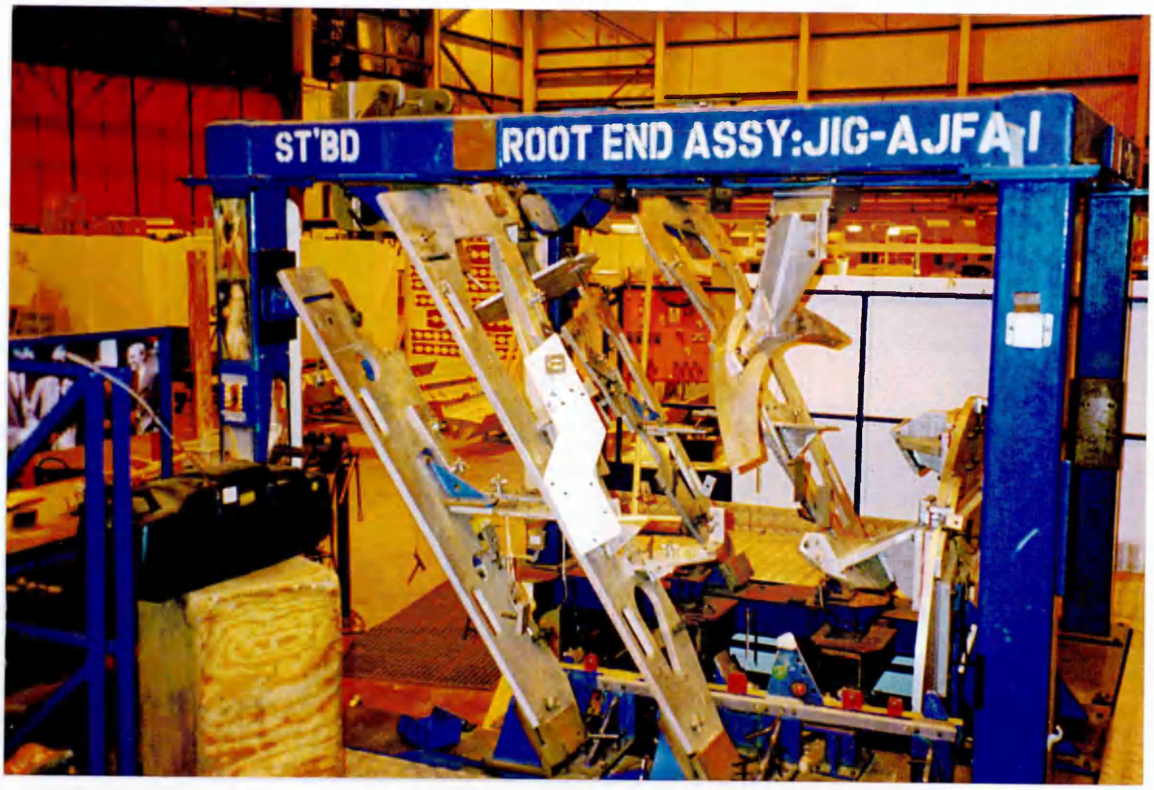


**Figure 6.2.3.1** **Stage 01 Bathtub Jig, (side view).**

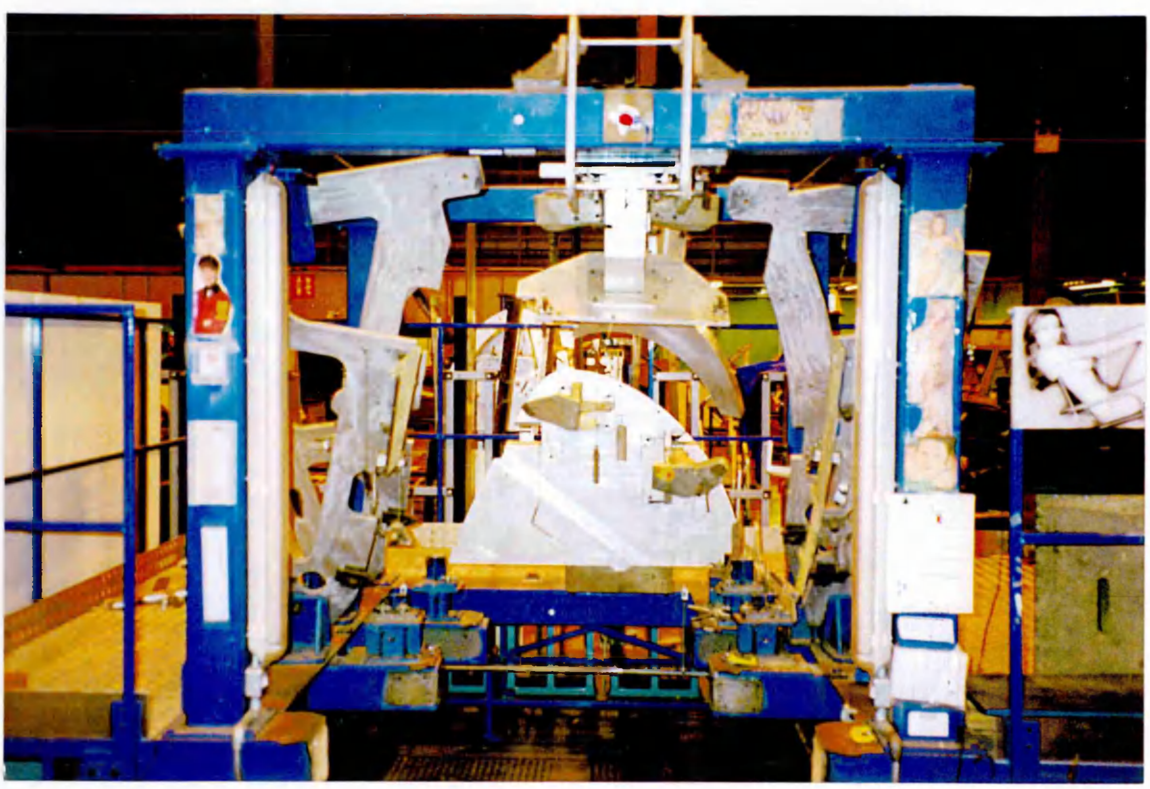

**Figure 6.2.3.1** **Stage 01 Bathtub Jig, (end view).**

- Stage 2 fixture is of an open type as the Bathtub is allowed to support itself structurally and so makes it is a far simpler design. The external panels require working from the outside so easy access is of importance. Attachment between fixture and assembly is again made at the front rib and slant rib datum points, see figures 6.2.3.2.

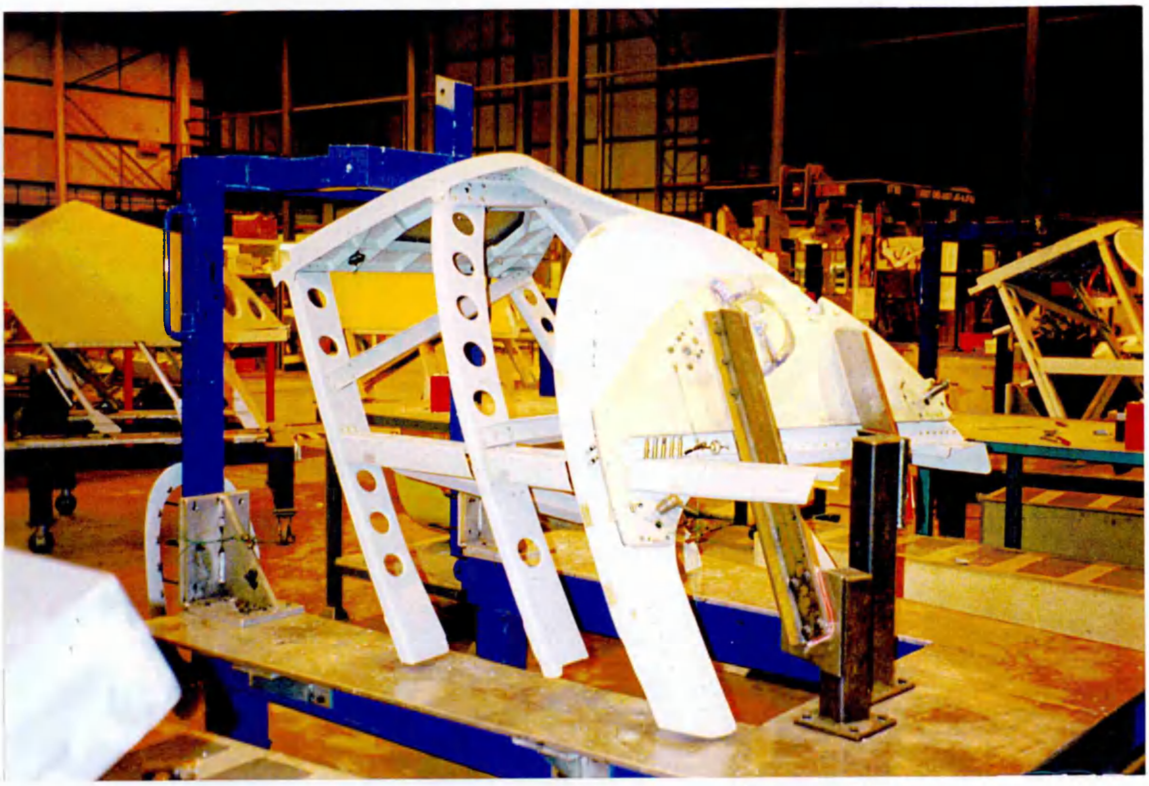

**Figure 6.2.3.2** **Stage 02 Fixture, (side view).**

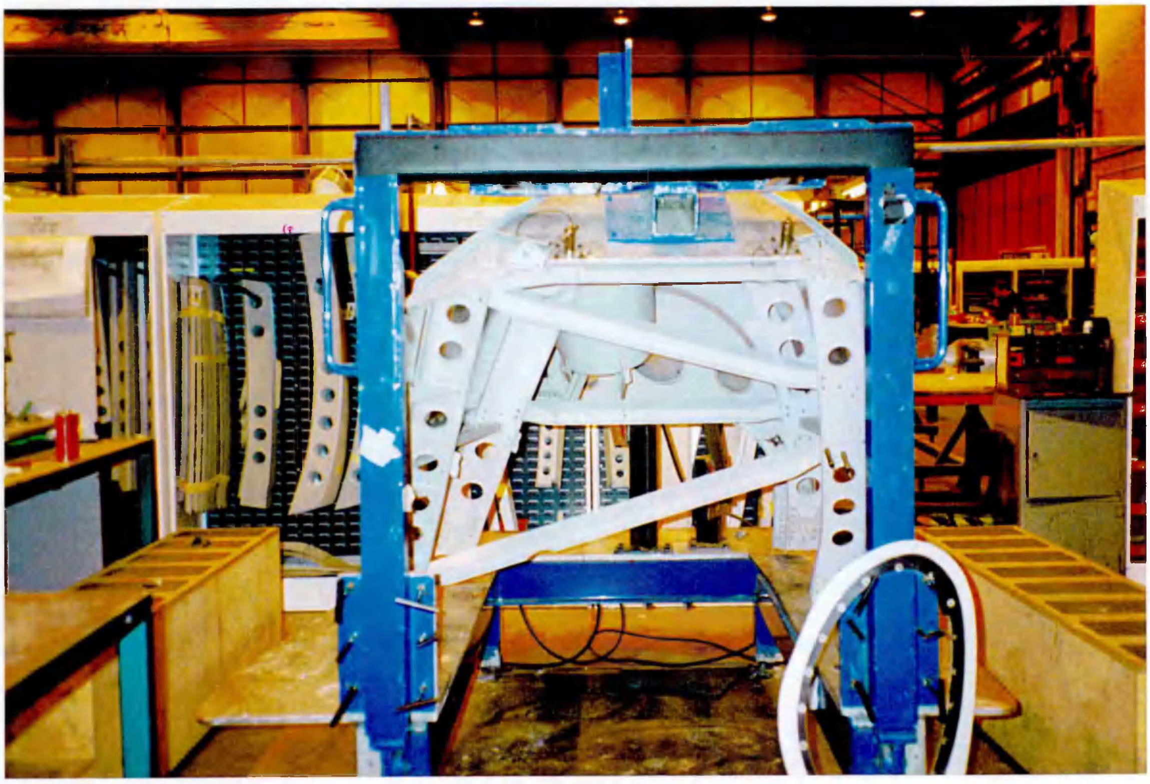

**Figure 6.2.3.2** **Stage 02 Fixture, (end view).**

- Transport fixture holds from the 'legs' of the Bathtub, very simple open type fixture. Used to move Bathtub assembly between work stations, see figure 6.2.3.3.

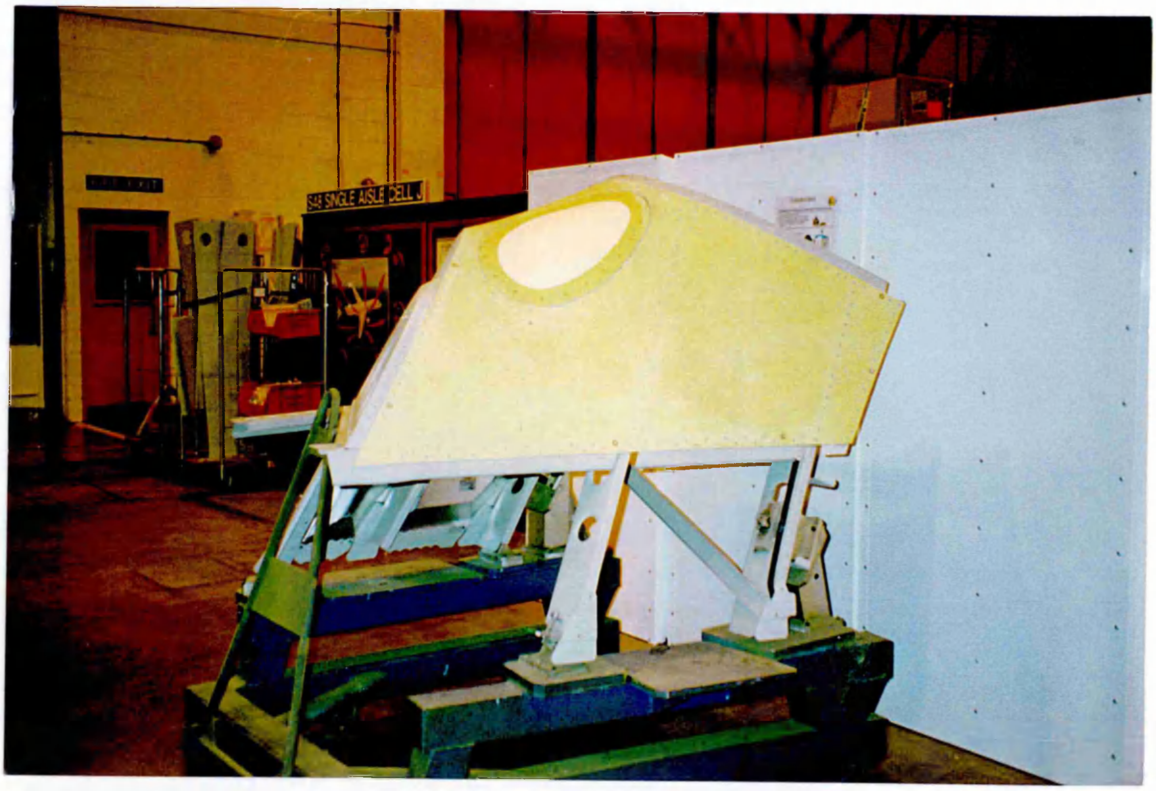

**Figure 6.2.3.3** **Transport Fixture**

- Stage 03 jig & fixture open type with heavy construction to support Leading Edge and Bathtub assemblies, see figure 6.2.3.4.

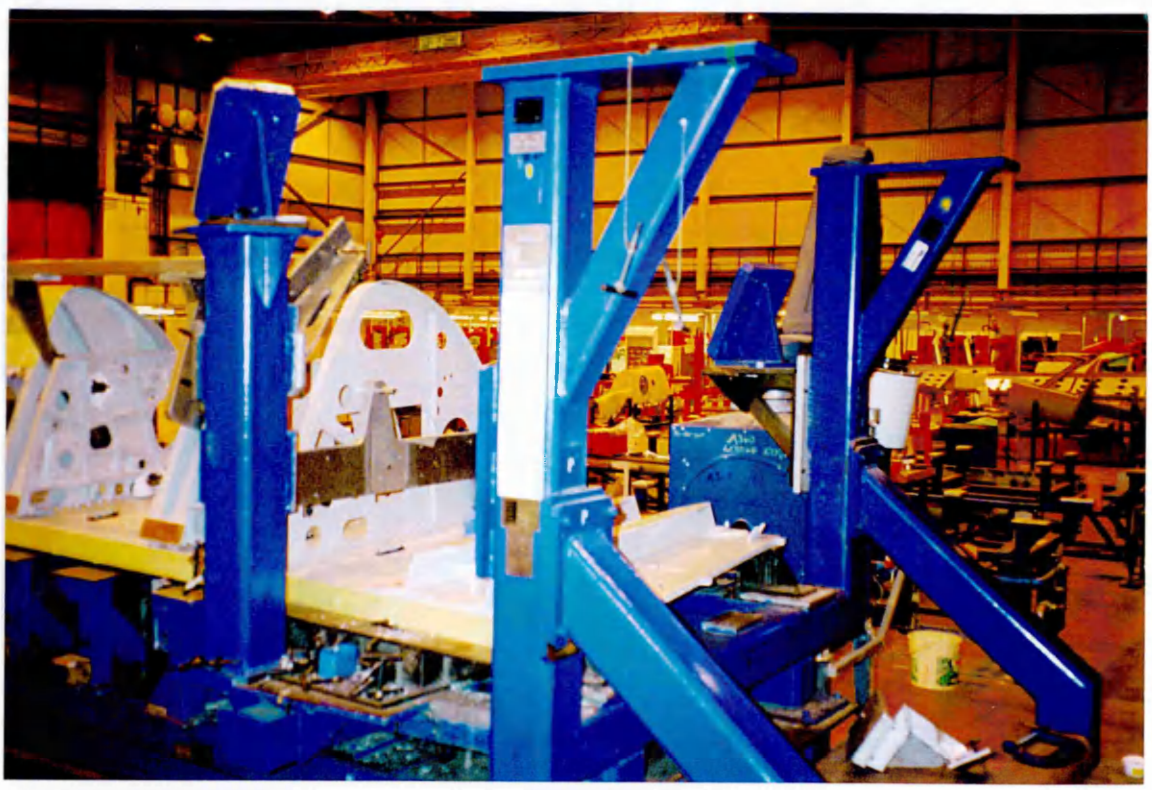

**Figure 6.2.3.4** **Stage 03 Jig & Fixture, (side view).**

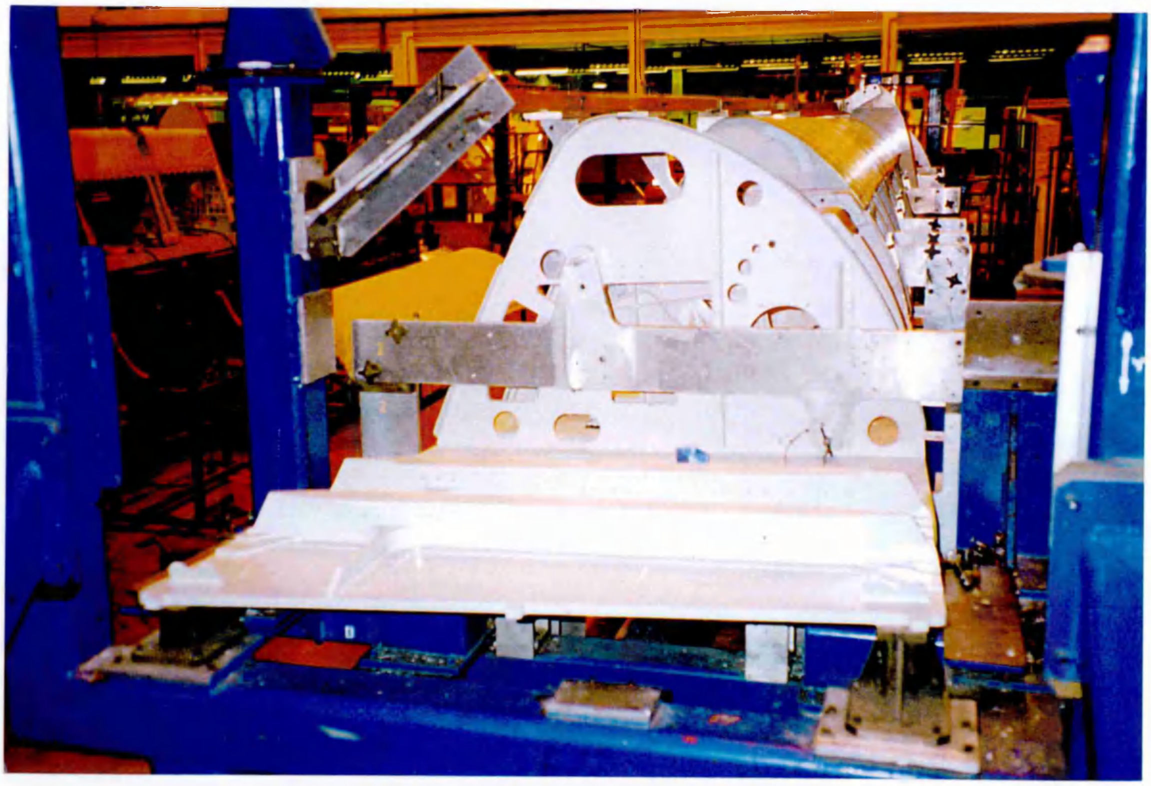

**Figure 6.2.3.4** **Stage 03 Jig & Fixture, (side view).**

In addition to the formal specified assembly tools ways to improve the original tooling and process have been made by make-do tailor made custom tooling attachments and modifications, see 6.2.3.5. These are not recorded in the tool inventory their use not officially recognized by QA.

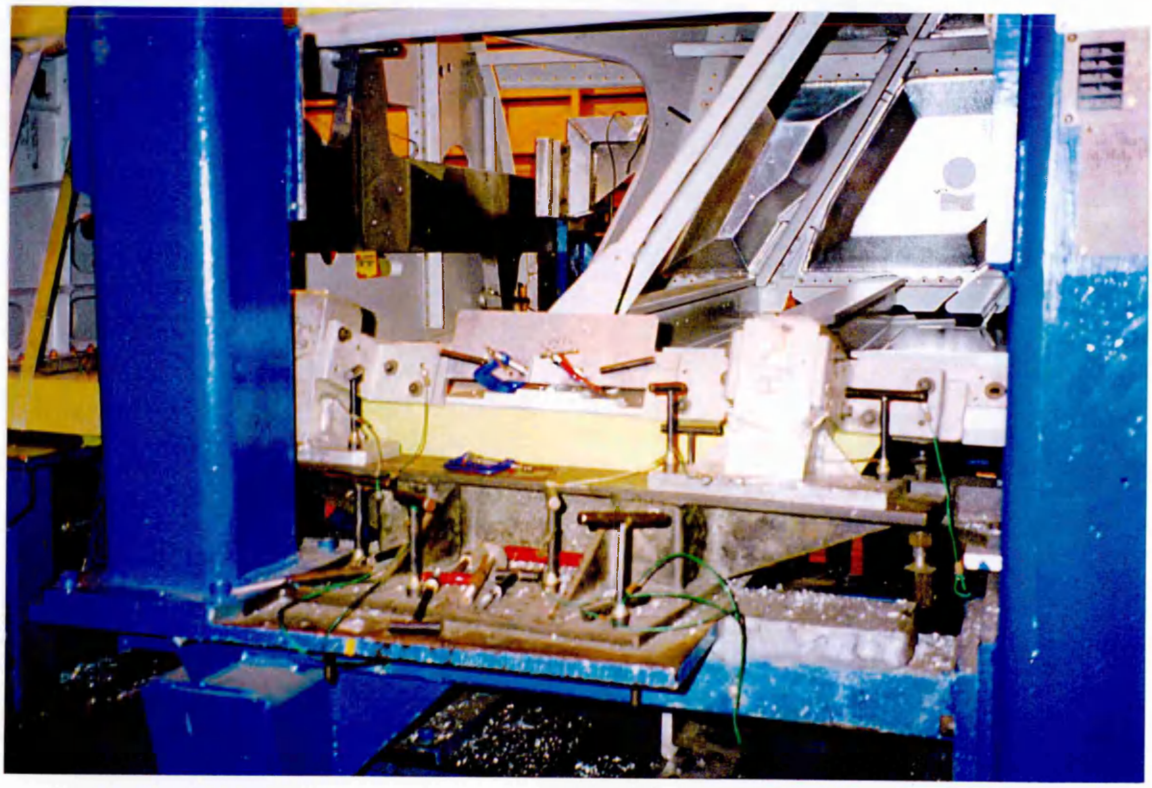

**Figure 6.2.3.5** **Bespoke tooling details**

### 6.2.4 Issues, constraints and assembly errors.

The Bathtub it was discovered is not an easy assembly to produce constantly to the required quality specifications. The assembly process is very labour intensive relying upon a very skilled work-force to make up for the shortfall in the limitations of the product design and manufacturing processes. Several important aspects of the build cycle contravene the intended performance criteria.

