3 An Integrated Methodology for Jigless Assembly (AIM-FOR-JAM)

3.1 Introduction

This chapter describes the development of a methodology to enable design for jigless assembly. As illustrated in the literature review there are many forms of ‘jigless assembly’ in addition to the more conventional forms of assembly using jigs, fixtures and tooling. This makes the development of a methodology all the more complex as it must cater for all types of assembly and provide some method of judging the ‘best’ assembly against a certain set of criteria.

It was decided that the methodology needed to be implementable at the earliest stage possible in the design cycle, as this is when there is greatest possibility for making changes and hence, the largest opportunity to save the cost of designing and building a product. However, a paradox occurs in that the earlier it is in a product’s life-cycle the less detailed information there is and yet, a methodology is being sought to specify the assembly to the smallest detail. Additionally, the matter is further complicated by the fact that the assembly is where a product ‘comes together’. The design or designer may not consider manufacturing or assembly at all, or at least minimally, and the assembly stage is where any shortcomings in the design or variations and errors in the build are brought to light and must be overcome.

What is required is a mixture of a ‘bottom-up’ approach to design to include assembly considerations, as well as, the traditional ‘top-down’ design approach, particularly prevalent in aerospace design, where design specifications are met and manufacturing and assembly seeks to produce this design. This mixture will not necessarily be equal because ultimately the form and function of the product must be met so that the customer will be satisfied and the build of the product must conform to the chosen design concept. This is particularly true in aerospace compared to, for example, the automotive industry. Although there are similarities in that the majority of components are made from sheet or machined metal, aerospace products tend to be designed to a much higher level of safety as their working environments are more hazardous. Nevertheless, there is still a lot of scope for aerospace designs to be more assembly oriented whilst satisfying their design requirements.

It is within this context that the methodology needs to perform.

The methodology should include foremost a means to capture the customer’s requirements that are useful to both the design and build teams, as they may use different models and terminology to describe their particular field. In this way, the customer’s requirements can be translated into the design, manufacturing and assembly processes and used as an ‘audit-trail’ throughout all processes to verify that the customer’s requirements are being met.

After the customer’s requirements have been recorded in a suitable way, the design can be optimised for assembly. The methodology to design for jigless assembly does not seek to automate the design process as engineering creativity and judgement is still left to the design-build teams. Instead, it provides a framework to analyse and compare competing assembly strategies and concepts that have been developed to realise the design. As part of the methodology, several important tools have been developed to aid the design-build teams in making choices between the differing strategies and concepts and these are described in section 3.2.1.

These tools and the overall framework then need to be organised into a logical, integrated methodology that encompasses all the relevant functions through design to assembly.

Finally, the designer can use the methodology to start from a top-level customer requirement's specification and match this to an optimum design by selecting the 'best' assembly strategy and concept, assembly features, manufacturing process capability, and allocation of tolerances and datums using the analysis and comparative tools introduced previously.

3.2 Description of the AIM-FOR-JAM Methodology

At the beginning of the research activity, there was no known process to '*design for jigless assembly*'. Four main areas of research, which were considered to be relevant and important in a potential process, were set-up for investigation. These areas are depicted in the diagram below. They were all inter-linked and interdependent in some way but at this stage it was unclear as to how.

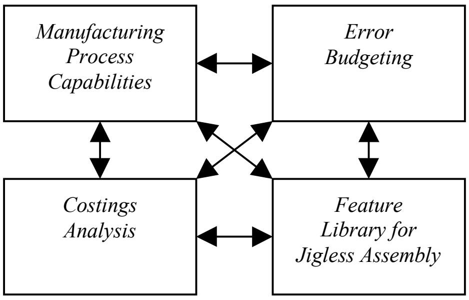


Figure 3.1 Four, main areas of research focus

A knowledge of Manufacturing Process Capabilities is vital in order to understand how designed parts are to be manufactured and to what level of quality. If parts are to be produced in a jigless manner, the manufacturing processes required to do this would need to be thought through.

Error Budgeting is an analytical technique previously used in the design of precision machine tools, co-ordinate measuring machines, etc., to achieve a stated error at a specified point. It was planned to extend this technique in the designing of assemblies to budget a certain amount of error within that assembly.

The Costings Analysis was required to compare the cost of current methods of design, manufacture and assembly against a jigless design, manufacture and assembly environment. This would provide an economic evaluation by which to judge the success of jigless assembly.

Initially, the Feature Library for Jigless Assembly was conceived to be the creation of …'a database describing structurally integrated features that will act as tooling elements during assembly' (Corbett, 1998) to facilitate jigless assembly. This original concept has been expanded and broadened and is described in subsequent sections.

3.2.1 Tools to Design for Jigless Assembly

These four 'building blocks', illustrated in Figure 3.1, were the fundamental areas of focus in the design for jigless assembly research activities. One of the major steps to enable design for jigless assembly was the development and definition of a process or methodology to follow in order to design for jigless assembly. If such a methodology could be developed by the use and integration of these four, fundamental building blocks and other design tools – the methodology could be followed as many times as required and for different applications to proactively design for jigless assembly. No specific methodology was known and the process to design for jigless assembly was rather vague and imprecise as most design tools were conceived and used for other purposes.

However, as introduced in the literature review, a good starting point for such a methodology was the work previously carried out by researchers at MIT, in collaboration with industrial companies such as Boeing and Ford (Whitney, 1995 and Cunningham et al, 1996). Their work was the first to bring together and establish a theory to proactively design assemblies, instead of other methodologies that considered the assembly process after the parts had been designed, such as the well-known Boothroyd and Dewhurst 'Design for Assembly' method (Boothroyd and Dewhurst, 1991). Although, the researchers at MIT admit that part of their theory attempts to formalise common engineering practices that tool designers have been using for many years.

Nevertheless, their theory served as a starting point for this