The assembly environment provided a changing thermal cycle especially in the light of a two shift production system: one shift during the day and a night shift, with no temperature control.

It is evident that the present jigs and fixtures are used as inspection gauges, GO and NO-GO for component acceptance. No on-line or supplier inspection data was present. The assembly components are not quantified against conformance specification.

The build philosophy contradicts the component design used and the quality requirements.

In building the Bathtub from the inside to outside, the datum points used are explicit with the point of required accuracy. The internal framework comprises components which are compliant as opposed to the external skin which is rigid, non-compliant, carbon fibre panels. Although the datum position points of the framework attachments are, therefore, not controlled. This is evident as the Bathtub sub-assembly needs to be adjusted to fit the Leading Edge Build Door.

On-going quality assurance and non-conformity problems are being addressed within the company and Airbus Industries on final assembly, see appendix D. Some additional issues and problems are highlighted:-

- Work-force, fitters are taught mainly verbally on the job - planning build instructions are out of date and not relevant.
- Fitters make up their own tooling to overcome problems. This is not recorded, adding to a black-art culture of skills for assembly work.
- Scrap parts - non-conforming parts are only apparent during assembly process.
- Supply chain is not constant, Kanban system not operating as required.
- Component part quality control not sufficient enough to meet assembly requirements.
- No in-process measurement of assembly during the transient assembly phase.

- Only assembly conformity check able to fit leading edge I.C.Y. plate gap measurement.
- Two shift assembly system, problems on one shift are not communicated effectively to next shift or recorded.
- Concessions required to pass high portion of assemblies, leaving the errors and problems to be dealt with downstream at fuselage and main wing final assembly.
- Compound curved panels pre-drilled, holes not matched to frame lands.
- Slave bolt panel fitting induces stresses into frame and panels causing distortion. Slave bolt torque loading not accurately applied.
- Holes missing in CFC panels, for slave bolting.
- Panel fit difficult to achieve.
- Condition of master tooling, panel moulds questionable.
- Tolerance wash is not compatible with overall wing datum system, causing fitting problems at final assembly.

## 6.3 Proposed Jig-Less strategies & techniques

Many of the identified enabling jig-less assembly techniques could not be considered, as the general quality of components and the degree of the control of the working environment, in terms of thermal considerations and process capability, fall short of the precision and repeatability required.

However, as a mature product design, at a time when the requirement for jig-less was not considered, and taking the view to improve the existing build quality, the fundamentals of good modern engineering practice will aid in achieving such returns.

Since so much reliance is placed upon the jigs and fixtures to impart control over the assembly it would be very difficult to replace the hard assembly tooling without major changes to product design. It was felt, since no digital definition was available for the Bathtub, no assembly or tolerance analysis could take place. Even so, if the Bathtub was 'perfect' every time when positioned for final assembly between wing and fuselage of the aircraft the root volume itself is prone to large variations. Therefore, optimisation should take place with regards to the whole assembly datum tolerance and build philosophies.

However the Bathtub assembly as a stand alone assembly could benefit from an improvement programme utilizing some of the aforementioned ideas and techniques.

To remove any of the existing jigs it could be possible to remove or simplify the Stage 1 jig. If the build philosophy was changed to incorporate Envelope Tooling ideas by starting from the outside, using the panels as the datum. Optimizing the build sequence so that the structure became self-supporting using the minimum of fixture support. The environments for thermal control and process capabilities of the components would have to provide a step change. Non-contact monitoring during assembly would provide the feedback loop to the assembly process.

A summary of initiatives which may be considered for the Bathtub assembly;

- Support and handling fixture supplied to provide higher degrees of freedom, improving access and therefore increasing mobility and flexiability.
- Envelop-tooling-build from 'outside-in'.
  Set the steps and gaps, use the multi-pin or similar flexible support.
- Optimize design, reduce fasteners and access panels.
- Alter the panel split lines, to optimise critical mating faces between panels thereby reducing critical steps and gaps tolerance.
- At high residual stress areas (e.g. top beam) use one piece molding.
- Design fibre lay direction in composite fibre panels to provide required compliance in given axis, thus aiding fitting at assembly.
- Improve quality inspection, designed acceptance sampling schemes on component parts.
- Introduce SPC data on parts, to aid control of quality in component parts.
- Introduce and maintain supply chain integrity, reduce assembly process delays.
- Optimize and maintain imposed assembly stresses at fastening stage.
- Build up sub-assemblies off line. Inspect and machine to spec, hole-to-hole.
- Optimize and maintain strict build sequence, in accordance with Stream-of-Variation theory.
- Produce slant rib as one piece machined billet or HIP casting, key component.
- HIP casting on selected beams to improve precision and strength.

- Conduct Design of Experiments, (DOE), assessment to ascertain the critical key features. To focus upon the main issues in the manufacturing system to aid JAC requirements.

- Standardise old design formats of the assembly and components into a current compatible digital format. To be used for manufacture, inspection and in-process monitoring purposes.

- Control the manufacturing and assembly conditions, especially the environmental conditions.

- Using the DOE data, construct a in-process assembly monitoring procedure utilising CMM or a non-contact measuring system.

# Chapter 7

## CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER WORK

### 7.1 Conclusions

The research defines the scope of JAC with the identification of the main issues and constraints, together with an appreciation of BAe current design and manufacturing capabilities.

An understanding of the Company history and culture in terms of aircraft manufacture has been gained which substantially influences the strengths and weaknesses of the current manufacturing operation.

The underlying fundamentals of the design and assembly process, in generic terms and has been compared and formulated in terms of the specific situation at BAe.

The use of the case study, Bathtub, was very important and contributed immensely to the focus of the research and the understanding of the nature and issues pertaining to assembly of typical airframe assemblies.

Overall the research has underlined the potential of a Jig-Less Assembly Concept and emphasised the immense challenges to the current and future initiatives in the technical as well as the business areas.

No generic 'cook-book', set of instructions, can be determined to install jig-less assembly into a manufacturing organisation, the proposed DFJA entity blueprint can only be used as a guide. Each situation and company will require its own tailor made Jig-Less Concept implementation strategy and action plans to become viable proposition.

The final assembly stage has been confirmed to be a key area which has the potential to offer substantial returns as well as play a major role in any change management process within the organisation.

Whole process is dependent critically upon fitters manual skill to overcome highly critical assembly errors. Dependence upon on these skills results in strategic risk to the operation due to many underlying problems being disguised or not becoming apparent.

Cannot overlay Jig-Less Concept on to existing method, significant change at highest level required. Too little time to implement. Currently ignoring of formal methods, never mind installing new methods, (example of need for special team).

Airbus airframe manufacture not holistic in approach, use of digital technology has not yet lead to integration until recently and it would seem difficult to envisage new developments having the impact to the operation as intended.

Isolated areas of enterprise have been observed but obscured by matrix organisation structure which is not aligned for easy implementation of initiatives, yet this despite many islands of expertise exist.

Some general observations resulting from the research for Jig-Less assembly implementation can be summarized:

I. The research has described a movement of emerging initiatives and technologies within the aerospace and other industries which aim to rationalise the assembly process. Many ideas, technologies and techniques have been recognised to have the potential to become enablers to a Jig-Less assembly concept.

II. Formal product and manufacturing design guidelines in the form of a DFX, (DFJA), framework are required to communicate customer requirements and therefore design intent through to product and the manufacturing system.

III. To meet the required quality within the product the demands upon the design and manufacturing processes will require a step change in their capability. Therefore, process capability is a major keystone to the foundations of jig-less assembly.

IV. Another keystone in the foundations for jig-less assembly is the use of computer-aided engineering systems. Therefore the product must be defined within a 3-D digital format, whereby all associated technologies and techniques maybe driven from a common source.

V. The impact of Jig-Less assembly implementation upon the organisation will be far reaching and the change management requirements will be difficult to install. All the elements within a manufacturing system, be it management or technical, will be influenced. Overlaying a jig-less assembly philosophy over a mature product and organisation will only frustrate the initiative producing a disappointing outcome.

VI. A fundamental understanding of the behaviour of the product and assembly process in physical and system control terms is thought to be of importance. The feedback loop and transient response within in the assembly process must be understood thus providing invaluable quantitative data to management for the selection of the most appropriate jig-less assembly strategy. Case study demonstrated the shear difficulties in the assembly process of a typical airframe assembly. The design of the product for its application to assembly but also the assembly process system requires a greater understanding and control. This is not apparent to the shop floor fitters or management.

VII. Many lessons can be re-learnt from past techniques and practices. Up-dated and repackaged using modern technologies and experience together can provide formidable aids to the jig-less assembly concept.

VIII. A high degree of capital and management investment is envisaged together with associated project risks for any substantial Jig-Less implementation plan. Management must be fully aware of the issues, corporate risk, and committed towards the concepts for any change management initiatives to be effective. Many mature and developing techniques can be of use now and in the near future, 'Blue-Sky' ideas which have come to light have high risks associated with them. Their capabilities to produce results will have to be proved against the high aerospace quality and safety requirements and, therefore, difficult to judge the full potential at this stage.

IX. A jig-less assembly environment will require a step change in component design and accuracy matched by the control of the environmental and process conditions.

X. Jig-Less Assembly Concept has the potential to become the catalyst for a company wide change management rationlisation process because each element within the manufacturing system and product design will be effected. Therefore, each phase in the process must be addressed with a common aim of JAC to work as designed. This, therefore, requires a holistic concurrent approach by each element in the manufacturing system.

XI. Jig-Less philosophy, built upon good science and engineering foundations House-of-JAC, and, therefore, must follow good practice in every discipline. Current initiatives and research found to be following the DFJA entity blue print.

A broad view point from the case study has been observed for jig-less assembly to succeed, producing an assembly to specification can be likened to cooking! 'Baking a Cake' !

The final result is dependent upon the selection and use of:-

- Quality of the ingredients, (components)
- The correct choice of recipe, (process plan)
- Cooking method and skill, (process choice and control)
- Cooking temperature and duration, (environmental control)

To fulfill the generic requirements of the above a strategic approach with a focused action plan is recommended to successfully implement jig-less assembly.

Choosing the appropriate manufacturing strategy for the product is critical two broad approaches are suggested:

These two strategies differ in their approach but they have a common aim, to gain and maintain control before the assembly process starts and keep control through the transient response phase of the assembly process.

Strategy (a) concerns itself with the least highest precision component parts providing less tolerance build-up and maximum rigidity. Each error source is followed through cause-and-effect analysis and, therefore, error propagation reduced to the minimum. Strict process control maximizing process capability is also required. Assembly sequence must be optimized and controlled, automation to be a consideration to gain repeatability.

(a)
- precision rigid parts
- deterministic error source & reduce/eliminate
- strict control process capability
- strict control of environment
- optimize assembly sequence

Strategy (b) philosophy and accepts that real life situation brings about error and that system noise to the assembly process is recognized and, therefore, internal and external disturbances are catered for and dealt with appropriately. Components are compliant in nature allowing in-process adjustments as required. Process control and manufacturing capability is maintained on a stochastic approach. Strict build sequence is required as manual assembly is deemed appropriate and, therefore, personal optimisation of the process is encouraged using flexible fixturing.

(b)
- compliant parts, self adjustment
- statistical error measurement & compensation
- control process capability
- in-process measurement & adjustment
- strict optimization of build sequence
- kinematic control
- supporting fixtures, flexible

Jig-less assembly concept is no panacea to existing problems or to deficiencies within any manufacturing system or organisation. The requirement for fundamental good practice robust engineering and business management will become ever more important, the foundation to any successful jig-less assembly implementation scheme, as traditional tooling and practices are replaced issues and problems will arise.

## 7.2 Recommendations for further work

Recommendations for further work can be grouped into general and specific initiatives.

General initiatives contain those in which all good practice engineering will benefit a further integration, concurrent engineering environment which will enhance a jig-less assembly;

- Manufacturing assembly integration - CAE, software and tool integration, linking of support activities.
- Design for assembly - optimization of product and manufacturing methodology with a view on the assembly process.
- Flexible tooling and automation - standardize and automate where possible. Tooling produced to be more adaptable.
- Identification of critical secondary process technologies. Reduction in tertiary manufacturing processes aiding final assembly.

The work specific to Jig-Less assembly are thus highlighted in the research. Bringing ideas from the past and up dating with today's knowledge and technology can reap rewards;

- Development of system control theory to model assemblies and their process.
- Design and develop a DFX product framework for Jig-Less assembly implementation, DFJA.
- The development of Envelope Tooling Philosophy, in conjunction with suitable tooling techniques.
- Development of flexible/reconfigurable tooling systems.

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# APPENDICES

# APPENDIX A

## NOTES ON INDUSTRIAL SITE VISIT REPORTS

# A (i)

BAe, Filton, Airbus Commercial Division.

# British Aerospace Filton

## Airbus commerical Division

**Visit Report**

Peter Snelling

July 1997

## Industrial Visit Report

- **Company:-** BAeAirBus (Filton). Advanced metal wing.
- **Company Business:-** Aerospace, manufacture/assy AirBus wings
- **Date:-** 29&30 July 1997
- **Visiting Delegate:-** Peter Snelling, Cranfield University.
- **Main Contact:-** Tim Wollaston, structural designer.
- **Purpose of visit:-** Industrial visit to familiarize delegate with company To investigate the design & manufacture of the case study, AirBus wing leading edge, sub assembly. Clarify the impasse regarding the confidentiality agreement between BAe and Cranfield. To collect copies of documentation ascertaining to said case study. (see appendix A, Pre visit objectives).

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- **Timetable, review :-**

29/07/97 am. Meeting T.Wollaston, general.

29/07/97 pm. Meeting R.Crab & S.Morris, L/edge design & manu.

30/07/97 am. Meeting R.Maddacena, L/edge assy.

30/07/97 pm. Meeting D.Luff, Tooling.

- **Personnel contacts acquired:-** Tim Wollaston, Structural Designer
Brian Turner, Structural Designer G/L
Ray Griffiths, Manager Adv.M/Wing.
Steve Morris, L/edge Design Structure
Rob Crab, Manufacturing Engineer.
Romeo Maddacena, Cell Engineer.
David Luff, Manufacturing Engineer.

- **Review, observations**

The main objectives were satisfied.(see appendix A ) Data relating to points of interest were mainly implicit in interviews, due to time constraint. Familiarization with BAe and the case study were achieved.

The confidentiality agreement contract has been resolved. A set of documents were copied and removed .

New contacts and resumption of previous working relationships were made.These were judged to be of use with a cascade effect for future contacts to be made.

Observations from ad hoc discussions and within meetings as aforementioned with the aid of the pre visit objectives paper.

The design and manufacture of the case study led to the realization that the working procedures between all disciplines were on one hand very formal and business driven to non existent. It was made clear that all though on going cost cutting and technical reviews are constantly in progress Any ideals which question the design and/or subsequent manufacturing process of a component is difficult to justify. It is assumed that because of the nature of the product and its mature position within its life cycle that any changes could not be cost effective. 'Knock- on' effects from any subsequent modifications are of concern and mainly fall short of the design concession, type approval requirements. This is driven by the product safety requirement.

These reasons inhibit the change implementation process.

Design procedures were not in existence or made clear.Design requirements and of particular interest any ICY requirements originate from design. Together with the design and manufacturing constraints these are derived from the conceptual primary functional spectification.Therefore the aircraft conceptual design criteria must always be adhered.

The relationships between components, sub-assemblies and assemblies are subject to no formal analysis in terms of overall tolerancing scheme especially any geometric tolerancing.

Tool handling, maintenance and modifications was not discussed due to time constraints.

Focusing upon the leading edge sub assembly for the Airbus main wing. Which BAe Filton amongst other sites has responsibility in producing for subsequent final assembly at BAe Chester.

The design and manufacture of the tooling was originally subcontracted and produced in North America, CanadAir.

Due to contractual changes the tooling and production remains at Filton. The component parts are in the main produced by subcontractors. No formal inspection took place and no in-house or contractors SPC data is present. Inspection seems to be in the form of if it fits or does not fit the jig/fixture then it must right or wrong. Using the jig/fixture in much the same way as a GO or NO-GO gauge. Feedback to the suppliers was not made clear.

A general overview was discussed of its function and general design and assembly criteria.

The shape and especially the top surface and 'D' nose assy which in the main is shrouded by the moving leading edge slat assembly. Is of critical importance to the primary function of the wing performance characteristics. It is this precision wing shape with its moving aerodynamic surfaces which produces a high performance wing package which in turn aids in providing the Airbus with its unique specification.

Many ideas and technology reviews have been produced or on going. Part reduction, part change and manufacture transfer were discussed. Although is not clear to the out come of these initiatives.

Information formal and informal regarding the circumstances and reasons why particular design and manufacturing features are in place are not clear.

Since the personnel themselves do not have any definitive answers. It may therefore be assumed it is indicative within the company culture and philosophy. Examples of this is can be made with the reasoning of the use of positive material, liquid or floating shim, within an assembly ?

The general design and manufacturing philosophy and specification needs to be clarified.

- **Documentation acquired**:- Drawings and documentation ascertaining to the leading edge sub assembly, F574 series.

- **Conclusions from visit**:- Overall a successful first industrial visit with many contacts made and many more questions to be answered. Detailed analysis of case study required.

- **Visit Rating*** :- Seven (7).

- **Future Actions**:- Extended site visit to establish working practice with regards to the case study assembly.

* *Visit rating . Purely subjective on the part of the delegate. The general feedback from the visit, additional to the quantitative results measured against the previsit requirements. Scale - Poor=0 Average=5 very good=10*

# British Aerospace , Filton

## Airbus Commerical Division

### Visit Report

Peter Snelling

December, 1997

# Industrial Visit Report

- **Company:-** BAe Airbus (Filton). Innovation & Technology Grp
- **Company Business:-** Aerospace manufacture/Assy Airbus wings.
- **Date:-** 05/12/97
- **Visiting Delegate:-** Peter Snelling, Cranfield University.
- **Main Contact:-** Brian Turner, Structural Designer.
- **Purpose of visit:-** Presentation by BAe Filton Innovation & Technology group on R & D work relating to Low Cost Assembly (LCA). Discover how the Jigless assembly tooling concepts have been used.

---

- **Timetable, review**

  Meeting and presentation by BAe project manager with regards to LCA. Viewed physical demonstrator, Proof-of-Concept.

- **Personnel contacts acquired:-**

  Brian Turner, Structural Designer G/L
  Colin Mitchell, Project Manager, Innovation & Tech Grp.
  Robin Hardi, Production Engineer.

- **Review, and Observations.**

BAe Filton via the R & D, Innovations & Technology group headed by Mr Colin Mitchell, has been pursuing a project with regards to reducing the cost of aircraft assembly.

The project initiative named 'Low Cost Assembly', (LCA) took a view upon all areas envisaged at operational level which maybe of benefit to the objective of cost reduction in aerospace manufacture.

LCA includes digital data derived from computer aided design systems, automated assembly supported by machine tools and subsequent precision part manufacture, part-to-part techniques. Jigless assembly concept was also envisaged.

The project involved the Filton and Chaddleton sites. The project's feasibility was to be demonstrated through 'Proof-of-Concept', the A321 top fuselage panel. The employment of 'hole-to-hole'/ 'part-to-part' techniques was to be the main thrust to the POC.

Part-to-part/hole-to-hole technique employ's the use of CAD/CAM to produce precision manufactured parts which are linked via associated Key holes or features. This ensures an accurate match of components. Time consuming fitting is thus reduced and therefore lends itself to automation in the assembly stages. Part of the project remit was to use existing in-house machine tools. The suitability and capability was to be assessed.

The physical sub-assembly demonstrator, A321 panel is made up from aluminum alloy skin , stringers and cleats, all which are riveted together. Finished panel overall dimensions are 2.5m x 2m which is assembled within a simple rotating fixture. The skin was not chemi etched to reduce weight.

The POC activities include:-

-Design & Tolerance
-Tolerancing
-Inspection Techniques
-Machine selection & Maintenance
-Temperature Compensation
-Environmental Monitoring
-Manufacturing capabilities
-Assembly Process

- **Documentation acquired** :- None.

- **Conclusions from visit :-**
 Very good presentation and informative meeting.Good source for future visit. Interesting work and knowledge which requires further investigation with regards to Jigless assembly concept.

- **Visit Rating*** :- Nine (9).

- **Future Actions**:- Extended visit for in-depth investigation into work and case study.

** Visit rating . Purely subjective on the part of the delegate. The general feedback from the visit, additional to the quantitative results measured against the pre-visit requirements. Scale - Poor=0 Average=5 very good=10*

# British Aerospace Filton

## Airbus commercial Division

### Visit Report

Peter Snelling

February 1998

## Industrial Visit Report

- **Company:-** BAe Airbus (Filton).
- **Company Business:-** Aerospace manufacture/Assy Airbus wings.
- **Date:-** 23/02/98 to 27/02/98
- **Visiting Delegate:-** Peter Snelling, Cranfield University.
- **Main Contact:-** Brian Turner, Structural Designer.
- **Purpose of visit:-** To assess the design and manufacture with regards to the case study demonstrator, Root End Leading Edge Fairing 'Bathtub'.

---

- **Timetable, review**

23/02/98 - Meeting with Brian Turner and final assembly shopfloor personnel.
Discussed aims and objectives for visit.
Observed and recorded assembly process, (ORP).

24/02/98 - ORP
Photocopied relevant data to manufacturing plan.
ORP at stage 3
Photographed process as required.
Meeting with development engineers.

25/02/98 ORP, stage 3, and photographs.
Meet Designer Richard Lunn. Discuss drawings.
Drawing office, copied relevant drawings.
Meeting with structural Designers.

| | |
|---|---|
| 26/02/98 | Visited BAe Chester site with manufacturing engineer for meeting with representatives from Chester, Samlesbury and Aerospatila. This meeting discussed final assembly problems. |
| 27/02/98 | ORP and copied data from meetings regarding 'bathtub' assembly feedback. Collected outstanding documents. Meeting with tooling designers and copied relevant drawings. |

- **Personnel contacts acquired:-**

Brian Turner, Structural Designer G/L
Aidan Daley, Team Leader (TL), ASSY.
Paul Ashton-Rickardt, Design (Tolerancing).
Drew Myers, A600 Designer Engineer.
Dave Emmett, Development Engineer.
Viv Bevan, Tooling manager.
Deryck Fudge, Tooling Designer.
Richard Lunn, Structural Designer.
Rob Williams (Chester), support Team Leader, Assy.

- **Review, and Observations.**

Incomplete and spatial case study observed data collation. This due to production shift working phase, build problems and part availability.

This section of the report will be completed after subsequent visits allows the data to be collated.

- **Documentation acquired** :- To be listed at later date.

- **Conclusions from visit :-** First visit to investigate the case study was productive. A extensive range of data and future areas of interest was made. Appropriately the shopfloor assembly was disrupted due errors in component parts availability as well as quality. This provides good data for future discussions.

- **Visit Rating*** :- Eight (8)

- **Future Actions**:- Future visit to complete study on manufacture and to discuss further on assembly problems and tooling design.

* *Visit rating . Purely subjective on the part of the delegate. The general feedback from the visit, additional to the quantitative results measured against the pre-visit requirements. Scale - Poor=0 Average=5 very good=10*

# A (ii)

BAe, Samlesbury, Military, (Eurofighter), Division.

# British Aerospace, Samlesbury

## Military Aircraft Division

### Visit Report

Peter Snelling

September 1997

# Industrial Visit Report

- **Company :-** BAe Military (Samlesbury). Advanced Tooling.

- **Company Business :-** Aerospace, Design/manu/assy EF2000.

- **Date :-** September 1 - 5 & 15 - 19, (2 weeks).

- **Visiting Delegate:-** Peter Snelling, Cranfield University.
  Nick O'Reilly, Salford University.

- **Main Contact:-** Kevin Fowler, Operations Development Manager.

- **Purpose and Objectives of Visit**

Industrial visit to familiarize delegate with Samlesbury working practices. Particular interest, design and manufacturing techniques being used or developed towards Jigless manufacture / assembly.
These visits consisted of two, one week periods. Each phase was made in conjunction with Mr. Nick O'Reilly of Salford University.
Joint industrial visits, with Salford is a requirement of the research program.
Current projects of interest include the design and manufacture of Eurofighter 2000.
Documentation directly or indirectly relating to said research, Jigless assembly.

- **Timetable, review . Phase 1 (week 1).**

The first phase at Samlesbury (1-5 sept.) is seen as an introductory and general fact finding period. The week consisted of obtaining contacts and filtering for the most relevant areas of interest. Thus this can be built upon for any future visits.

To summarize, phase one provided an outline of the current fundamental advancements at BAe Military, Samlesbury. Concerning flexible manufacturing, process capabilities, and developments towards assembly optimization using software tools, CAD/CAM.
Additionally areas for future research have been identified and a network of contacts formed.

<u>Monday, 01/09/97</u>

AM:- K. Fowler general introduction meeting and site tour.

PM:- Interview with J. Carberry, tooling development.
Examined supplied literature.

<u>Tuesday, 02/09/97</u>

AM:- Presentation by D.Fisher. Carbon fibre composite processes (CFC), and Proof of Concept (P.O.C).

PM:- Interview with R. McKeown, tooling development. Existing tooling concepts, E.M.A.P and flexible floor.

<u>Wednesday, 03/09/97</u>

AM:- Complied contact list, reviewed and planned next stage. Reviewed E.M.A.P videos.

PM:- Site tour by D. Fisher, concerning C.F.C production and manufacture. In conjunction with 02/09/97.

<u>Thursday, 04/09/97</u>

AM:- Meeting with F.Peacock, digital product pre-assembly concerning EF2000 philosophies , design and manufacture. Meeting with P.Hartley, integration of VALISYS and CATIA CAD software.

PM:- Informal discussions with K.Fowler with regards to the visit and future aspects of the research.

<u>Friday, 05/09/97</u>

AM:- Documented and reviewed the previous week. Gathered and copied available data. Outlined and planned next phase. Made provisional arrangements to prospective and existing contacts.

PM:- Meeting with M. Lewis, operations development. Assembly tolerance prediction using VALISYS and VSA.

- **Personnel contacts acquired**

Samlesbury site,

Kevin Fowler - Operations Development Manager.
John Carberry - Tooling Development, modular tooling.
Russ McKeown - Tooling Development, flexible floor.
Dave Fisher - Operations Development, C.F.C, G.D + T, I.C.Y
Rohan Chalmers - EF2000 assembly using VALISYS.
John Robins - VALISYS assembly philosophy for EF2000 fuse panels.
Dave Gillet - Tooling Manufacture.
Dave Trafford - P.O.C tooling design.
Frank Peacock - Digital pre-assembly support.
Peter Hartley - Senior designer - EF2000.
Mark Lewis - Product diagrams, assembly/fixturing development.
Malcolm Blount - Manufacturing development.
Mark Jackson - VALISYS and VSA.
Shariq Abbas - VALISYS programmer.
Mark Wilton - VALISYS contractor
Willie Scott - VALISYS assembly, jig and tool pick-ups.

Warton Site,

Paul Charnock - EF2000 final assembly.
Paul Jarvis - EF2000 Final assembly.
Bill Sargent - Feature based design.
Tony Clarke - F.O.A.S, Future Offensive Air System.

- **Review and Observations**

The main objectives were fulfilled. A general overview of the Samlesbury site, its work packages and facilities was observed.
Working relationships with Nick O'Reilly,Salford University and BAe Military personnel were made and strengthened.
Change of direction for Peter Snelling research was suggested by K.Fowler.
The product development and subsequent management of the Jigless concept was discussed.
Familiarization of the Samlesbury site was experienced and was felt that the general layout of facilities was adequate.
The management of projects and their communications seemed complex, and would require further investigation.
This was shown by the product mix of military and commercial work. These work under two different design and manufacturing philosophies but under a military organizational culture.Cause and effect due to this situation would require in-depth investigation.
Internal reports and reviews are impossible or difficult to obtain access to.
The technology advancements and investment is evident. the potential success of these program's is difficult to assess against the risk factor.
General reluctance to recognize formal management / design tools and techniques was evident . QFD, DFM/A , etc were all shown a negative response.
Internally formed ideas and techniques seem to be repackaged from traditional working practices used externally.
This was demonstrated by the Product Diagram which is unclear at this stage due lack of complete documentation.
Reasons for this can be attributed to a hard-core section driving the new technology, without a comprehensive overview and input from the many sources available.
Documentation with permission was copied and removed but lacking detail.

Overall the drive towards reducing tooling, while producing the production product, EF2000, is evident. Only time will show its potential for success.

A real risk factor is present with much learning to be done. This will bear for future projects. The present investment in the manufacturing capability is not only due to the drive to reduce costs, but due to the consequences of poor product definition, specification and project management. Since the product conception and gestation period, time-to- market, is of a time order not normal in most products. This has brought about many of the difficulties. Going with the next and latest technology, changing specification and multi partner project all play their part in up-stream causes to the effects in down-stream assembly challenges.

The manufacturing philosophy for EF2000 covers a number of disciplines and addresses issues comprising of, build assembly techniques, tooling and gauging, and I.C.Y. control.
The overall design philosophy has been to minimize part count moving to fewer more complex multi functional components. This requires the need to develop and use advanced materials and processes.
The component tolerances are increasing becoming tighter this then drives the requirement for the manufacturing capability to respond accordingly.
The use of advanced machine tools is one the solutions employed.
This application of advance machine tools and techniques dictate a need for alternative tooling assembly solutions in their own right.

The tooling is defined as primary component and assembly tools, including the inspection gauging systems and machine tools.
Issues of consideration include minimizing jig- to- jig transfers, as features which assist in quick set-up and assembly.

Work to date with respect to reducing overall costs and a flexible working facility includes the development of ‘re-configurable/modular tooling’ and ‘flexible floor’ concepts. This philosophy of reducing dedicated tooling goes against the industries traditional view and seen with some skepticism from certain quarters to its success.

The 're-configurable/modular' tooling allow the majority of the tooling functionality to be replaced improving the manufacturing process capability whilst being aided by component 'self tooling'. The need for some fixturing will still be required to support and transport the assembly.

The 'flexible floor' concept proposes that specific assembly floor area is to comprise of a matrix jig/fixture locators in which said mobile jigs and fixtures may be temporary connected when required. This allows the jig/fixture to be part of the assembly and may be placed according to demand where ever in the flexible floor area. Thus reducing expensive dedicated and jig to jig transfers. this is not yet operational and therefore unproved.

'Modular tooling' attempts to standardize jig/fixture designs. Using preparatory extruded aluminum section. Jigs /fixtures can be constructed as a kit with short lead times and then be disposed of when required. The sections can be broken down for storage or used for another jig/fixture. Only used in a pilot scheme to date with encouraging results.

Recent work has been to investigate the next stage of assembly tool definition through a series of design and manufacturing studies that build upon experience but address the generic aspects of assembly tooling. Issues may include alternative materials, manufacturing and assembly metrologies, re-configurable/modular tooling with the key drivers, cost and lead time reduction.

Reference to the Jigless/Flyaway tooling research program, the aim is to investigate the implications of the implementation of said concepts within the manufacturing environment and to analyze the functionality of the concepts. Issues to be addressed include,

- The product definition and specification and how this effects the manufacturing process.
- The management and transfer of the concepts and technology.
- The current jig and fixturing methology.
- The key assembly features and why ?
- The options and boundaries of Jigless assembly.

These and further issues will require investigation at some point if the Jigless concept can become a viable reality.

- **Documentation acquired, internal BAe reports.**

  -The use of VALISYS for Aircraft Assembly in a Machine Tool Environment.

  -Carbon Fibre Composite Process Improvement.

  -Manufacturing Engineering, Tooling and Production Planning Procedures Manual Tool Design.

  -Eurofighter 2000 Manufacturing Brochure.

  -Low Cost Re-Configurable/Modular Tooling.

- **Conclusions from visit :-** The overall impression of the visit was good. The personnel were co-operative within the constraints of their working environment. A great deal of data from a wide range of topics and sources was collated. The documentation to back up the work is not available/restricted or lacked meaningful detail. The techniques and programs being put in place require feedback to their success.

- **Future actions:-**

In terms of the Cranfield research a greater emphasis upon commercial is required and a comparison made later with military.
Future visits require a more detailed focus upon a chosen area.

# A (iii)

Short Brothers, Belfast, Aerospace Division.

# Short Brothers, Belfast

## Aerospace Divison

### Visit Report

Peter Snelling

December 1997

## Industrial Visit Report

- **Company:-** Short Brothers Aerospace plc.
- **Company Business:-** Aerospace manufacture/Assy, contractor.
- **Date:-** 03/12/97
- **Visiting Delegate:-** Peter Snelling, Cranfield University.
- **Main Contact:-** John Moore, manufacture/design Engineer.
- **Purpose of visit:-** Introductory first visit to assess attitude to Jig-Less tooling concept and gain insight into facility.

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- **Timetable, review**

AM:- Site visit regarding manufacturing operation, including.
- Bombardier 'Global Express' air stair door.
- Digital master gauge jig setting.
- 'Global Express' stabilizer.

PM:-
- 'Global Express' main fuselage production line assembly.
- Fuselage automated panel production.
- Engine cowling, nacelle.
- Thrust reverser.

- **Key Words & Subjects:-**

Jigs and fixtures, Jig-Less, hole-to-hole, I.C.Y, non-contact measuring systems, key-features, 'JACK' software, SPC, cause-&-effect, TQM, master gauge, Flyaway tooling, composite, design philosophy, King hole, process capability, organization culture, component integration, auto riveting. DFMA.

- **Personnel contacts acquired:-**

  John Moore, Manufacture/Design Engineer.
  Glen Rutherford, Manufacturing Engineer.

- **Review, and Observations.**

The limited time in which one had to observe some of the work undertaken at the manufacturing function which was of interest quickly became apparent.

Although the fleeting visit did reinforce ideas and aspects of similar work being carried out in other companies.

The company culture encourages innovation and the personnel are willing to experiment and the management are supportive. The company requires this attitude to win contracts within the global aerospace markets. Although this is tempered by the limited budget, due to low product life cycle and short lead times on contracts. Thereby only techniques and technologies, (T&T), with low to medium risk will be implemented gradually.

The T&T`s used which may be considered to be helpful and come under the umbrella of the Jig-Less Tooling Concept, (JTC), were observed.

The use of part-to-part, (hole-to-hole), has been implemented extensively throughout new product introduction. Thereby fully utilization of CAD/CAM tools, CADDS5. This was demonstrated on the 'Global Express' air stair door which the contract was won to a tender which forced the reduction of assembly tooling and the use of implicit DMA, part reduction a major element. The original design was transformed from a mainly a fabricated assembly into a assembly of a simpler design and parts machined from billet. Incorporating the key features and assembly holes.

Although this is not perfect and alignment fixtures are still used to assembly the critical parts. The saving on the assembly tooling is quoted £210k. Achieved by final assembly main J&F's tooling being reduced from 10 to 3.

The use of Key-Feature recognition and optimization of datum systems within the design stage are utilized.

The use of modular moving Jig's and fixtures,(J&F), are used in conjunction with the digital non-contact master tooling gauge system to set.

Classic J&F's on assembly are used extensive on products where close tolerances and I.C.Y are a requirement.

Temperature control environment was not evident at any stage.

Witnessing the assembly of the 'Global Express' stabilizer highlighted the hybrid nature of fusing conventional aircraft design and construction with the use of modern composite materials. Thus producing their own set of problems. The reasoning and issues behind this were not clarified.

The 'Global Express' main fuselage barrel assembly production line was demonstrated. This consisted of starting with the fuselage middle section, floor sections placed in position and located via a 'Key-Hole'. The remaining panel sections are positioned using profile boards and then assembled. Two complete singular sections are then attached end to end using the 'Key-Hole' as a datum location. Once one pair of barrels have been attached they are hoisted away from the rig. The process is then repeated sliding in the fore and aft sections utilizing the moving bed within the rig. The whole barrel section is then assembled together. This process seemed to be effective although the manpower requirement is reduced the initial cost must have been considerable and product change inflexible. One would assume the overriding justification made on product life cycle and turnover.

The supply of these main fuselage panels is provided in another facility on the site. Utilizing the part-to-part technique the CNC pre-drilled skins and associated pre-drilled ribs and stringers are dry built. Followed by disassembly, hole deburring and temporary attachment of the ribs and stringers. These are then loaded onto the auto riveting machine and finally riveted automatically. No Jig's are used in this process. These panels are then attached to wooden profile fixtures as a pair. These provide the basis in which to transport, inspect and rework the panels.

The system is not perfect and requires a limited number of skilled work force to inspect and rework as required. Having said that the level of production and reduction in J&F's demonstrates the benefits. The original J&F's for this task was leveled at 80 Jig's @ £80K, £6M. Compared to the new system, 40 off @ £1K, £40K. Additional costs are the £2M auto riveter the CAD/CAM and learning curve costs.

Ad hoc points of interest are shown in the 'Regional Jet' fuselage build. The utilization of billet machining's within the structure could allow for the development of Jig reduction and Flyaway tooling concepts.

The use of SPC has not been a major element within the environment although it has been recognized as an important area within the TQM. The use of sub-contract suppliers have shown evidence of this by supplying below standard work. Quality standard to 6 sigma is envisaged to improve cause-&-effect analysis at operational level and improve the company bench mark.

- **Documentation acquired** :- None.

- **Conclusions from visit :-**

  Informative visit. Demonstration in which to approach the challenge set within the aerospace industry. Interesting work and enthusiasm from a forward looking company. Focus and dissemination of areas in which Jig-less assembly concepts and techniques are in use or being developed requires quality time for investigation.

- **Visit Rating*** :- Seven (7).

**Future Actions**:- Extended visit for in-depth investigation into working practices . Feedback from learning curve on techniques and practices would be of benefit in future.

* *Visit rating . Purely subjective on the part of the delegate. The general feedback from the visit, additional to the quantitative results measured*

# A (iv)

GKN Westland Aerospace, Isle of Wight.

# GKN Westland Aerospace, Isle of Wight

## Visit Report

Peter Snelling

February 1998

# Industrial Visit Report

- **Company:-** GKN Westland Aerospace, Isle of Wight site.
- **Company Business:-** Aerospace manufacture/Assy, contractor.
- **Date:-** 17/02/98-PM 18/02/98-AM
- **Visiting Delegate:-** Peter Snelling, Cranfield University.
- **Main Contact:-** Peter Johnson, Tooling Manager.
- **Purpose of visit:-** Introductory first visit to assess attitude to Jig-Less tooling concept and gain insight into facility.

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- **Timetable, review**

AM:- - Site visit regarding manufacturing and design operation.
- Meeting with Peter Johnson.

PM:- - meeting with Peter Johnson and Deryck Jones.

- **Personnel contacts acquired:-**

Peter Johnson, Tooling Manager.
Deryck Jones, Head of Manufacturing.

- **Review, and Observations.**

The visit consisted of two and one hour periods. This was productive to the extent in which to compare against similar aerospace operations.

The composite operation seems to be their strong point. The design and tooling is a mix of traditional and with the introduction of modern CAE tools.

The investment in capital equipment is in much evidence. 5 axis 14m x 7m working area, machining centre and extensive CMM capacity in which are both within an temperature controlled environment.

The use of Jig`s & Fixtures, (J&F), are widely in use at sub-assembly and final stages.

In view of tooling and product design this is a developing area of which the capability of process and assembly tooling is in question.

The use of a formal DFA procedure is not used although part reduction is encouraged whilst reducing tooling. Part-to-part techniques is at an early stage. The composite product line allows for multi function component design thereby producing a single product.

The use of CAD systems in are in use, CADDS5 and CATIA. This produce many problems in data transfer internally and with sub-contractors.

Tolerance management software was investigated but purchase because of cost and envisaged benefits.

The product in which Westlands specializes is in engine cowlings, nacelles. In which tooling reduction is a area which has been recognized where cost reductions can be made.

The ratio of metal fabrication to composite assemblies produced 35% to 65%.

Part reduction in the metal assemblies is being achieved via solid billet manufacture in main frames within the structure. This used within the engine cowlings has potential for flyaway concept to be implemented.

The design philosophy and strategy is not defined.

Although a tooling procedure is in place to conform to QA.

It was stated that the process capabilities and digital form of inspection techniques could not fully replace physical classic assembly tooling in the near future. The risk to the existing operation resulting from going down this road is felt to be to great.

Resulting from the discussions has provided much interest in the Jig-Less tooling ideas, with an open invitation for further meetings.

- **Documentation acquired** :- Westland Aerospace 'Structures in the `90s' and AIS 'Composite Materials' brochures. Lower cowl structure-C27J PDR document.

- **Conclusions from visit :-** Very informative from such a brief visit. Main expertise lies in composite design and manufacture. Some elements of Jig-Less techniques are used or being considered. The lack of a product and tooling strategy is evident. Attitude to Jig-Less tooling concept warmly received with an invitation to present ideas to management and future extended working visits.

- **Visit Rating*** :- Seven (7).

**Future Actions**:- Take up invitations for extended visit for in-depth investigation into working practices and discuss tooling issues with wider audience.

* *Visit rating . Purely subjective on the part of the delegate. The general feedback from the visit, additional to the quantitative results measured against the pre-visit requirements. Scale - Poor=0 Average=5 very good=10*

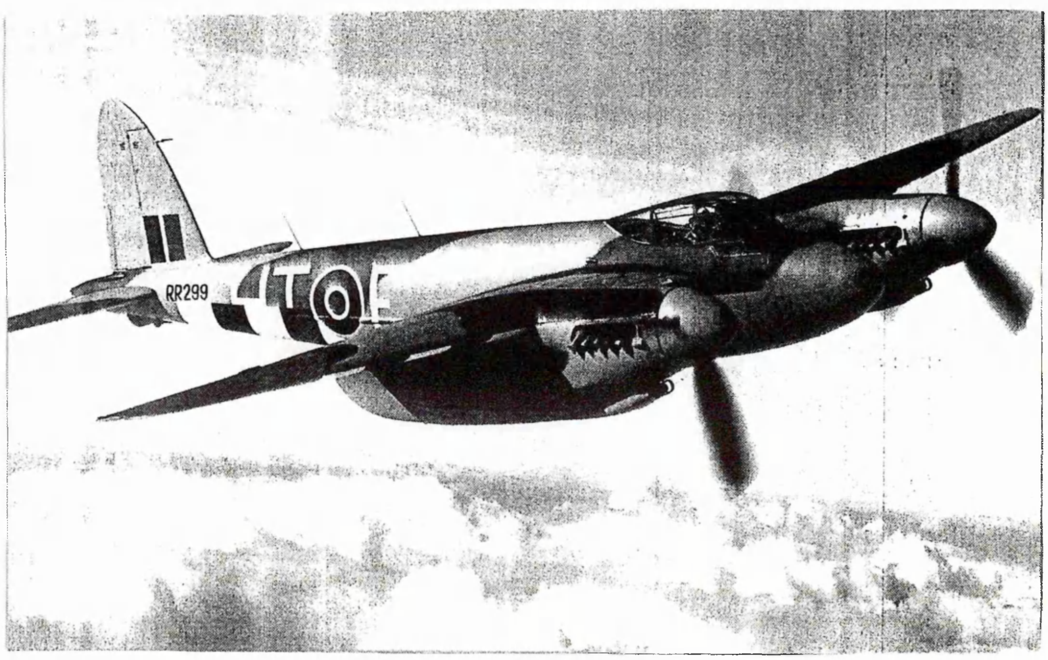
# APPENDIX B

DE HAVILLAND MOSQUITO - DESIGN & MANUFACTURE

# Appendix B

## De Havilland Mosquito Design And Manufacture

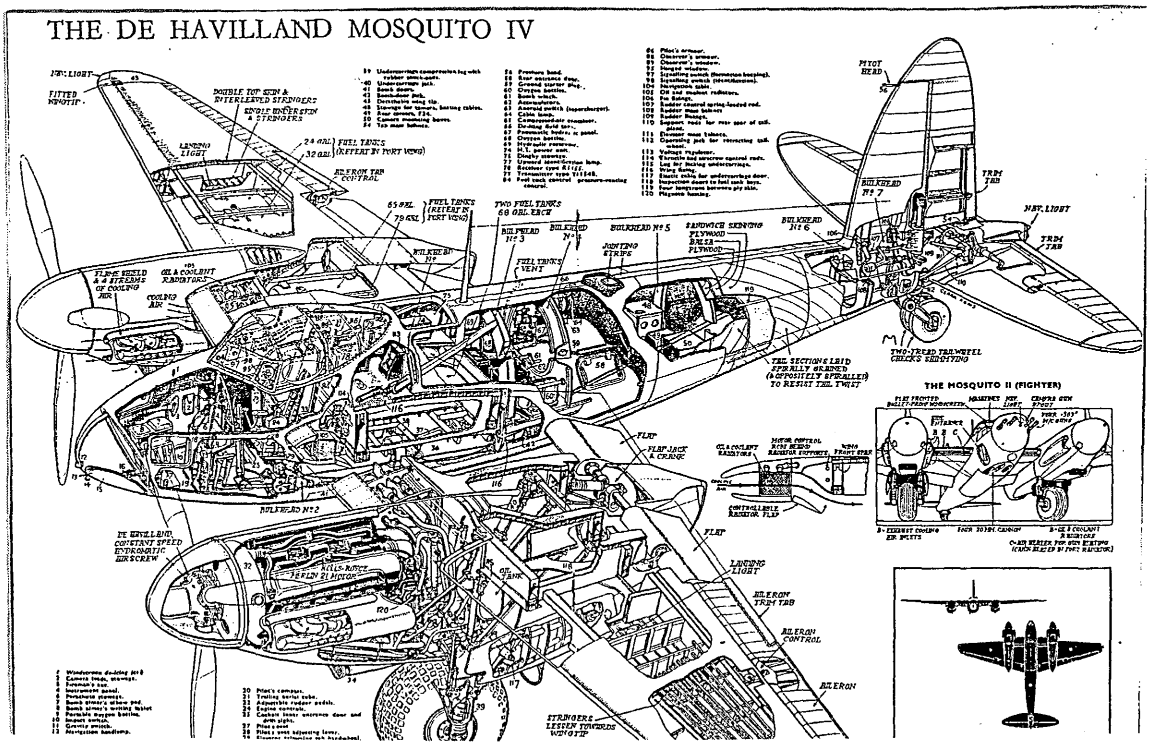
The de Havilland Mosquito, the first modern aircraft of all-wood construction to go into RAF service, was also the fastest operational aircraft anywhere in the world. Its genesis was rapid too; from the start of design until it went into operation use, a period of only 22 months elapsed.




A lot of thought was given to the design of the Mosquito for production needs. As soon as the Ministry had made it clear that large-scale production would be required, de Havilland's were able to invest in more sophisticated tooling and to plan production on a very efficient basis. Of course in those days cost wasn't the main importance; the main consideration was to get airplanes out to the RAF.

The structure comprised a balsa plywood sandwich monocoque, introduced by de Havilland before the war, with a smooth surface and part stressed-skin construction. Light, strong and very fast, this method of construction was used in the D.H.91 Albatross airliner in 1937. In 1938, spurred on by the Munich Crisis, de Havilland proposed an unarmed wooden two-seat bomber, relying on its speed to evade interception and to escape if attacked. Embodying the lessons learnt from the D.H.88 Comet racer and Albatross, it was powered by a pair of Merlin's. The Air Ministry was deeply committed to a massive aircraft construction programme of all-metal, stressed-skin designs. Wood was cheap, plentiful and easy to work. De Havilland, highly experienced in wooden construction, was convinced that its method was the answer to doing things in a hurry. By employing skilled woodworkers it avoided putting additional demands upon metal supplies.

When loads are properly distributed in a monocoque structure, the principle is similar to that of an eggshell. Although it is so thin, it is adequate for normal stresses; however, it does require reinforcement where stress concentrations occur. This can be resolved by having a separate thin internal skin, held away from the outer skin by stiffening strips. The vertically-split fuselage that was adopted considerably simplified assembly operations in later production stages, when services and equipment were installed.



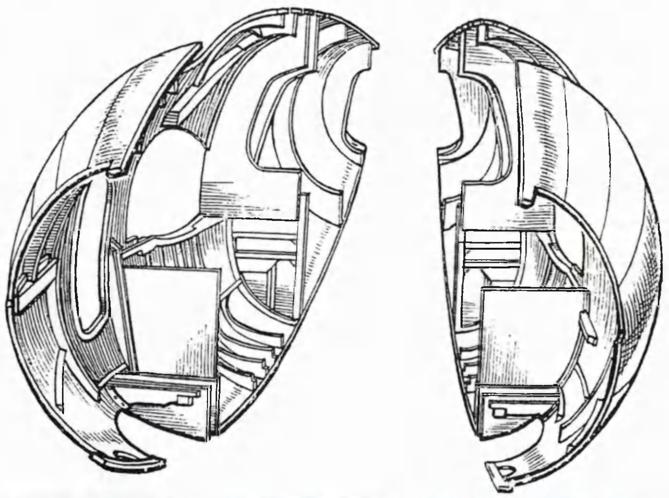

I think one of the big innovations was this idea of splitting the fuselage down the centre-line. Each half consisted of a sandwich shell, formed from an inner and outer spruce plywood skin separated by a core of balsa wood and also some wooden formers. Because the two halves of the fuselage were manufactured separately, the installation of much of the additional internal equipment and services could be made before the two halves were joined together.

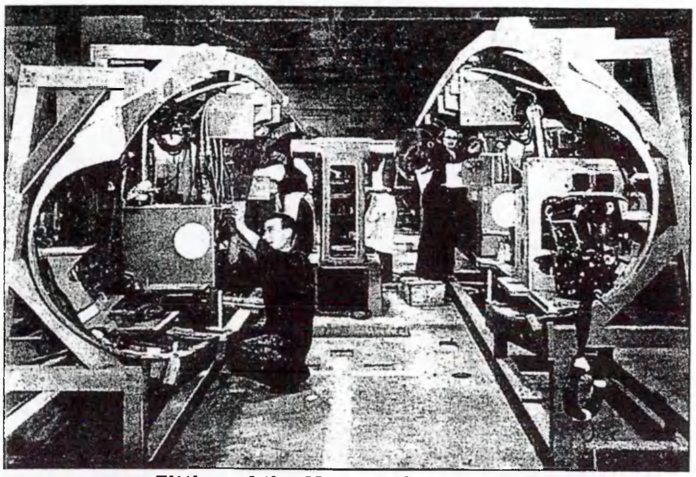
Each half of the fuselage was initially built in the horizontal position with the joint face downwards. Male formers were constructed representing the inside shape of the fuselage shell; originally these were made of mahogany, but concrete was found to be an easier material to get hold of and it would be cheaper too; so all the later airplanes were built on cast concrete formers.

There were internal formers as there are in any airplane and to accommodate these, slots had to be cut into these moulds - cut into the mahogany or cast into the concrete - to accommodate these formers inside the other bits of equipment.

So, first of all, these internal members were laid into the slots in the mould, and then, what would become the inner skin of the fuselage - which was three-ply birch wood, was then placed over these glued structural members. The rear fuselage was really single curvature, so there wasn't any difficulty in doing that - the skin was simply wrapped around the mould. In areas of sharp curvature - like the front fuselage, you could not form the ply wood into the three-dimensional shape very easily, and in those cases, narrower strips of ply were laminated together using scarfed glued joints to give the required double curvature shape.

Having got all that in position, steel straps were placed over the assembly. The straps were tightened with turnbuckles, which held the whole thing together until the glue had cured. There were holes provided in the straps to allow the excess glue to escape. When the glue had set, the straps were removed for the next stage in the assembly. Between the inner and outer skins was a stiffening structure of spruce members. They were laid in place on top of the inner skin, as were the reinforcing strips that went round doors and cut-out apertures. The spaces left between the spruce members were filled with balsa wood blocks, cut individually to fit one at a time, removed and glued, then replaced. The steel bands were re-fitted and tightened over the assembly again while the glue set.



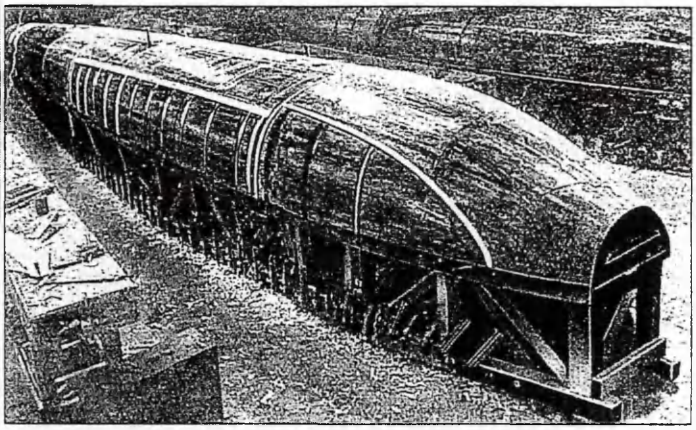


**TOP AND ABOVE Fitting of the Mosquito's internal equipment was greatly facilitated by the split fuselage construction, enabling installation before the two fuselage halves were united.**

When all that had set, the steel bands were then removed again and the outer surface was smoothed off to form an absolutely uniform surface. The outer birch ply was then put on top of that with glue. The steel bands were yet again put back and tightened up. When that was all finished and had set, you had a half fuselage. One of the descriptions used was 'like a lobster shell'.

The completed fuselage halves were now taken off the moulds and mounted vertically in special fixtures. For speed and ease of production as much as 60% of the internal fittings were later bolted to the fuselage side by means of ferrules embedded in the fuselage structure before joining the halves together. As much of the equipment to be installed was pre-drilled, these ferrules had to be accurately located to match up with the existing holes in the equipment. Accurate templates were used to drill a number of holes into the internal skin of the fuselage and part way into the balsa core. In these holes were glued the ferrules consisting of a plywood disc carrying a wooden plug in which was located a threaded metal ferrule - to pick up the bolts attaching the equipment. At this stage also the bomb doors (which had previously been moulded in with the fuselage shell for ease of manufacture) were cut away from the fuselage moulding and equipped in a separate operation with the necessary hinges and fittings.

The whole of the design had paid attention to the ease of manufacture. One good example of this was the arrangement of the services in the fuselage. Control cables were as far as possible arranged to run on the port side of the fuselage whilst the hydraulic lines ran along the starboard side. In that way most of the systems could be installed before the halves of the fuselage were mated.

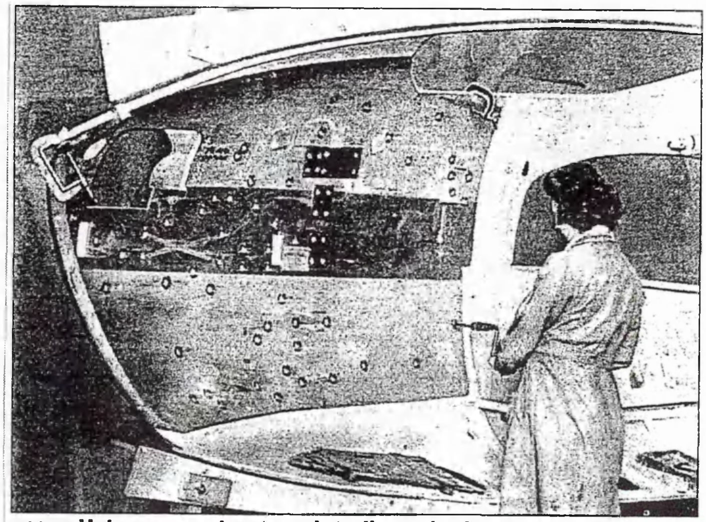


ABOVE **The first stage of Mosquito fuselage assembly. Bulkheads and other members of the internal structure are located in slots in the mould.**

The two halves of the fuselage shell had to be clamped together during the final gluing together. The front fuselage was more difficult to hold because of the double curvature, but a fixture was devised which held the halves together firmly. during the assembly of the fuselage, the wing cut-out had to be spanned by a jury-strut in order to prevent distortion taking place. Aft of the wing, the fuselage was held by wooden circular clamps which embraced the section completely. Turnbuckles were used to tighten up these clamps while the glue set.

The mating edges of the fuselage shell had a Vee-shaped projection running all along one side with a corresponding depression on the other edge. These edges were glued together. Plywood butt straps recessed into the skin were added on the inside and outside surfaces to reinforce the joint. These were glued and screwed into position. Once the two halves were joined together, the rest of the internal equipment was then installed into the completed fuselage structure.

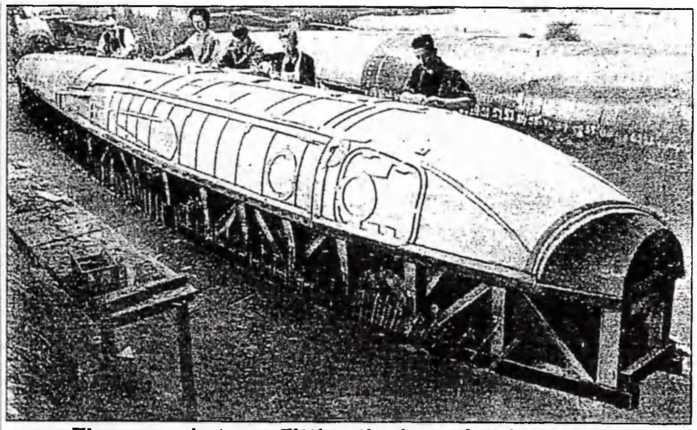
The wing was assembled in one piece extending from tip to tip. it was of fairly conventional two-spar design, with chord-wise ribs maintaining the aerodynamic profile. The top skin was load-carrying and consisted of two plywood skins separated and reinforced by closely spaced square-section stringers of Douglas Fir. The bottom skin was similar but with only a single outer skin carrying the stringers - because the compression loads weren't so great in the bottom skins. The tank doors in the bottom skin near the root were balsa sandwich plywood panels.



ABOVE **Using a wooden template jig and a brace and bit, a worker drills the fuselage interior for attachment ferrules.**

The two spars were of box section. The top and bottom laminated spar booms were connected by two plywood webs located on the forward and aft faces.

The top boom was originally made from three laminations of Fir 1.45 ins. thick. Because of the problems associated with obtaining timber free from defects to such a thickness, the design was later modified to use a greater number of thinner laminations, which resulted in a weight penalty of only three pounds per aircraft due to the increased area of glued joint. The lower boom was similar but the laminations were only 0.4 of an inch thick.


ABOVE The second stage. Fitting the inner fuselage skin and the between-skin structural members.

A special technique had to be developed for sawing these laminations to an accuracy of one hundredth of an inch. One of the advantages which was discovered was that the rough sawn surfaces accepted glue much better than a smoothed surface. So there was a double gain there. The adhesive used in the wing assembly was Beetle glue applied with rubber squeegees. The booms were clamped in special fixtures while the glue was setting. When the glue had set, the booms were taken out and given a final machining to reduce them to the correct dimensions for assembly into the spars and were then jig-drilled for the attachment of later assemblies.

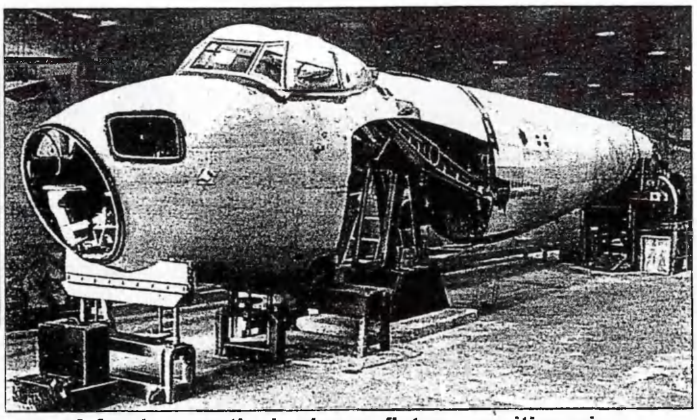
The spar webs were assembled from short lengths of plywood using glued scarfed joints. The whole spar was completed by gluing the webs one at a time to the edges of the booms. At one stage it was found that the glue was taking an awful long time to set. So, under pressure of production, a method was introduced to accelerate the curing by heating them electrically. For the time there was some very subtle monitoring equipment to make sure that the temperature was kept uniform along the length of the spar.

As far as assembly of wing stringers to the skin was concerned, the stringers were first dropped into the slots on a flat table to locate them accurately. The stringers were then attached to the wing skins by screwed and glued joints. Pressure exerted by the screws was adequate to ensure the integrity of the glue joints whole the glue cured. After the stringers had been attached to the wing skins, the whole lot was painted with red dope.

The spars were then installed in an assembly jig and the ribs were inserted between them. The ribs were of conventional design with spruce booms and plywood webs. The wing skins were pre-drilled using a template prior to attaching them to the ribs and spars. Incidentally, some 4,000 brass screws were used to assemble each top skin and stringer assembly. Special trolleys were designed to transport the partially completed wings from the build fixtures to final assembly.

After that, the leading edge and shrouds were fitted. The aileron and flap hinges were attached at pre-drilled holes in the rear spar. Shims were used to ensure that the hinge-lines were correctly aligned. The wing was finished off in madapolam fabric and red doped, over which was placed a layer of primer. Finally a coat of camouflage paint was applied. The electrical and hydraulic systems were then installed in the wing. The fuel tanks were mounted between the spars and the engine mountings bolted in place.

The tail surfaces were just miniature wings. Both had two box spars, which were in effect miniature versions of the wing spars. The tailplane was assembled in a similar jig to that used for the wing.


ABOVE **A fuselage on the boxing-up fixture, awaiting wing attachment.**

Each undercarriage leg consisted of two symmetrical 16 SWG sheet steel pressings which were riveted together along their front and rear edges. In order to ensure that the shock absorbers would have a clear run, a broach-type tool was pulled through the leg after assembly. The shock-absorbers were rubber blocks of an elliptical shape with light alloy spacers between them which fitted into the inner contour of the leg. This simple construction was a production-orientated design as it eliminated any need for accurate machining such as would have been necessary with an oleo unit.

Final assembly was a relatively simple operation the aircraft traveled round a U-shaped track, laid out at a low working level, that supported the aircraft throughout its assembly. The wing was mounted on cradles outboard of the engine nacelles. With the wing set and leveled in position, the fuselage was lowered on to it and bolted up, and the fuselage side panels below the wings assembled.

The complete tail unit was installed on the rear fuselage. The radiators were installed in the leading edge on pre-drilled holes, jig-drilled to ensure interchangeability. The installation of the engines was one of the last operations in the assembly sequence.

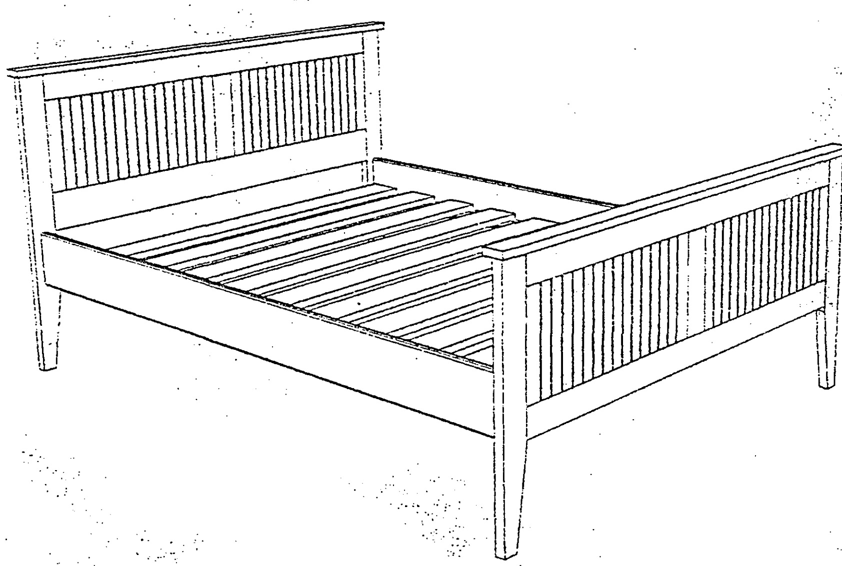
The aircraft lowered on to its undercarriage and wheeled to the paint shop for final checks, engine runs and test flights.

A great advantage of the wood construction was that production, spares and serviceable repairs could readily be effected by subcontracting to firms employing carpenters of average skill. Notable were firms making school furniture or doors, or carrying out high quality coachbuilding.

# APPENDIX C

## IKEA SELF ASSEMBLY BED - INSTRUCTIONS

# 1506



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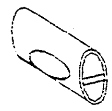
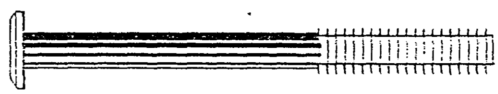
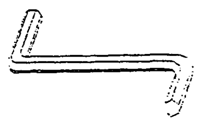
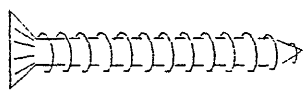
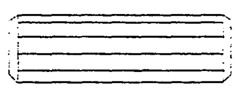
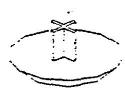
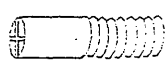
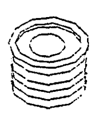
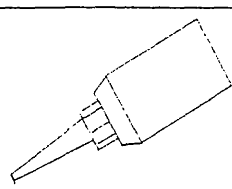
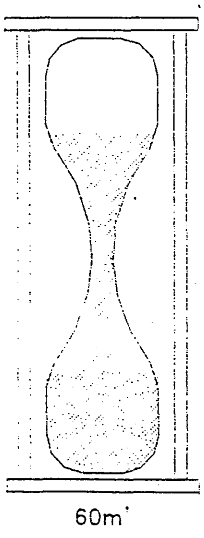
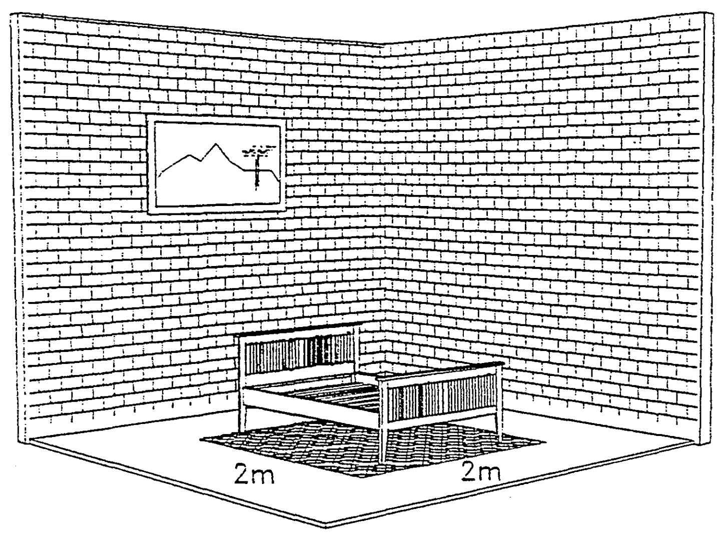
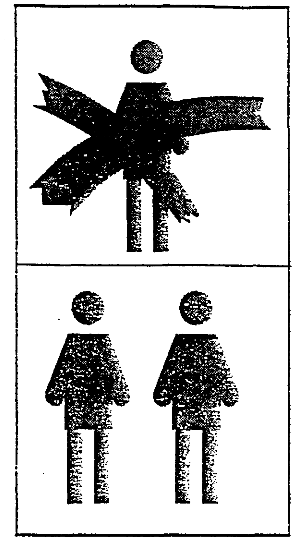
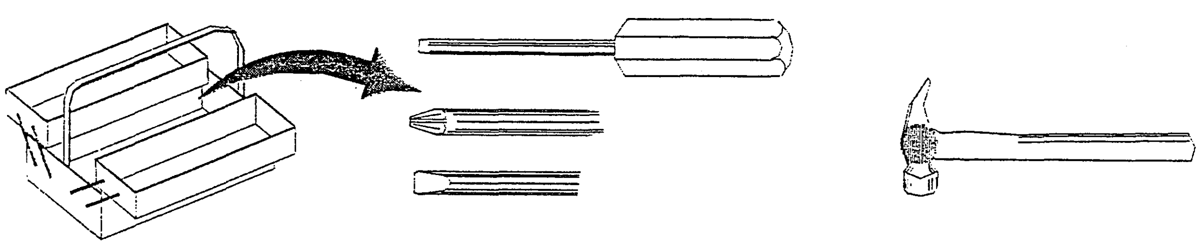
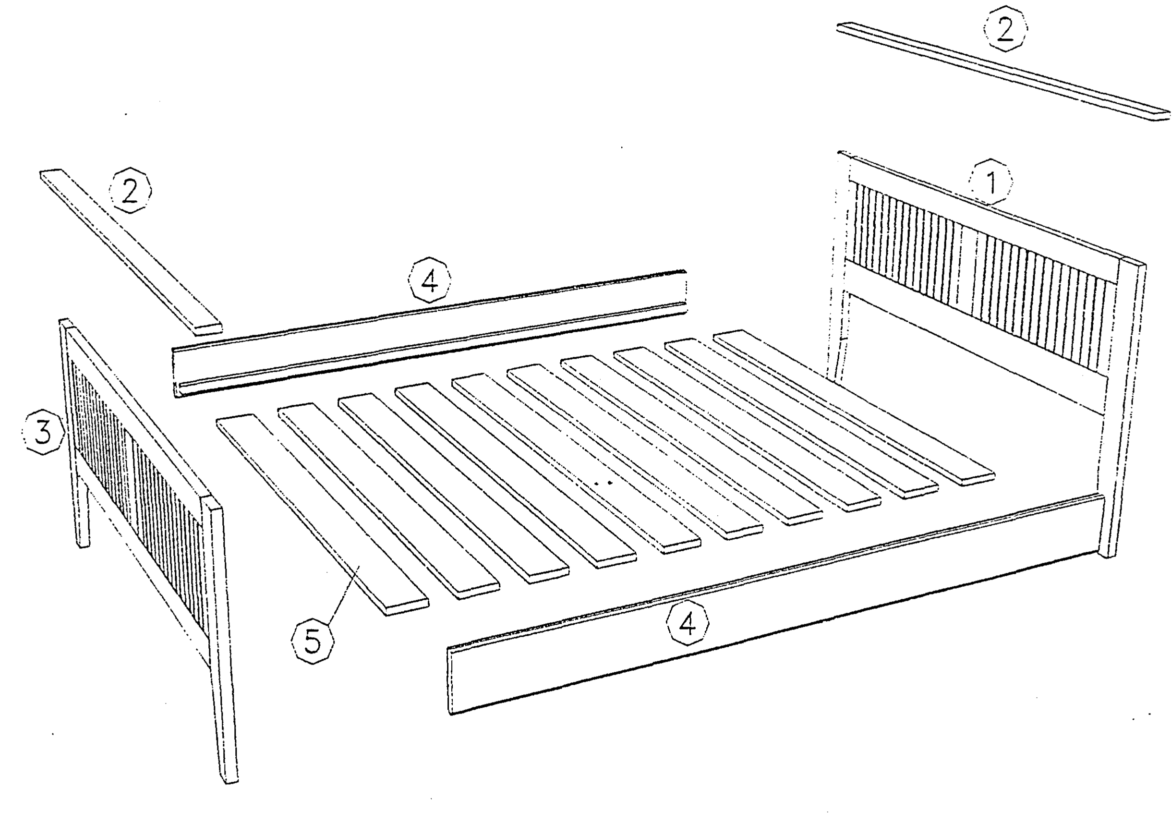
| B x4 |  | 10x14mm |
| C x4 |  | M6x65 |
| D x1 |  | 4mm |
| E x20 |  | 4x40mm |
| F x8 |  | 8x40mm |
| G x4 |  | 25/3x16/8mm |
| H x8 |  | 5x24mm |
| J x8 |  | 12x9mm |
| K x1 |  | 20gr. |


60m'

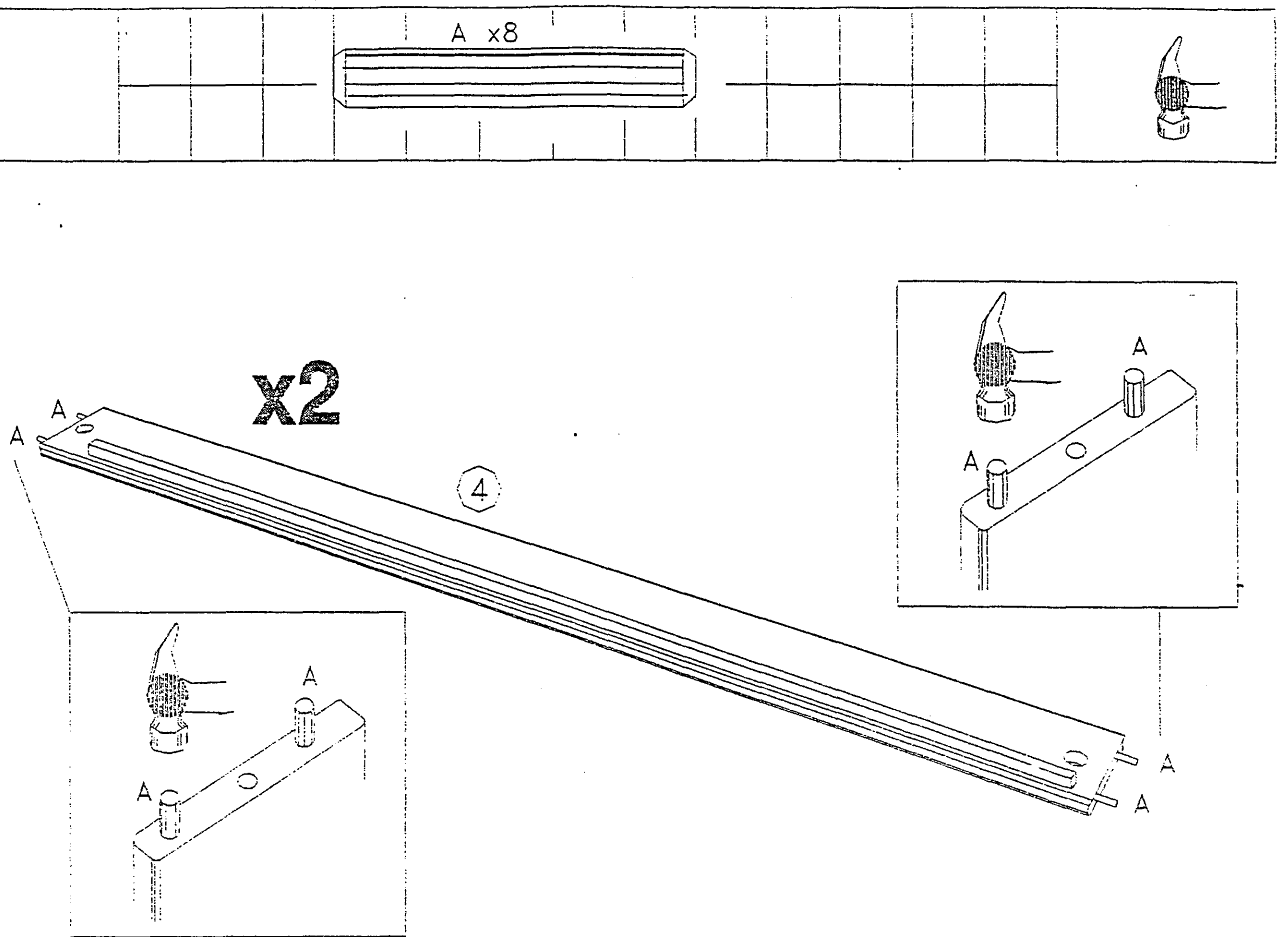

2m
2m






1
2
2
3
4
4
5

# 1

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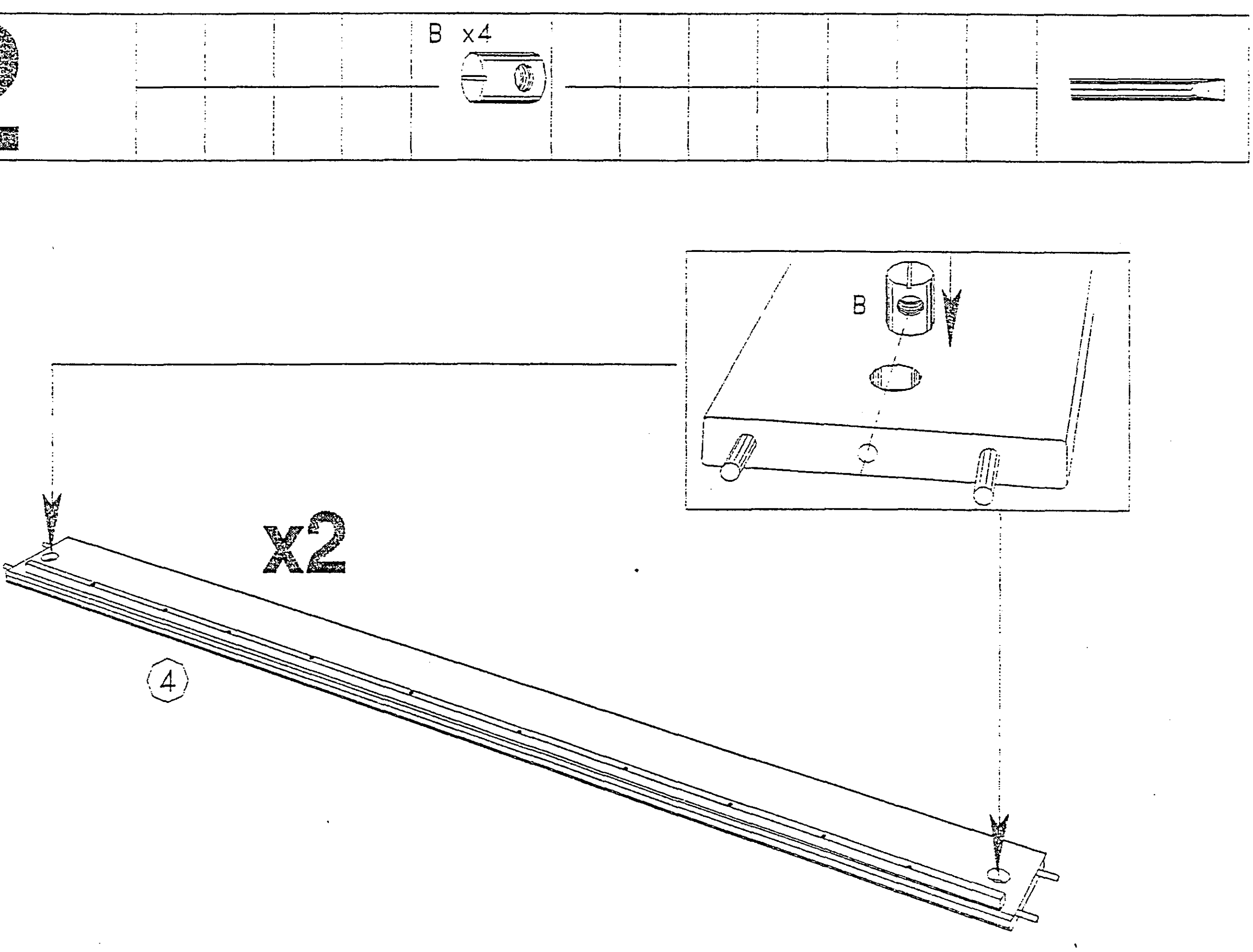

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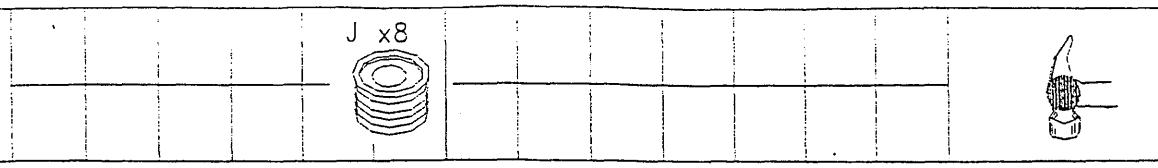
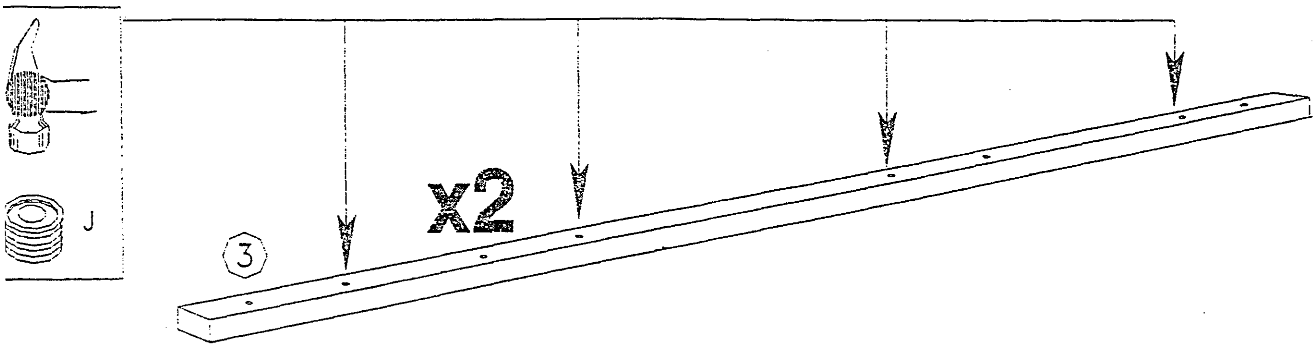
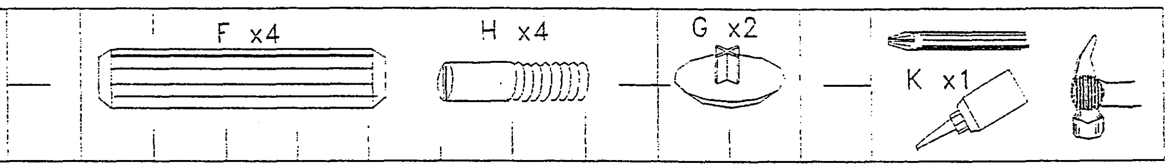
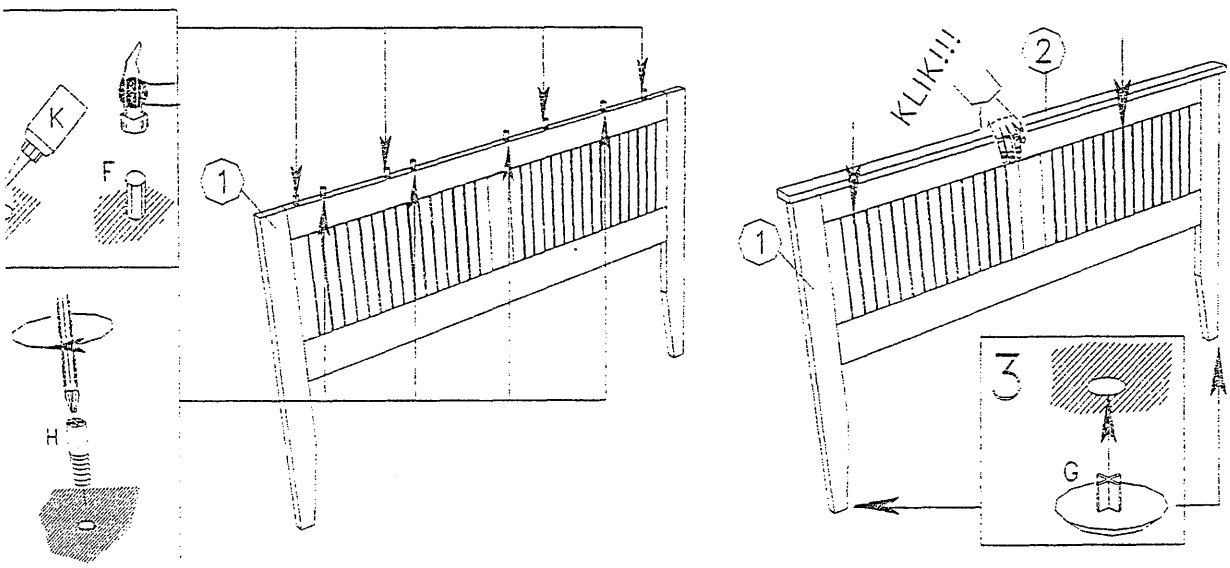

J x8

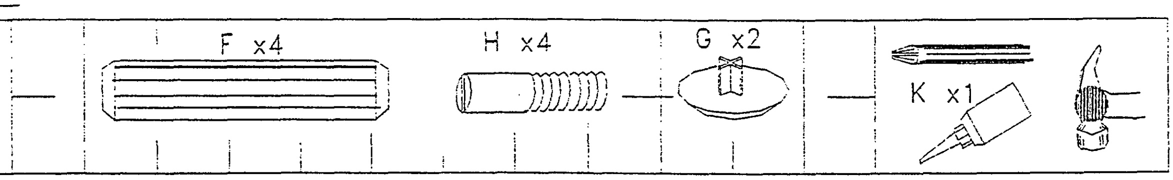

J
x2
3

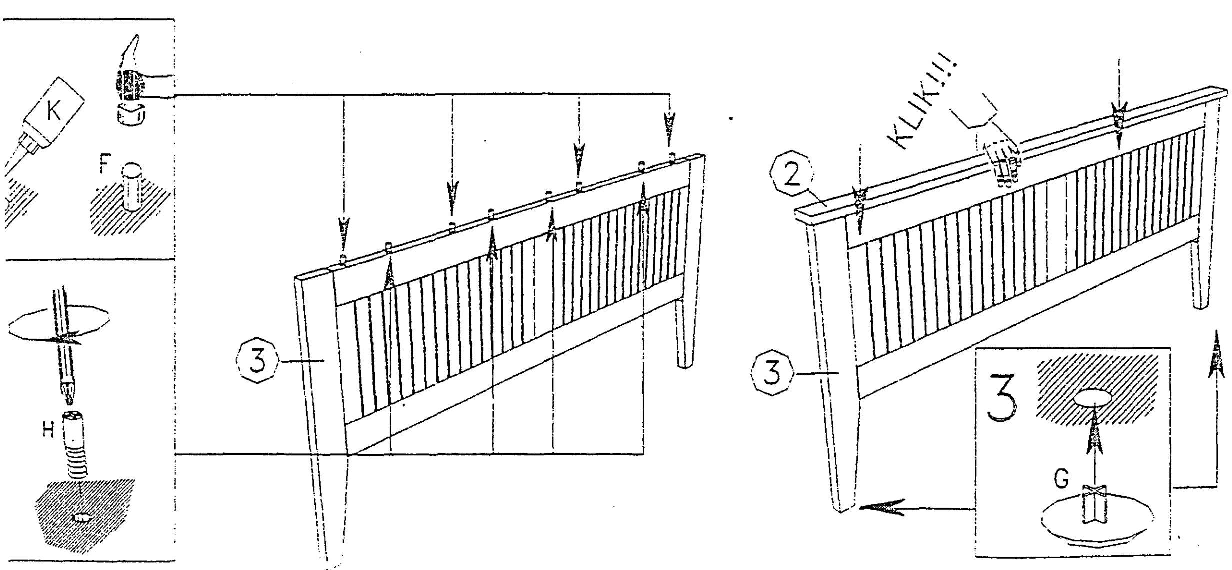
# 4


F x4
H x4
G x2
K x1

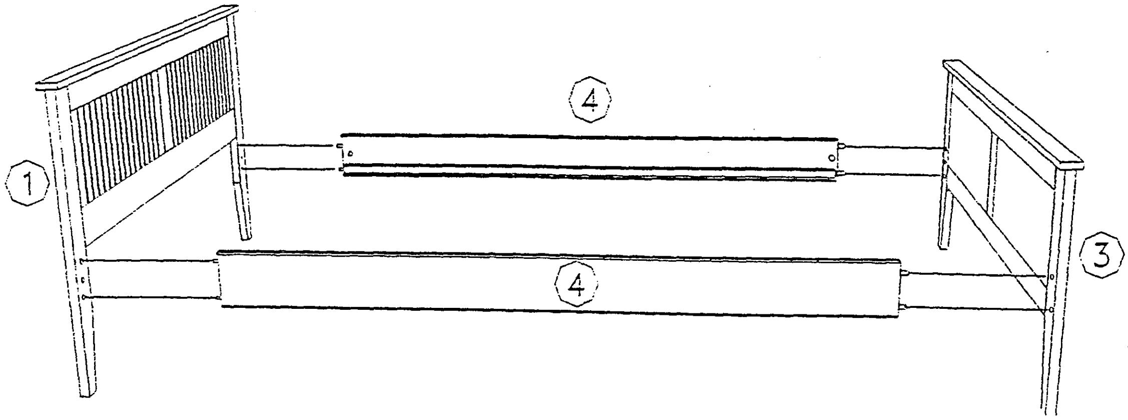

K
F
H
1
KLIK!!!
2
1
3
G

# 5


F x4
H x4
G x2
K x1


K
F
H
3
KLIK!!!
2
3
3
G

## 6

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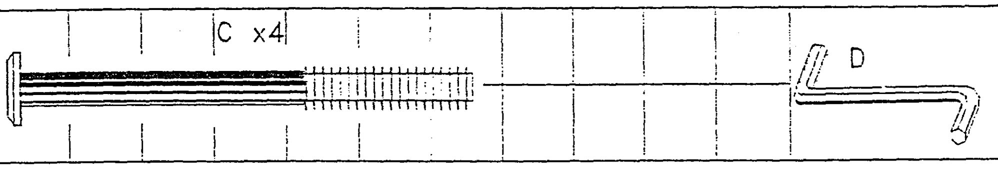


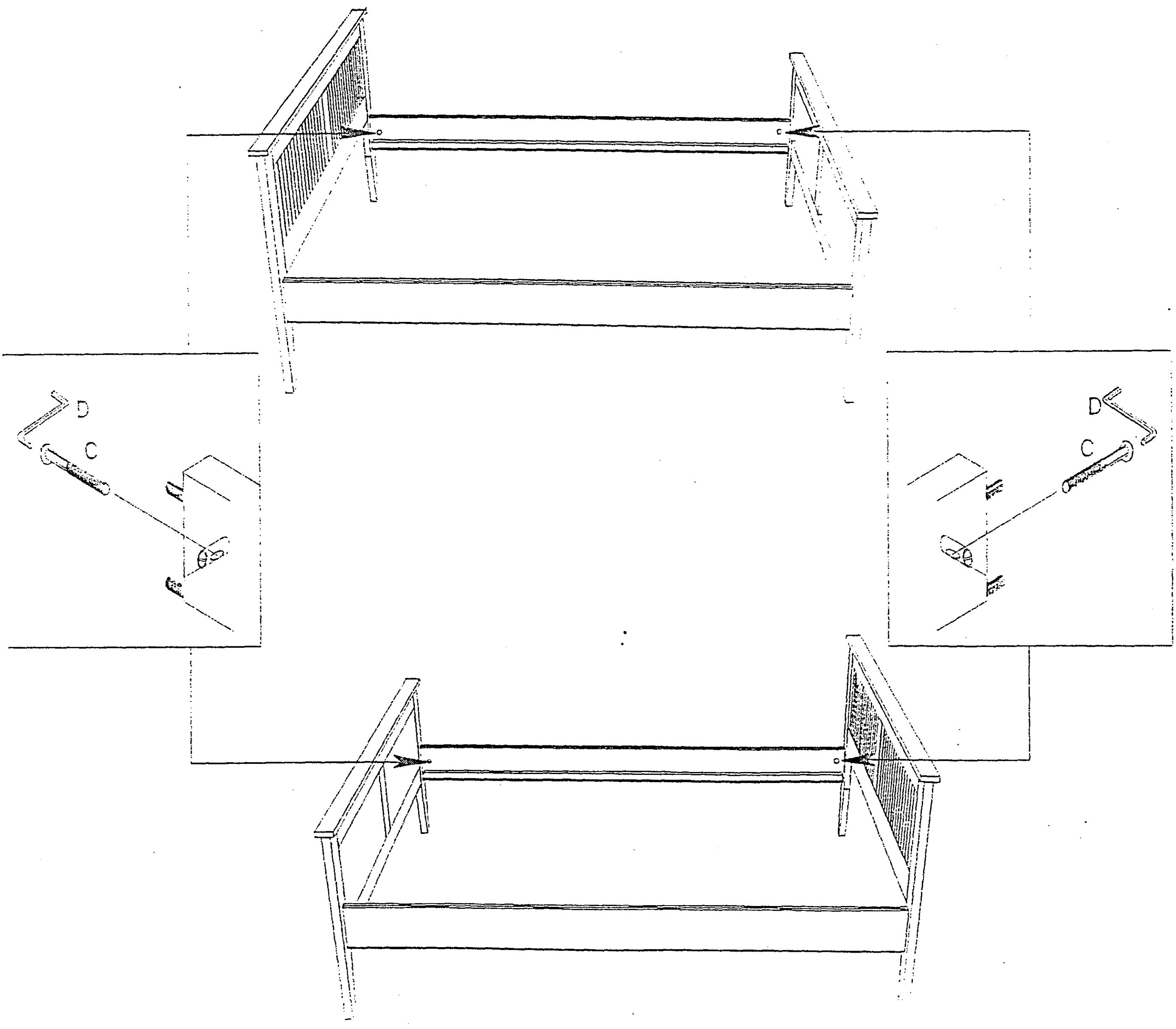

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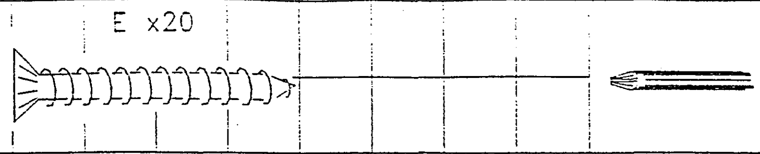
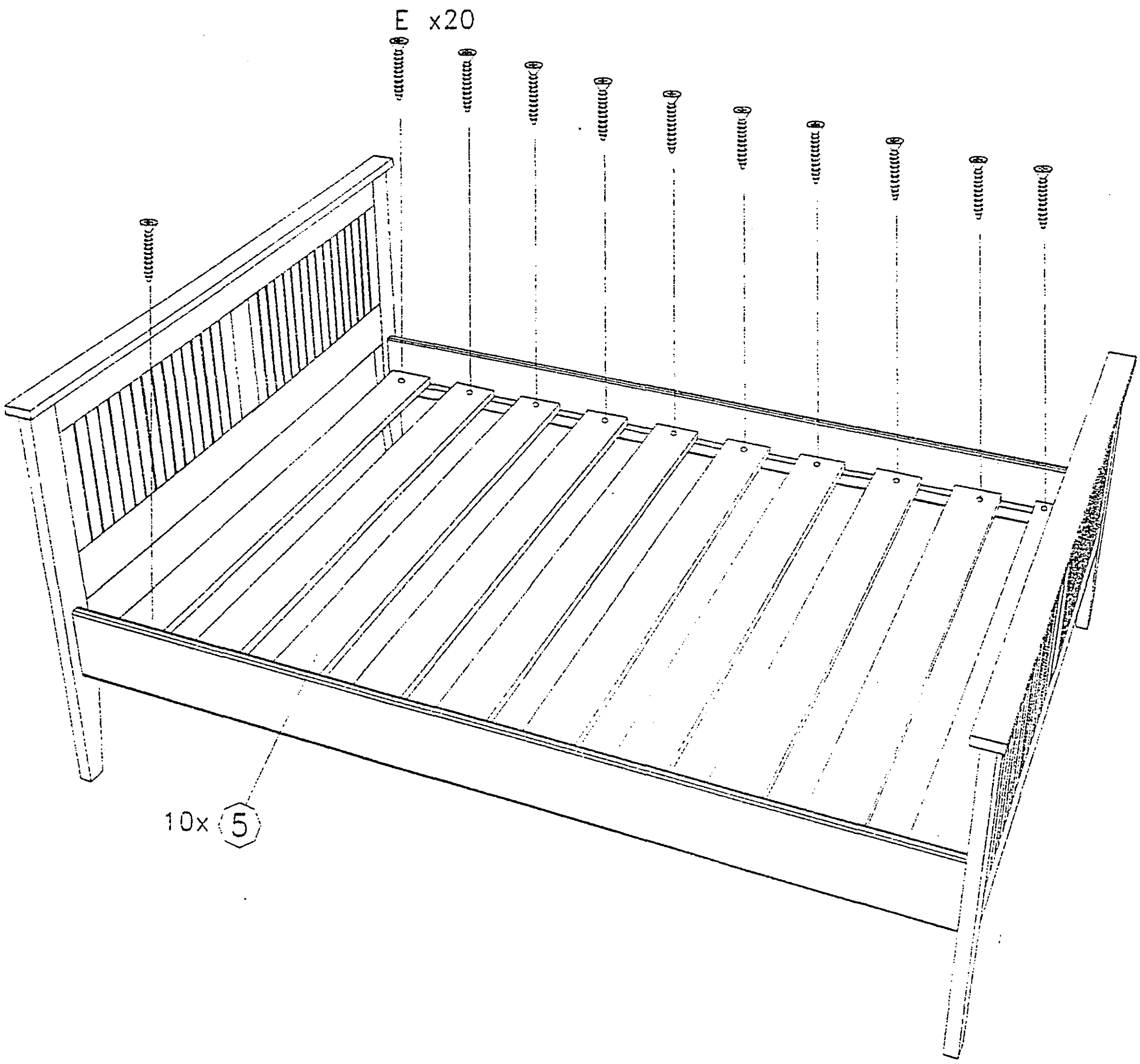


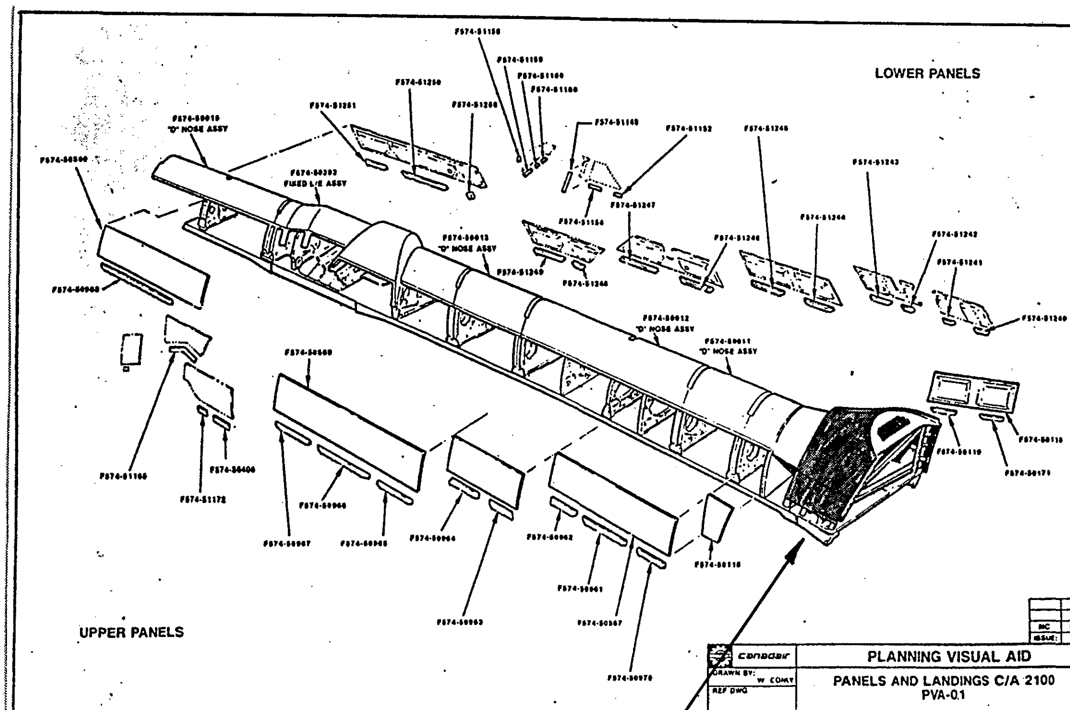



# APPENDIX D

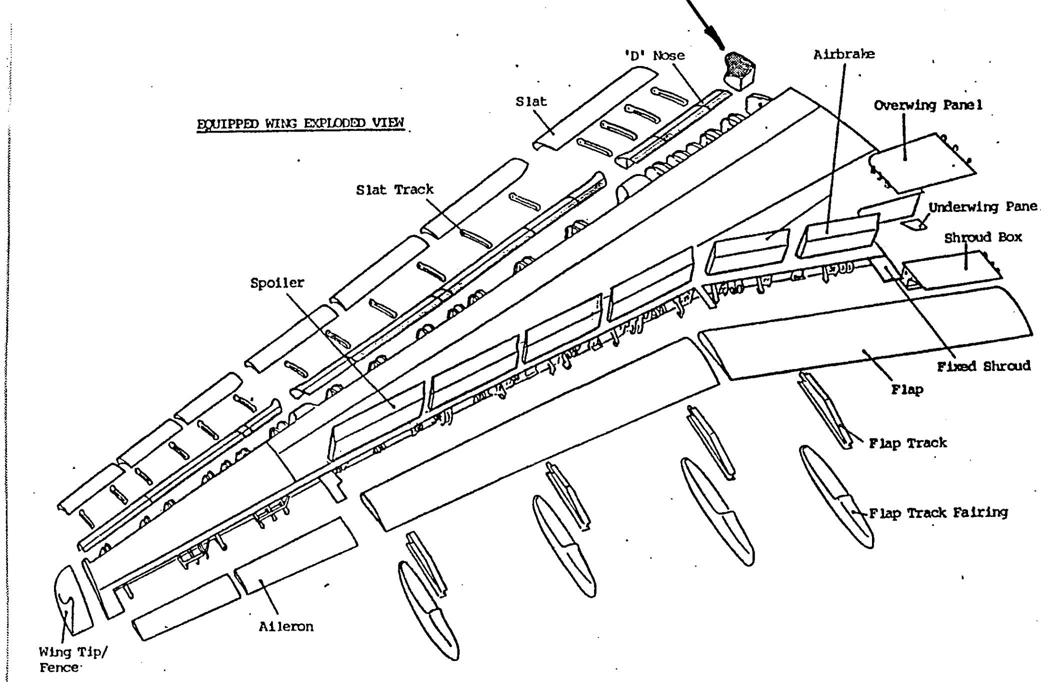
CASE STUDY - BATHTUB DATA

# BATHTUB ASSEMBLY & MAIN WING ASSEMBLIES - AIRBUS

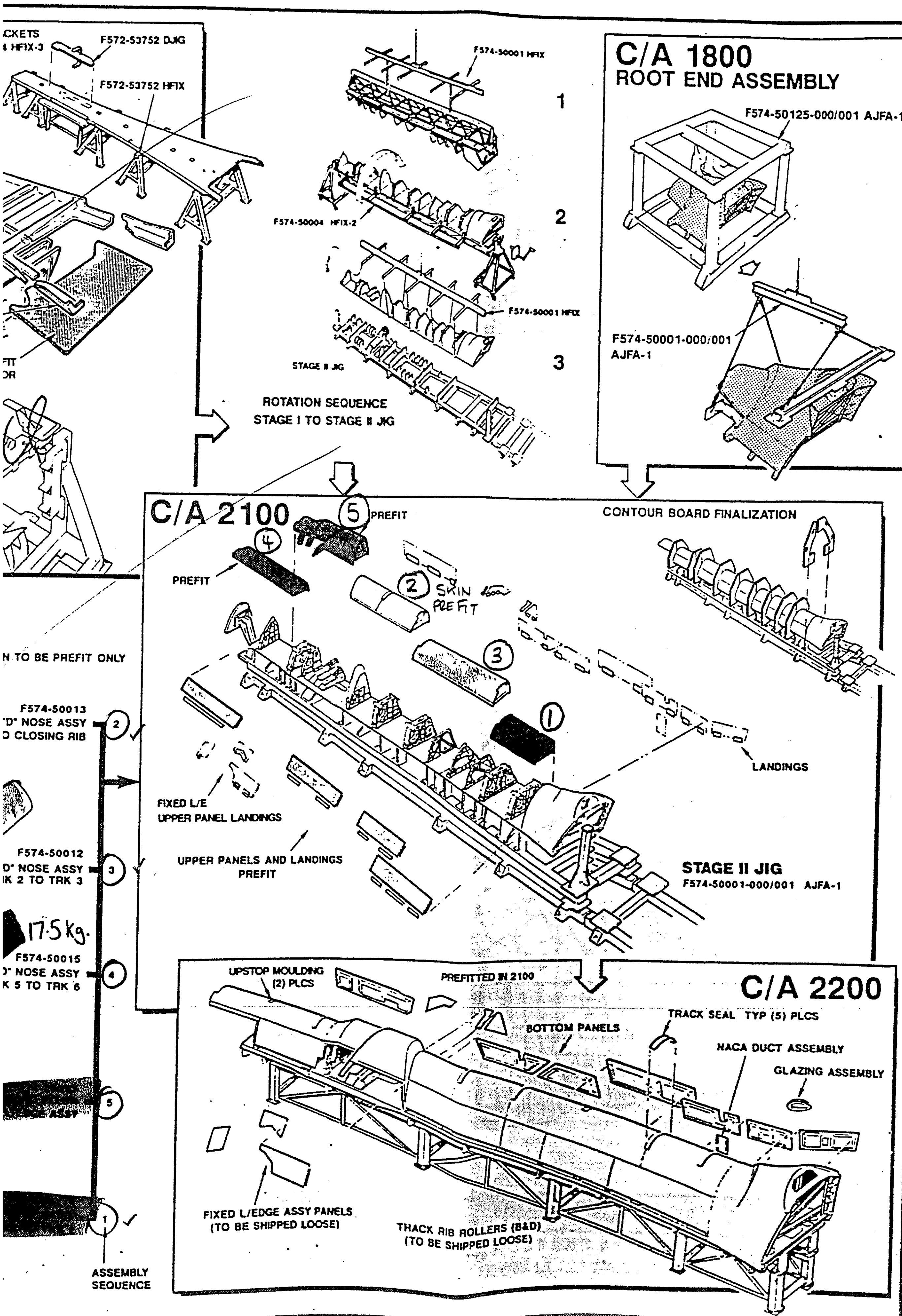
- **Leading Edge Assembly**



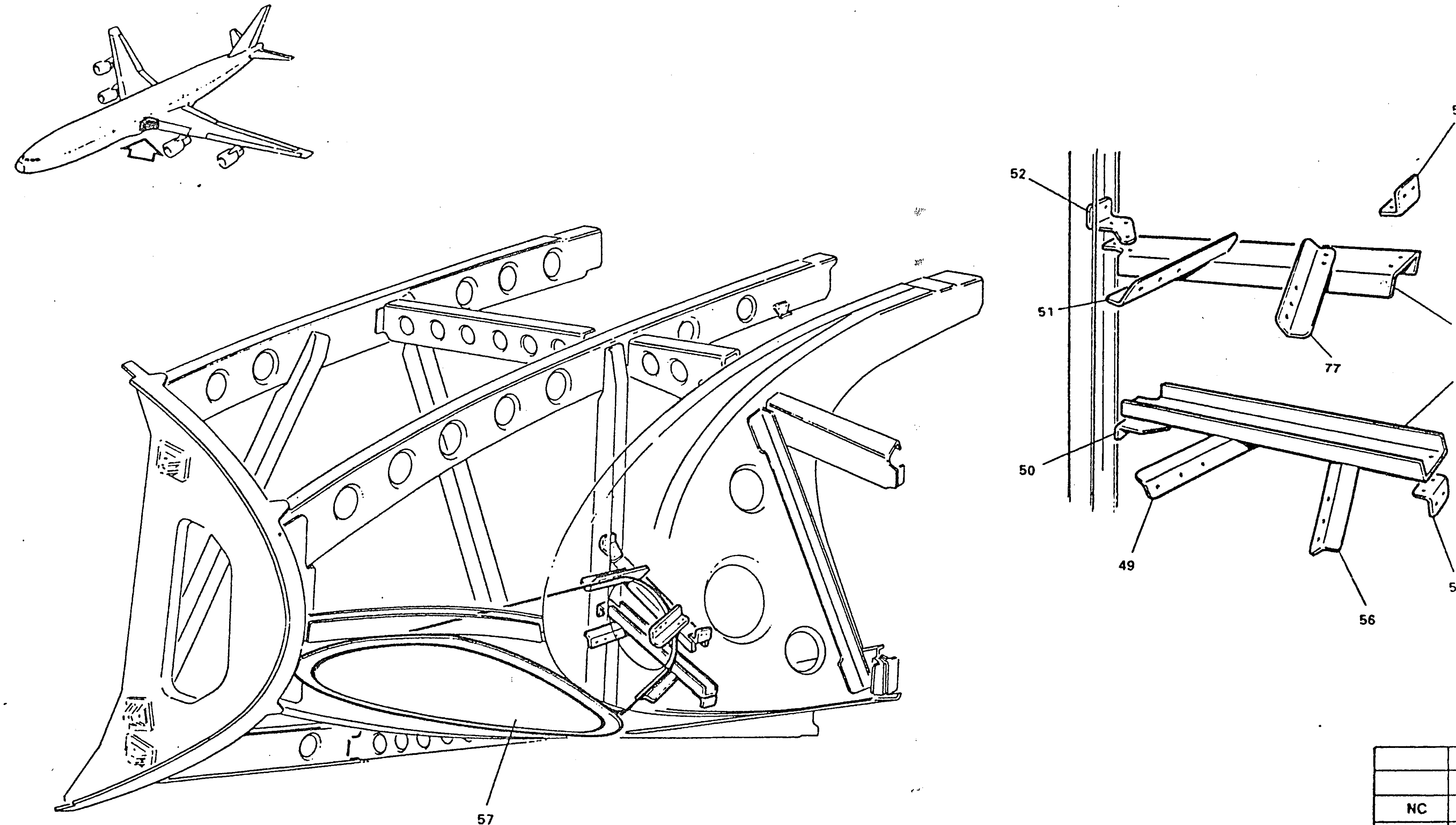

**BATHTUB ASSEMBLY**




- **Main Wing Assembly**



CKETS
4 HFIX-3
F572-53752 DJIG
F572-53752 HFIX
FIT
OR
F574-50001 HFIX
1
F574-50004 HFIX-2
2
F574-50001 HFIX
STAGE II JIG
3
ROTATION SEQUENCE
STAGE I TO STAGE II JIG
C/A 1800
ROOT END ASSEMBLY
F574-50125-000/001 AJFA-1
F574-50001-000/001
AJFA-1
C/A 2100
5
PREFIT
4
PREFIT
2
SKIN
PREFIT
3
1
CONTOUR BOARD FINALIZATION
LANDINGS
N TO BE PREFIT ONLY
F574-50013
"D" NOSE ASSY
D CLOSING RIB
2
FIXED L/E
UPPER PANEL LANDINGS
UPPER PANELS AND LANDINGS
PREFIT
F574-50012
D" NOSE ASSY
K 2 TO TRK 3
3
STAGE II JIG
F574-50001-000/001 AJFA-1
17.5 kg.
F574-50015
D" NOSE ASSY
K 5 TO TRK 6
4
5
C/A 2200
UPSTOP MOULDING
(2) PLCS
PREFITTED IN 2100
TRACK SEAL TYP (5) PLCS
BOTTOM PANELS
NACA DUCT ASSEMBLY
GLAZING ASSEMBLY
FIXED L/EDGE ASSY PANELS
(TO BE SHIPPED LOOSE)
THACK RIB ROLLERS (B&D)
(TO BE SHIPPED LOOSE)
1
ASSEMBLY
SEQUENCE




| | |
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| NC | |
| ISSUE: | |

**canadair** | **PLANNING VISUAL**

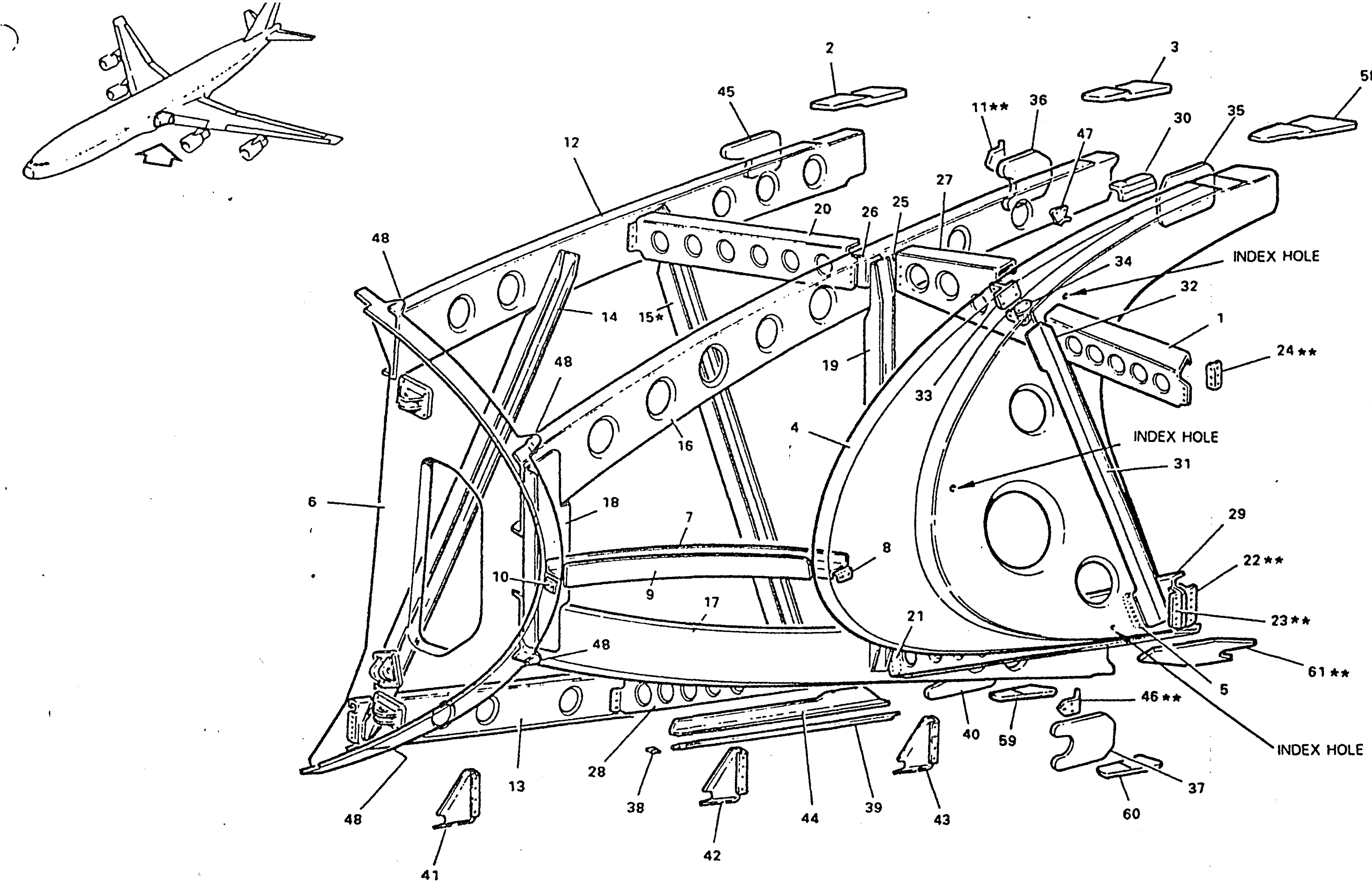
DRAWN BY: W. CONLY

REF DWG F574-50169
F574-50134
F574-50125

OVER-BUILD DOOR
FIXED LEADING EDGE ASSY (RO(
F574-50125-000/001 PVA-01

C/A 1800

SHEET 2




* SLAVE BOLTED ON FINISHED HOLES

** REF ONLY - INSTALLED IN 1900

| | |
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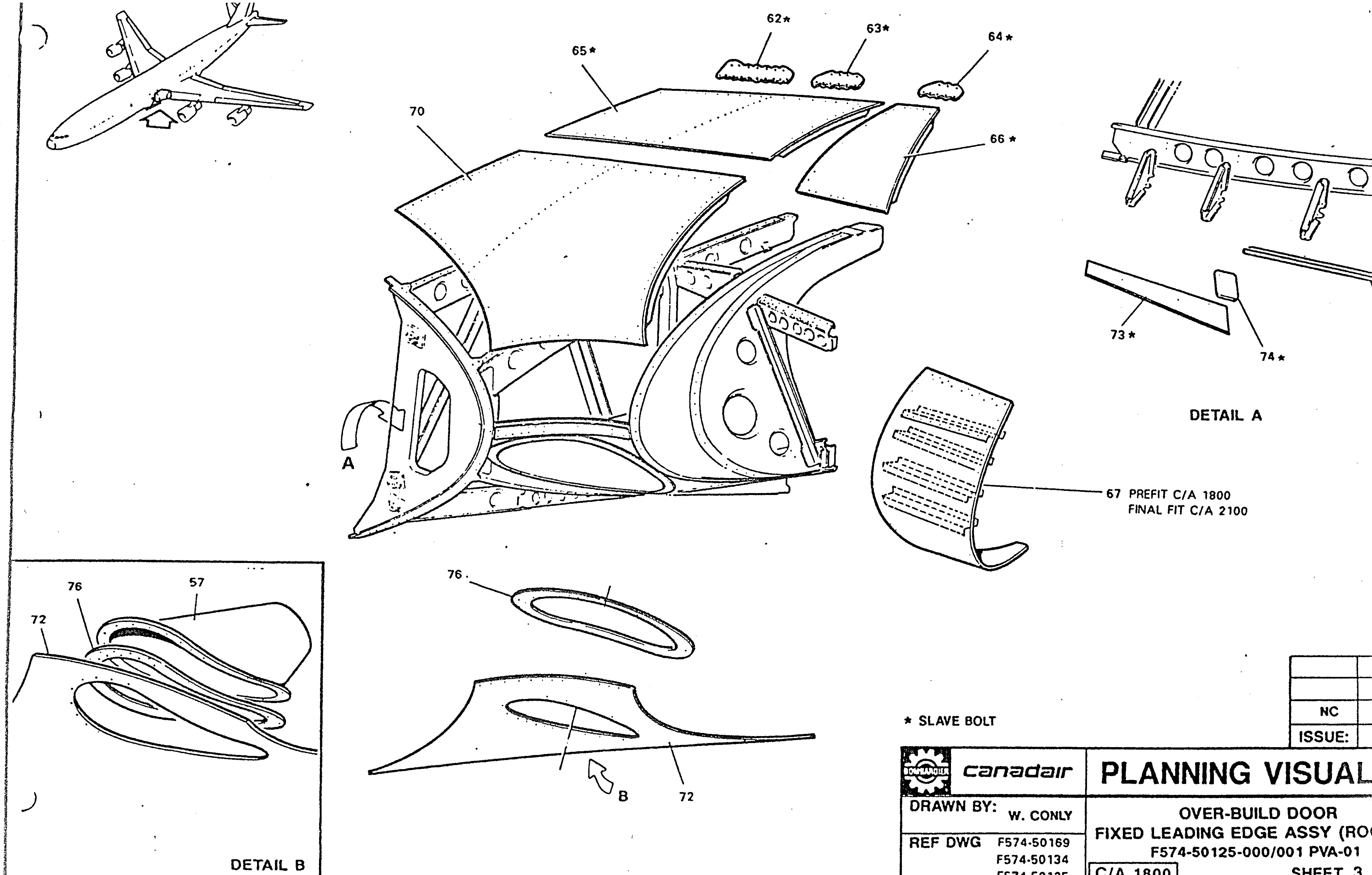
| canadair | PLANNING VISUAL |
| DRAWN BY: W. CONLY | OVER-BUILD DOOR<br>FIXED LEADING EDGE ASSY (RO |
| REF DWG F574-50169<br>F574-50134<br>F574-50125 | F574-50125-000/001 PVA-01<br>C/A 1800 SHEET 1 |




* SLAVE BOLT

| | |
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| NC | |
| ISSUE: | |

canadair

# PLANNING VISUAL

DRAWN BY: W. CONLY

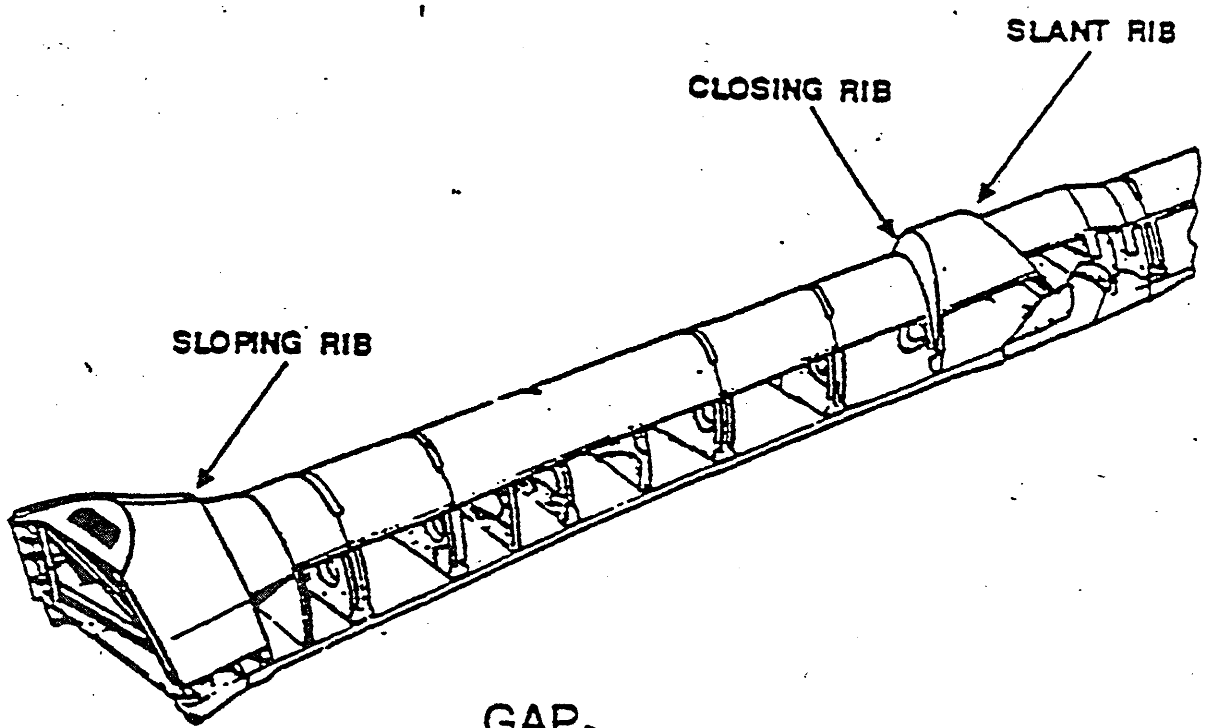
REF DWG F574-50169
F574-50134
F574-50125

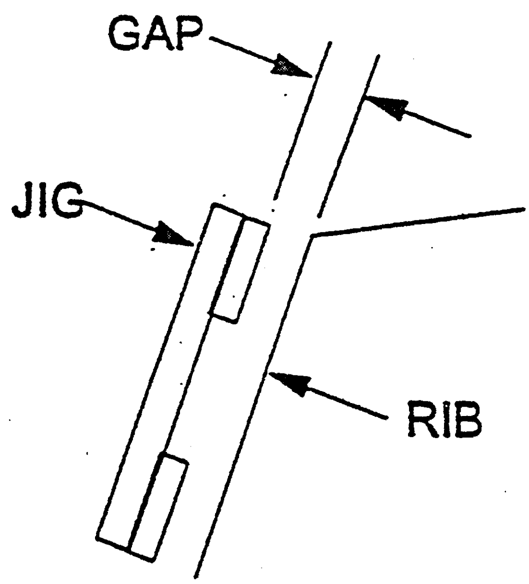
OVER-BUILD DOOR
FIXED LEADING EDGE ASSY (ROO
F574-50125-000/001 PVA-01

C/A 1800

SHEET 3

# STAGE 3




## SLAT INTERFACES

| STAGE 03 | DRAWING TOLERANCE | POINT 1 | POINT 2 | POINT 3 | POINT 4 |
|---|---|---|---|---|---|
| SLOPING RIB ROOT END | 43.00 MM +/- 1.50 MM | 43·54 | 42·11 | 42·34 | 43·56 |
| SLANT RIB PYLON | 43.00 MM +/- 0.50 MM | | | | NOT APPLICABLE |
| CLOSING RIB | 10.00 MM +/- 1.00 MM | | | | NOT APPLICABLE |

RECORD DIMENSIONS

| DATE: | 15-08-95 | K.S.PHILLIPS | ICY. ENG. INSP. |
|---|---|---|---|

# Inner Leading Edge "Bathtub" Quality Issues



**Main problems reported by BAe Toulouse:**

- Attachment holes - misaligned / misshapen
- Steps and gaps Panels to Structure
- Structural fouls
- Missing parts

**Actions taken:**

- Operator Awareness campaign implemented at Chester and Filton sites
- Quality Check list to be embodied
- Target Aircraft for checks MSN 204
- Verification checks to be carried out for minimum Aircraft 10 sets
- Audit activity increased

# AEROSPATIALE QUERY SOLUTION PROGRAMME

## Inboard fixed leading edge assembly

| No: | Bathtub Project Number | Description | Proposed Actions & Solutions | Query Owner | Target MSN | Completion/ comments |
|---|---|---|---|---|---|---|
| | 1 | Landings and fishplates - AS experience loss of land on these parts during drilling. | From msn 182 no more problems seem to have occurred due to their being no contact from AS. BAe to return to previous state of delivery once new drill jigs have been manufactured. New tools are currently being re-designed and manufactured by sub-contract firm. MSN 208 to be checked in Toulouse by BAe representatives | G. Joughin & G. Hughes | Tool target wk43<br>New tool target = MSN 216 | REMAIN PENDING UNTIL POE IS MET |
| | 2 | Top and bottom mid bathtub leg positions- BAe to check position of mid top and btm legs with regard to build door pick-up locations. | Checks carried out on MSN 203, 208, 212 & 205 plus various a/c in different build stages at Filton. All leg dimensions where 977mm +/- 1mm. Similar checks to be carried out in Toulouse. (see attached sketch for details, sketch 1) MSN 207 checked in Toulouse and found to be of a similar standard. | G. Joughin & G. Hughes | MSN 208 during wk 42 (msn 208 ok)<br>MSN 212 during wk45 | CLOSED NOV BI-LATERAL |
| | 3 | Anchor nuts at lifting positions - to be reviewed reference to damage at AS/BAe. | Problem investigated and anchor nuts are now being changed from fixed type to type with floating centres. Mod paperwork completed and mod to be submitted at next available opportunity, conformation to be supplied by Airbus Procurement. MP H13806. | Filton design & A.P. | New mod: No. 46075<br>st4 = 260<br>st6 = 286<br>st7 = 258 (21)<br>st8 = 267 (2) | REMAIN PENDING UNTIL POE IS MET |
| | 4 | Build door / Beam setting slip - no set dimensions for setting of bathtub to the build door. | Set of slips manufactured but found to be of no use due to design of jig at Filton. Problem closed after further discussion. | | | June Bi-lateral |
| | | Stringer drilling - the idea of drilling the top of the stringer full size and the bottom pilot size at Chester to be kept. | Further discussion required to evaluate any problems which have been experienced with previous assemblies drilled full size - C.O.S. to be changed, full size top & pilot bottom. | BAe & AS | From MSN 220 (as per P22 build program) | REMAIN PENDING UNTIL POE IS MET |
| | 5 | Kevlar panel mismatch - mismatch between the 2 off Kevlar panels on the bathtub in the fillet fairing area. | All panels at Filton Aerostructures to be checked upon arrival of master tooling from Samlesbury. All parties to be informed if any discrepancies are found between panels and jigs. note:- temp solution - panels trimmed at Filton, no reported rework from A/S. | Dave Saunders | Refer to Bathtub minutes | |

# Bath tub to Wing Root end fitment Investigation carried out on MSN 208 & MSN 212

**B Ae Actions following on from monitoring exercise completed on above aircraft.**

- Formulate a policy enabling return to original product specification
- Establish target aircraft for above
- Establish number of aircraft to carry out monitoring exercise
- New addition to delivery specifications
  - Permanent fixing of upper Joint plate F574-50137 to Sloping rib
- Establish Samlesbury actions to rectify Kevlar panel discrepancies

Time scale for above actions to be determined at next Project team meeting November 19th 1997

# Bath tub to Wing Root end fitment Investigation carried out on MSN 208 & MSN 212

- Investigation completed on MSN 208 (week 42)
  All findings indicate BAe deliver a good quality Bath tub of a fixed constant build
- Discrepancy discovered between LH & RH Root end wing volumes on MSN 208, due to wing marry up processes at Poste 40 (LH found to be 4mm greater than RH)
- Investigation currently being carried out on MSN 212
- Initial investigation findings indicate NO visible problems on MSN 212
- **CONCLUSION**
  - Filton / Chester to formulate policy of returning to original product specifications
  - MSN 211 findings indicate probable build discrepancy during Wing marry up operations
  - BAe Toulouse Quality Department to monitor MSN 211 LH for possible discrepancy on Bath tub fitment, due to visible misalignment of Front spar to Rib 1 Cruciform of approximately 4mm
  - Aerospatiale to investigate possible difference in build criteria at Poste 40

**Subject: Verification of consistent Build standard and Quality of Bath Tub assemblies, monitored on MSN 212.**

The following report is the documented findings of the investigation / monitoring exercise carried out on aircraft MSN 212 LH and RH as agreed at the Aerospatiale / British Aerospace Engineering Bi-lateral meeting.

MSN 212 Bath tub installation to Wing Root ends monitored in similar vein to that carried out on MSN 208. Initial findings indicated that both Left and Right hand assemblies fitted to aircraft with NO visible discrepancies found.

In addition to above, an exercise was carried out to establish what affect the inner aft strut (F574-50156) has on the installation of Bath tub to wing. The LH strut remained attached to upper and lower Beams during fitment of Bath tub, while the RH strut was removed prior to fitment, Neither method proved to have had any adverse affect on the final assembly of Bath tubs to wings. (e.g. on RH side , Strut refitted to upper and lower Beams with all piloted attachment holes aligned).

Further to Aerospatiale action to monitor Poste 40 operations from previous exercise on MSN 208, MSN 211 Root end volume was investigated and found to reflect that of MSN 208 (i.e. LH greater than RH by 4 mm). Therefore the possibility exists of experiencing a gap condition to that experienced on MSN 208.

Action:

AS Quality Department are now investigating manufacturing processes incorporated at both Nantes (Centre section rib 1), and at Toulouse (Poste 40 wing marry up) facilities.

BAe Toulouse Quality to monitor MSN 211 LH for possible gapping problem between Bath tub to Wing.

Conclusion:

The monitoring exercise carried out on both MSN 208 and MSN 212 has established that BAe does now deliver a good quality product, which is consistent to drawing requirements. Resultant outcome is, it should now be possible to return deliverable standard of Bath tubs to the original work share agreement between Aerospatiale and ourselves. This however will only be achievable after the formulation of an 'in house' policy to return to original product specification.

# APPENDIX E

## ENVELOPE TOOLING

*The Fairey Aviation Co., Ltd.*

# AIRFRAME ASSEMBLY PRACTICE

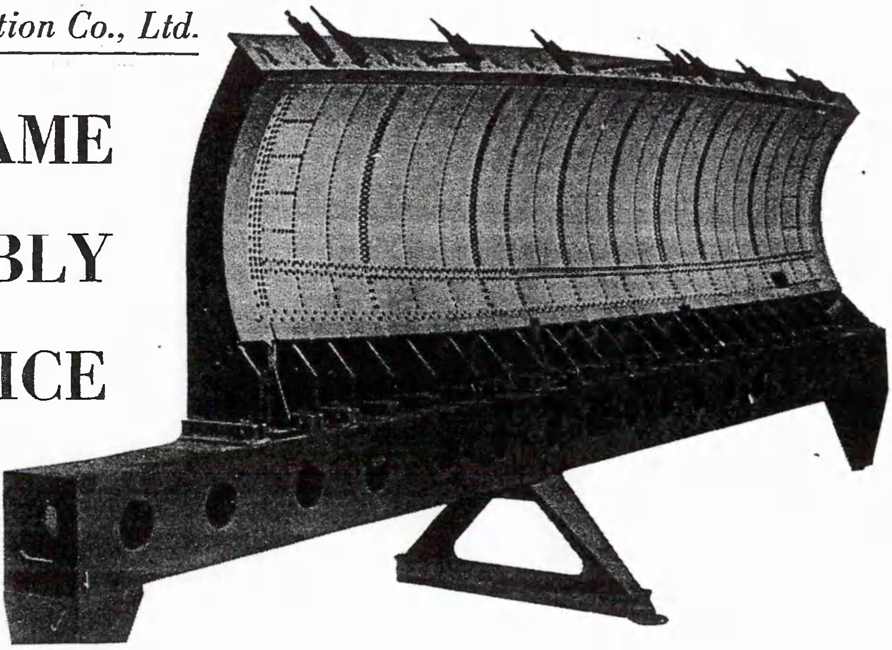


Fig. 1. A typical envelope-type jig designed for bomb-door assembly. This example illustrates the amount of double-curvature that can be obtained without pre-forming : flat skin-panels are used in building the component.

## *A Review of the Fairey Envelope System and Method of Jig Construction*

MORE than 80 per cent of the work of airframe manufacture is devoted to assembly. Consequently, assembly technique and the design of assembly equipment constitute quite a large, almost specialist, field in which there is considerable scope for the development and application of efficient methods. Tooling practice for airframe assembly varies from one firm to another, but since the manufacture of stressed-skin aircraft became established, most of these differences have been comparatively minor variations of the same basic principle.

During the last three or four years there has been a trend, particularly in the building of aerofoil-section components, towards reversal of the usual method of building—from the structure outwards to the skin—and to control the assembly from the skin-surface inwards. This trend is due, primarily, to the very stringent skin-smoothness requirements that are the outcome of the conditions imposed by high-speed flight. However, examination of an extended and much more general application of the principle by the Fairey Aviation Co., Ltd., suggests that for general as well as specific reasons there is much to be said in favour of reversing hitherto-accepted practice for the assembly of skin-covered components.

An outline of the Fairey system, to which the name of "envelope tooling" has been given has already appeared in *Aircraft Production*.* This present review is a more detailed consideration of the system and the methods of producing the assembly fixtures—or assembly jigs, as they may well be termed from the form that they take. The name refers to the aerodynamic form or envelope of the aircraft upon which the system is based. Very briefly summarizing, the envelope type of jig consists of a template (Figs. 1 and 14), accurately shaped to the external form of a portion of the aircraft and supported by a series of formers erected at intervals along a rigid base. The airframe unit is built up on the template, drilled through from the outside and also riveted on the jig.

### Formers and Template

The former profiles represent contours established at a predetermined distance *outside* the skin-plating of the aircraft and are lofted at the same time as the actual aerodynamic outline. Inherent accuracy of the profiles is, therefore, obtained at the outset of design and the possibilities of inaccuracy and delay that could arise from separate calculation at a later stage are avoided. The former stations are determined during the design of the aircraft and are established at points away from the positions of frames, ribs and other stabilizing and structural members. In this way, maximum accessibility is obtained for riveting and certain difficulties of fixture construction are avoided.

*A RECENT trend, due to much more stringent requirements for skin-smoothness, has been to control the assembly of certain airframe components from the skin inwards. Envelope tooling, the system developed by Fairey Aviation Co., Ltd., carries this principle further and applies it much more widely than hitherto, and also offers advantages additional to those of skin-smoothness control.*

*An outline of the system appeared in "Aircraft Production" for January, 1950, and in this article the special equipment developed and the method of assembly-jig construction are examined more closely.*

A complete set of former contours is reproduced on a single metal sheet, and each one is cut out and finished in turn to serve as a template for spindling or routing the actual former. Formers are made from a paper-base phenolic - resin impregnated plastic material.

The jig template, of 14 s.w.g. light-alloy sheet, is attached to the contoured faces of the formers by countersunk-headed screws inserted through the template into the formers and secured by nuts. Wherever possible—and in a large number of cases it is possible—the sheet is sprung into the form of the template. A smoother contour is obtained in this way than if the flat sheet were preformed, though in some examples of double-curvature forms, stretching or wheeling is necessary. The *inside* form of this sheet represents the *outside* form of the aircraft.

After being placed in position the plate is sprayed with a suitable film for marking-out. The outline of the skin of the component—that is, the boundary edges of the skin panels—are laid out, as well as the positions of the

* *Envelope Tooling, January, 1950.*

ribs or frames or other internal members, and the positions of rivet- and other attachment-holes. The layout is checked and holes are drilled through at attachment-hole positions to convert the sheet into a large drill-template. The edges of the skin-panels are also defined by a series of holes drilled outside the marked-out outline and, on jigs for components that have detachable covers or doors, the outline of the aperture is similarly defined.

### Pick-up Fittings

Where necessary, pick-up fittings, either the actual aircraft fittings or tooling dummies, are set up on the template to control the accuracy of inter-component attachment points. For locating such a fitting in its correct position relative to the form of the template, a special piece of equipment has been designed (Fig. 2). It consists of a horizontal datum-member, clamped to the base of the jig and carrying a vertical member, on which in turn is mounted a second horizontal member that projects towards the template. At the end of this second horizontal arm is a small platform with a fully universal mounting (Fig. 3). All three arms of the equipment are jig-bored accurately with $\frac{1}{2}$in dia. holes—in the horizontal members, a single line of holes at 2-in centres and, in the vertical member, two lines of holes staggered to give 1-in centre adjustments.

These holes permit the platform to be set at any required position in space and, by adjustment of the platform, it is possible, in addition, to obtain any compound angle that may be required. The setting of a fitting is done in the toolroom by mounting the universal platform on a sub-base (Fig. 4) where any alignment and angular adjustment can be made with convenience and precision. This setting is made with due regard to the centre-distances between adjacent holes in the carrying members, so that by specifying certain hole positions in the three members, the final position is accurately obtained when the equipment is set up on the fixture.

In mounting the fitting in position, the method adopted is to arrange a box on the structure of the jig, into which an attachment extension of the fitting can project and around which molten Cerromatrix can be run (Fig. 3). The extension, or shank, of the fitting is grooved (Fig. 4) to give a key for the Cerromatrix.

To as great a degree as possible, the constructional elements used in building these assembly-jigs have been standardized. Standard, square-section grey-iron castings supplied in three lengths are used for bases and frames. Standard castings are also used as attachment brackets for formers. The three-point support principle has been adopted to give stable support on any surface, and duplex- and single-leg castings are also standardized. The various ways in which these units can be built up into jigs or fixtures for various types of airframe components have also been codified and made the subject of drawing standards. Most of the schematic, exploratory, part of the work of design has, therefore, been eliminated and a fixture for practically any type of component can be produced from stock parts without the delays inseparable from a *de novo* design.

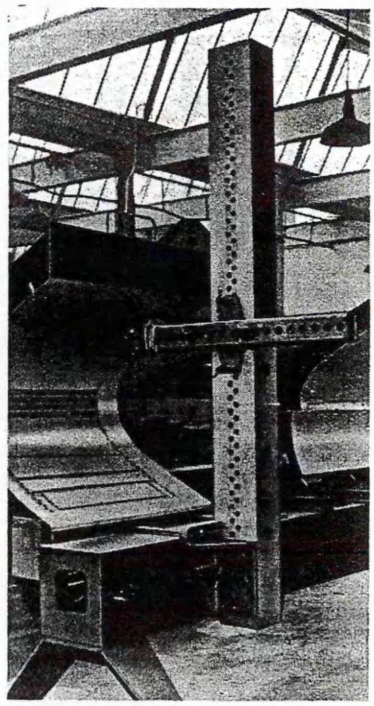


Fig. 2. Method of holding locating-brackets or pick-up fittings while they are being set in position on the jig. The jig-bored datum-bar, post and arm, permit accurate longitudinal, vertical and transverse settings.

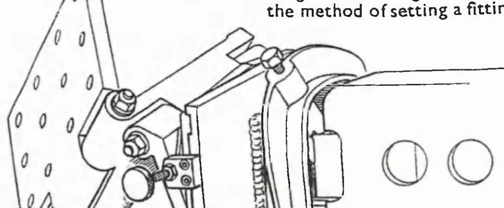
Although this review is primarily concerned with their use in the envelope type of fixture, it will be obvious that these elements are practically universal in their applicability. They can be equally well used for the construction of fixtures for purely structural assemblies, such as the picture-frame type for bulkheads, or table-fixtures for spar-assemblies. A further advantage of the square-section elements is that they can be re-used many times, as fixtures become obsolete and are replaced by others.

### Marking-Out

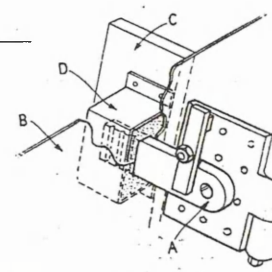
Clearly, the main problem in producing assembly-jigs of the envelope type is that of marking-out the templates to establish the positions of the structural members. The equipment that has been developed for this purpose, simple, effective and extremely ingenious, is indeed the basis of the whole system of envelope tooling. Dimensions are laid off as ordinates from horizontal and vertical datum-surfaces, and longitudinally from a datum at the left-hand end of the fixture (Fig. 5).

All marking-off is done from what is, in effect, a mobile marking-out table (Fig. 6). It consists of one of the standard jig-base castings with two sides machined and scraped to give accurate plane surfaces that serve as horizontal and vertical datum-faces. Along the whole length of each surface is machined a slot $\frac{1}{2}$in. in width, which is used for clamping purposes. Attached to the back of the casting are

Fig. 3. (below). The universal mounting at the end of the horizontal arm of the rig shown in Fig. 2. The detail view (lower right), shows the method of setting a fitting on the jig-structure.



A = Fitting
B = Envelope template
C = Former
D = Box for Cerromatrix



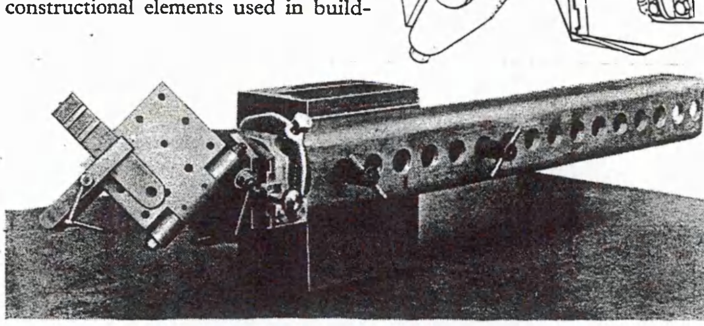



Fig. 4. (left). The fitting is set in the toolroom, with the horizontal arm of the rig mounted on a sub-base.

*AIRFRAME ASSEMBLY PRACTICE (Continued)*

brackets by which it can be related to the base of any assembly-jig as required. This problem of relating the two units is of fundamental importance to the whole system: accuracy must be unexceptionable and is the primary objective. Obviously, however, it is important, not only that the relationship should be achieved reasonably quickly, but that it should be possible to repeat it as often as necessary and equally quickly, if modifications to the jig-template should be required—and in aircraft practice modifications are inevitable.

This objective has been attained very simply: the brackets already mentioned are jig-bored to receive location-pins for aligning the top plane surface and accurate alignment of the vertical surfaces is obtained through the attachment faces of the brackets, which are machined accurately parallel with the front face of the table. Longitudinal relationship is given simply by inserting a location-pin through one bracket into a hole in the front face of the jig-base; alignment of the top (horizontal) plane surfaces is given by pins inserted through the tops of the brackets to rest on the top surface of the jig-base (Fig. 7).

During the marking-off, the two units are clamped together by bolts passed through the brackets. The mobile table and its associated equipment have a weight of something of the order of a ton and if supported only by the fixture, could cause distortion and introduce errors into the marking-off. Ease of handling and avoidance of distortion are, of course, reasons for mounting the table on a trolley, but, in addition, a special mounting has been adopted for minimizing the load in any local circumstances. The table itself rests on four vertical spiral springs (Fig. 6), which in turn are carried in pairs on two screw-jacks. When the table is to be attached to a jig-base these jacks are adjusted until the top-surface alignment pins are "easy" on the top of the base and could actually be withdrawn with an effort comparable to that required for a push fit.

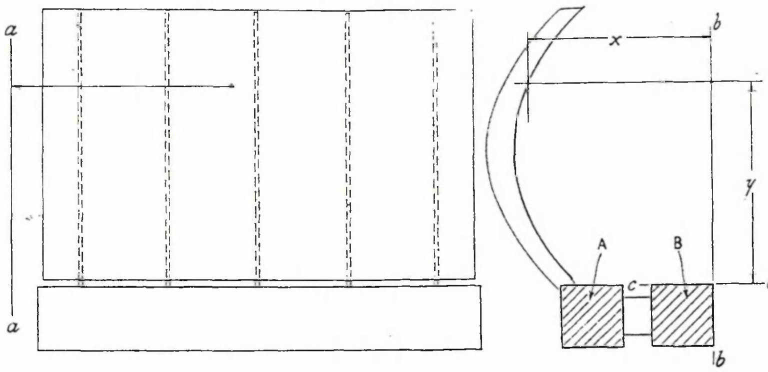



Fig. 5. Diagram illustrating the manner in which the template is marked out from horizontal and vertical (longitudinal and transverse) datum-lines.

a, a = Datum for longitudinal dimensions
b, b = Datum for transverse dimensions
c, c = Datum for vertical dimensions
x = Transverse dimension
y = Vertical dimension
A = Jig-base
B = Marking-out table

### Scribing-tower

The main item of marking-off equipment proper is the scribing-tower (Fig. 6), from which vertical and angular datum-lines are laid out on the jig-template. Excessive weight in this equipment would carry with it penalties of both inefficiency and inaccuracy, and throughout its design the objective has been to combine lightness with rigidity. The scribing-tower is a square, lattice-girder structure, some 5ft 6in in height and built up from square-section steel tubing with a wall-thickness of 20 s.w.g. It is carried on a base of cast light-alloy—again to save weight—which slides on the top surface of the marking-off table on hardened steel pads.

The tower can be tilted on its base through a full 90 deg from vertical to horizontal. Two clamping quadrants are mounted on the base of the tower, on the eccentric ends of a transverse spindle, which can be partly rotated by a handle. By rotating the spindle, a small movement is imparted by the eccentric ends of the spindle to the quadrants, which, when the tower is clamped to them at an angular setting, are, in effect, integral with it. This slight additional movement is used to give the final fine-adjustment of angular setting (Fig. 8).

To give support to the tower at settings in the range, 45 deg to horizontal, a stand (Fig. 6) has been designed of very light 22 s.w.g. steel tube. The stem of the stand is telescopic and gives a range of adjustment of 22½in. When the tower is being used wholly

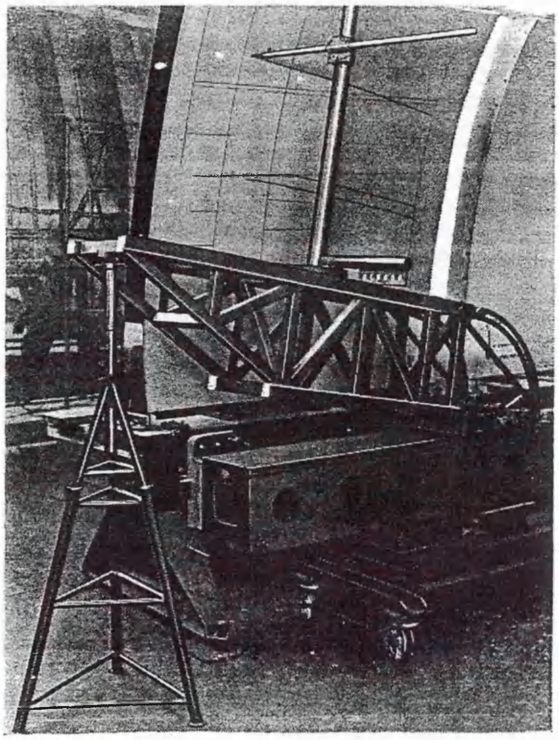
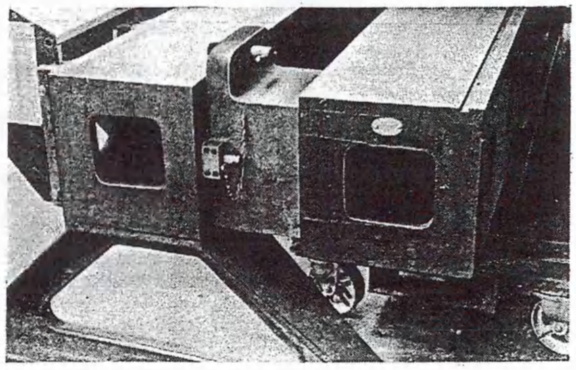
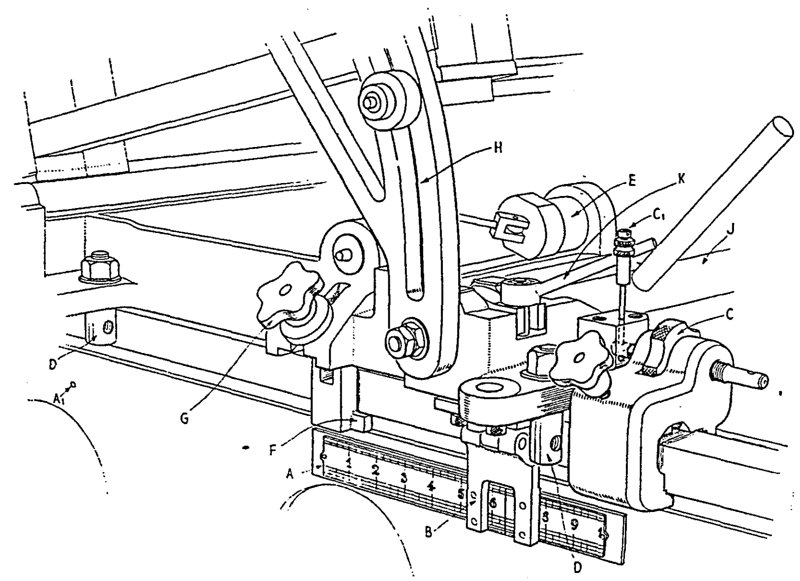


Fig. 6 (left). The scribing-tower set over at a low angle (between 45 deg and horizontal) and supported by the tubular stand from the floor. The top portion of the stand can be detached and used on the marking-out table separately.

Fig. 7 (below). One of the brackets by which the marking-out table is connected to the fixture base. One of the two pins is shown that give horizontal alignment between the table and fixture base and also the pin for the longitudinal relationship.






A = Graduated scale
A1 = One of 10in-centre datum-holes
B = Cursor
C = Fine adjustment for longitudinal position of tower
C1 = Locking-pin
D = Fixed alignment-pin
E = Casing of loading-spring for pivoted alignment-pin
F = Clamping-tongue
G = Clamping-nut
H = Clamping-quadrant
J = Transverse spindle, with eccentric ends that engage clamping-quadrant and give fine adjustment of the tower-angle.
K = Clamp for transverse spindle

Fig. 8 (above). Constructional details of the scribing-tower base.

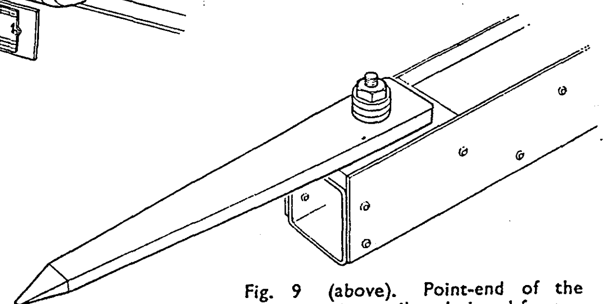


Fig. 9 (above). Point-end of the square-section scriber designed for use with the tower.

over the marking-off table, the top portion of the stand can be removed and used separately by placing it on the top of the table. If the tower should overhang the table, however, the whole stand is used (Fig. 6) to give support directly from the floor.

Squareness of the tower in relation to the marking-off table is maintained in a manner resembling that of a slide-rule cursor. Two pins, mounted in the base, project downward in front of the vertical plane surface of the table. A third pin, on the other side of the base, carries at its end a small ball-bearing, which is kept in contact with the back vertical face of the table by spring loading the pin and has the effect of drawing the two fixed pins at the front into close contact with the vertical datum-face (Fig. 10). For taking up any loose movement between the base of the tower and the table, particularly when it is set over at an angle, two tongues, which engage the longitudinal slots in the table plane faces and are carried on a single bracket (Fig. 10), are drawn outwards by a screw inclined at 45 deg, with the effect that the tower is firmly clamped against both horizontal and vertical datum-faces. A second clamp engages another longitudinal slot machined in the back face of the table casting.

Attached to two of the vertical corner-members of the tower are 10 s.w.g. steel strips, the edges of which are finished accurately square with the front vertical datum-face. These edges serve as the actual scribing datum and give, in effect, a "relieved" face of the full width of the tower. On the base of the tower is carried a transparent cursor, the zero-line on which is accurately aligned with the scribing datum-face on the side of the tower and is used to set the tower at any required dimension from datum along the marking-off table (Fig. 8).

In order to obtain this dimension quickly, small holes are jig-bored in the front face of the table, at 10-in centres. These holes are related to the datum from which the longitudinal dimensions of the component are taken and the positions of the formers along the jig-base are also accurately set in relation to the same datum. The ends of a 10-in steel rule can be located in the jig-bored holes and any dimension greater (or less) than the nearest multiple of 10in can be quickly obtained by setting the cursor on the tower-base to the appropriate point on the rule. A screw fine-adjustment similar to that on a vernier-gauge permits the final accuracy of setting to be obtained with ease and certainty.

### Scribing Equipment

For use with the tower, a square-section scriber has been designed. Here again, lightness has been the objective and the stem of the scriber is made from light-alloy 2-in square-section extrusion with a wall-thickness of 20 s.w.g. Strips of 16 s.w.g. steel are riveted to opposite sides and serve as the datum face of the scriber, giving again a relieved face which is laid against that of the tower. At one end, the space between the two strips is filled-in to give

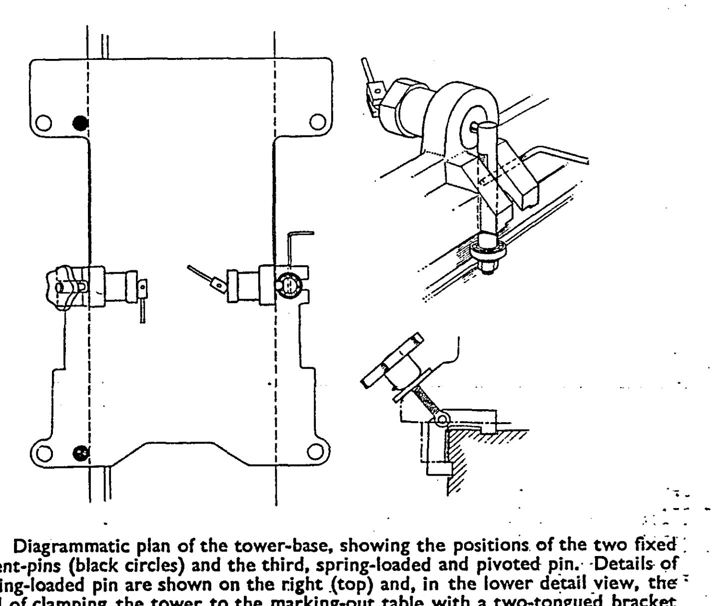


Fig. 10. Diagrammatic plan of the tower-base, showing the positions of the two fixed alignment-pins (black circles) and the third, spring-loaded and pivoted pin. Details of the spring-loaded pin are shown on the right (top) and, in the lower detail view, the method of clamping the tower to the marking-out table with a two-tongued bracket is illustrated diagrammatically.

***AIRFRAME ASSEMBLY PRACTICE* (Continued)**

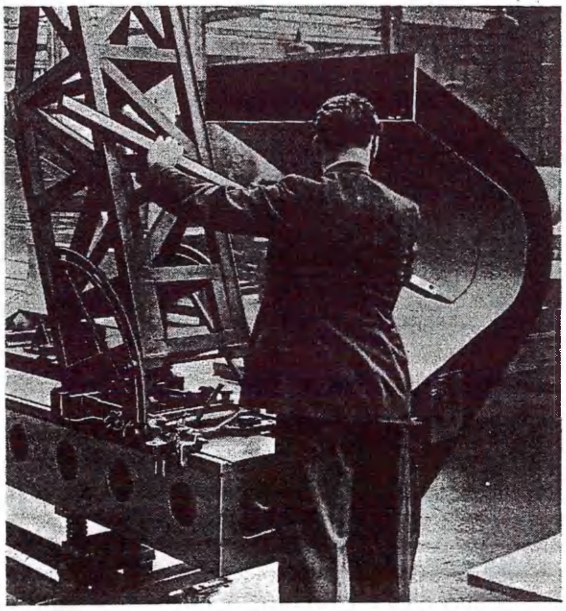


Fig. 11. Method of using the square scriber for marking out the envelope template. The scribing-tower is here shown set over at a small angle to the vertical. Angles are set by aligning the point of the scriber with two calculated "fixes" on the envelope template.

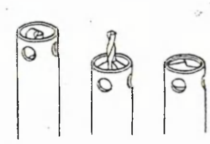


Fig. 12 (below). Sleeve extensions are fitted to Desoutter Mighty Atom pneumatic rotary units to give depth control of countersink and of the flush-milling of rivet-heads.

a flush surface across the whole width of the scriber. This surface serves as a seating for the scriber-point—a flat strip of tool-steel tapered to a point and ground to a scribing-edge from one side only.

This construction has been adopted to maintain the single datum-line throughout, from the cursor setting on the table, *via* the datum-face on the tower and the datum-face on the scriber, to the datum-side of the scriber point, all of which are, in effect, a single straight line when the tower is vertical. Also, the use of a flat strip permits an easy check of the truth of this final, but detachable, section of the straight line to be made by laying the strip on the plane surface of the table and testing it for "rock."

When in use, the scriber is held manually against the datum-face of the tower. In laying out angular lines, reliance is not placed on setting the tower itself to any form of graduated scale. Instead two "fixes" are calculated—as widely spaced as possible on the area to be marked-out—and the angle is obtained by setting-over the tower until the scriber, by manipulation, will intersect both points.

Horizontal (or nearly horizontal) lines are laid out by another type of scriber, mounted on a base which is an enlarged form of the normal plain workshop scribing-block. It has a circular base, with a tubular column 3in in diameter, and the scriber-point is carried in the end of a tubular arm. Here, the point is of silver-steel rod, $\frac{5}{16}$in in diam, but its mounting in the end of the tubular arm is eccentric. By slacking off a set-screw, the mounting can be rotated in the tubular arm to give a fine adjustment of height.

Dimensions in the vertical plane are obtained in a similar manner to those along the table. A tubular post is securely clamped to the front of the table and carries at 10in intervals, welded-on pads, which are accurately jig-bored at 10in centres to receive the graduated scale already mentioned. Incidentally—a very necessary precaution in workshop equipment—the posts are sufficiently robust to withstand, without loss of accuracy, considerably heavier treatment than they should normally receive.

### Marking-out Problems

Several special problems arise in laying-out datum-lines on three-dimensional forms and some special items of equipment have been designed to solve them. There is, for example, the relatively simple case of a line on a tapered form that in plan view appears to be parallel with the centre line, but because of the taper is inclined in elevation. This case has several more complex variants, but even the one mentioned can be a difficult problem in setting-out. An extremely simple solution has been provided by a special scriber, a variant of the standard type for horizontal lines already described.

The general construction (Fig. 13) is the same, but the horizontal arm which carries the scriber, is keyed to the vertical column in order to maintain it in constant 90-deg relation to two datum-pins in the base. The scriber-point itself is perpendicular and is free to swivel in the vertical plane round the end of its arm. In using the scriber, the pins are located against the front (vertical) datum-surface of the table. In this way the scriber is guided to produce the line parallel in plan view.

As it is moved along on its base, the scriber climbs the gradient caused by the tapering of the form, to which it accommodates itself by swivelling round its arm. A bob-weight on the scriber-point itself keeps it firmly

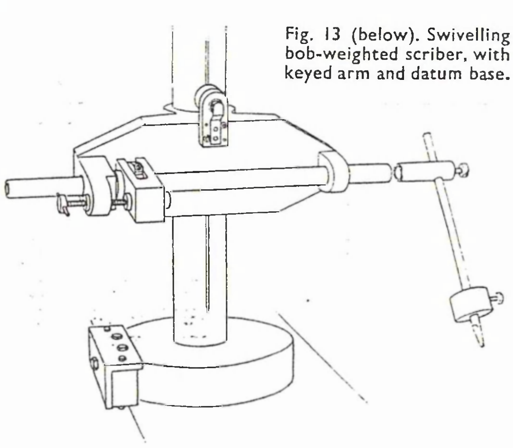


Fig. 13 (below). Swivelling bob-weighted scriber, with keyed arm and datum base.

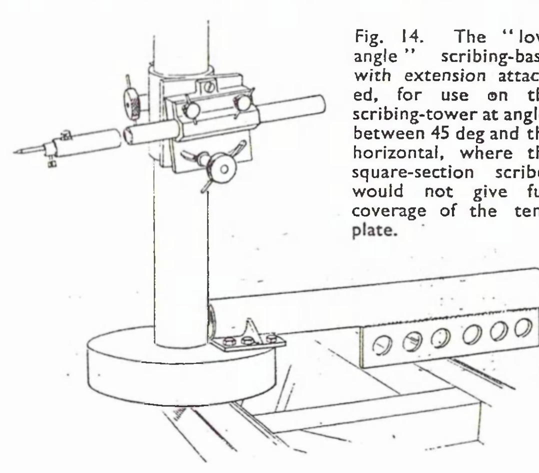


Fig. 14. The "low-angle" scribing-base, with extension attached, for use on the scribing-tower at angles between 45 deg and the horizontal, where the square-section scriber would not give full coverage of the template.

in contact with the template. By reversing the scriber-point in its arm and placing the bob-weight on its tail instead of near the point, this scriber can be used for marking out the upper or lower portions of a curved template. For the more difficult case, where the line is inclined both in plan and in elevation, a straightedge is clamped to the top of the table at the required plan-view angle and serves as a guide for the datum-pins in the scriber-base.

For use on occasions when an exceptionally long reach is required—as, for example, in marking out a template of deep curvature—a scriber with a triangulating brace between arm and base is used to prevent errors in marking-out arising from deflection at the point. When the tower is set over to angles between 45 deg and the horizontal, a point is reached below which the usual square-section scriber has not sufficient reach to cover the template from top to bottom. Use is then made of a variant of the base-and-column type of scriber, with an extension on the base to permit its being seated on the tower (Fig. 14).

When the template has been fully marked out, pilot-holes $\frac{1}{8}$in. in diameter are drilled through, and subsequently opened out to $\frac{1}{2}$in diam. These holes are really guides for the structure-drilling and rivet-milling attachments that are used. Each attachment consists of a sleeve extension fitted to a standard Desoutter Mighty - Atom pneumatic unit. The sleeve serves both as a guide-bush and as a depth-gauge, because its axial relation to the tool which it encloses can be adjusted by nuts at the back end (Fig. 12). Cut-countersinks are used on the skin and a combined drill and countersink produces rivet-hole and countersink in one operation. For milling the rivet-head flush with the skin, a single-lip end-mill is used. Here the sleeve serves primarily as a depth-gauge to prevent penetration of the surface.

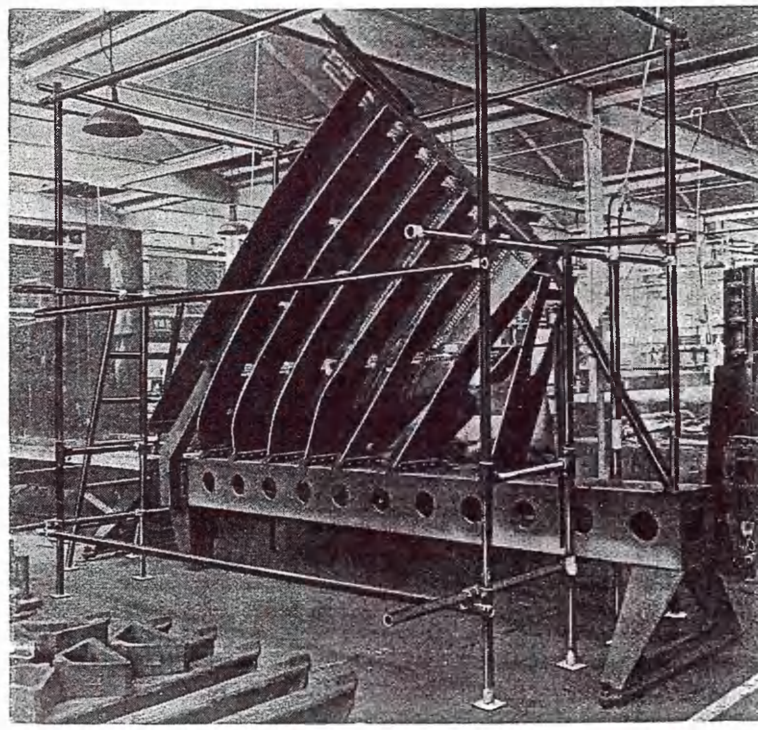


Fig. 15. An interesting type of envelope-jig showing how the construction is applied to an aerofoil-section unit. In this jig, for tail-fin assembly, the envelope template extends from the rudder-hinge spar on one side, completely round the leading edge to the front-spar line on the other side. A similar construction is used for wing-component assembly jigs.

### Assembly Procedure

In assembling an airframe component in a jig of this type, the skin-panels are first located against the inner surface of the template and held in position by locating-pins that engage tooling-holes in the panel. The purpose of defining the exterior edge of the panels is to make it possible to trim them accurately to size before they are assembled. It is perfectly practicable to do this, even on a prototype aircraft, by locating oversize panels on the jig-template, drilling through the boundary-defining holes, removing the panels and trimming them to the inner edges of the holes. Exactly the same procedure is followed on hatch covers or doors.

This procedure was actually adopted in building the prototype Fairey G.R.17, the first aircraft on which the envelope system was used throughout, and the accuracy of mating between the skin panels of adjacent components is very noticeable. A particularly difficult example is the skin cleavage-lines on the double-fold wing and an acid test of its practicability was provided by the bomb door, a double-curvature unit, and its mating aperture in the underside of the fuselage.

Actually, on this component, $\frac{1}{16}$in was left on the edge of the door as an "insurance policy," and, on assembly, it was found necessary to remove just that amount from the edge in order to obtain a fit. The possibility of obtaining a really accurate match in this way eliminates the time-absorbing necessity of offering-up and trimming oversize panels after assembly. On a production contract, of course, the panels would be routed to finished size before being placed in the jig.

When the trimmed skin-panels have been located for assembly (they are not predrilled, except for tooling-holes) the internal members are similarly

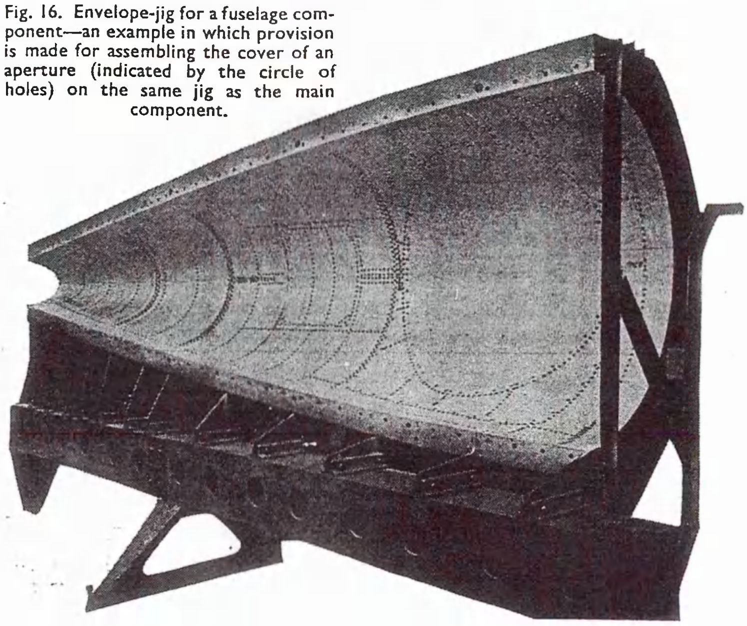


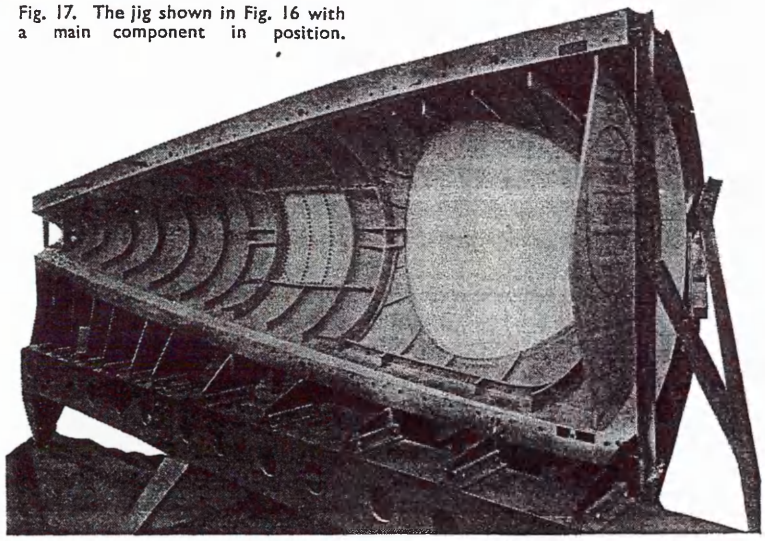
Fig. 16. Envelope-jig for a fuselage component—an example in which provision is made for assembling the cover of an aperture (indicated by the circle of holes) on the same jig as the main component.

*AIRFRAME ASSEMBLY PRACTICE (Continued)*

located from tooling-holes and clamped in place. The whole structure is then drilled from outside the template. Hole-sizes are controlled by a colour code. Riveting is completed on the jig: the preformed head is held up on the outside and the gun applied to the shank inside the structure. Here, the accessibility of the jig is of great benefit—both sides of the work are open—and the method of riveting tends to push the skin into what is, in effect, a mould of the aircraft form and assists in attaining the correct contour. Irregularities due to tolerance variations on panel thickness, are minimized on the external surface, as the difference is pushed to the inside of the plating.

Advantages of the envelope method are that work on the jig-templates can be begun as soon as the external shape of the aircraft has been established, and on the actual jigs as soon as the assembly breakdown has been settled. By the time detail design has been completed the jigs can be well on the way towards completion. The jig-templates can also serve as a means of checking the accuracy of first-off frame- and rib-profiles before assembly. For units such as tail-surfaces, in which light-gauge skin is usual, the solid support afforded by the jig-template during riveting is beneficial in eliminating the quilting and oil-canning effects that are too often seen on these components.

Fig. 17. The jig shown in Fig. 16 with a main component in position.



The equipment described in this article has been patented by the Fairey Aviation Co., Ltd., who are prepared to negotiate licences for its manufacture and to give advice on a consultative basis in the application of the system generally.

## Captain J. Laurence Pritchard

A STATEMENT from the Royal Aeronautical Society announces the forthcoming retirement of Capt. J. Laurence Pritchard who, for the past 25 years has held the post of secretary to the Society. An appeal is being made for funds for a testimonial and a promise of the sum of £500 has already been made by the Society of British Aircraft Constructors. Further details are to be announced later.

## City and Guilds Appointments

The City and Guilds of London Institute announce that following on the retirement of Professor R. S. Hutton, chairman of the council, and Brigadier H. Clementi Smith, chairman of the executive committee, Sir Frederick Handley Page has been elected chairman of the council and executive committee.

At a meeting of the council and executive committee on the 24th March, votes of thanks were passed to Professor Hutton and to Brigadier Clementi Smith for their work during their terms of office.

The Council of the City and Guilds of London Institute have conferred the distinction of Fellowship of the Institute (F.C.G.I.) on the following:—

Harold Grinsted, C.B.E., A.C.G.I., B.Sc.(Eng.), F.R.Ae.S.

William Herbert Grinsted, M.B.E., A.C.G.I., M.I.E.E.

Gerald Lacey, C.I.E., A.C.G.I., B.Sc.(Eng.), M.I.C.E., M.I.W.E., F.R.S.A.

Sir Kenneth Grant Mitchell, K.C.I.E., A.C.G.I., M.I.C.E., M.Inst.T., M.I.E. (Ind.).

## Princess Test-Piece

A FULL-SCALE replica of a section of a Saunders-Roe Princess wing was recently transported to Bristol as deck-cargo aboard the steamer *Channel Coast*. The section, which measured 26ft × 31ft × 5ft 9in was loaded aboard at Samuel White's yard near the Saunders-Roe East Cowes works and was shipped, in a special cradle, to Cannon's Marsh, Bristol, where it arrived on the following day. It was then transported to Filton by road and delivered to the works of the Bristol Aeroplane Co., Ltd., for test purposes.

It is intended to use the section for full-scale installation test-running of the coupled-Proteus units with which the Princess is to be powered. A similar method of testing was adopted for the double-Centaurus units for the prototype Brabazon and proved highly successful.

### *FORTHCOMING PAPERS*

**A selected list of lectures to be given before engineering and scientific institutions during the coming month.**

THE ROYAL AERONAUTICAL SOCIETY

May 4 "3rd Louis Bleriot Lecture," by Sir Frederick Handley Page, C.B.E., F.I.Ae.S., Hon. F.R.A.e.S.

May 25 "Wilbur Wright Memorial Lecture," by Sir Richard Fairey, M.B.E., F.R.Ae.S.

INSTITUTION OF PRODUCTION ENGINEERS

**London Graduate Section**

May 4 "Production Control as a Tool of Management," by M. J. Sargeant, Grad.I.Prod.E.

**Wolverhampton Section**

May 3 "Production Engineering Training," by T. B. Worth, M.I.Mech.E., A.M.I.E.E., M.I.Prod.E.

**Wolverhampton Graduate Section**

May 9 "'X' Ray of Castings," by J. D. Hislop, B.A. (Cantab.).

**Southern Section**

May 18 "Tungsten Carbide Tool Application," by F. H. Bates, A.M.I.Prod.E.

**Shrewsbury Sub-Section**

May 31 "Payments by Results Critically Examined," by E. C. Gordon England, F.R.Ae.S., M.I.Prod.E., F.I.I.A.

THE INSTITUTE OF METALS

May 10 "Gas Turbines," by Dr. H. Roxbee Cox, D.I.C., B.Sc., F.R.Ae.S., F.I.Ae.S. (U.S.A.).

## Aluminium-Alloy Nomenclature

THE publication, by the British Standards Institution, of specifications for aluminium and aluminium-alloys, brings, within one system of nomenclature, materials, both cast and wrought, that have become familiar under several different systems. The better known of these systems included the BS, D.T.D. and other series. The Aluminium Development Association has prepared a useful wall-chart, relating in simple form, the new system of nomenclature with those it replaces. This chart covers the materials in their various forms and, in addition, gives the approximate composition of each item.

Certain B.S.I. specifications have yet to be published, and a note to this effect appears on the chart. It is also pointed out that while the related schedules and specifications listed are the nearest equivalents to those of the new series, there may be differences on points of detail. The chart is drawn up in such a manner that anyone who has become familiar with the other systems should have no difficulty in identifying materials under the new.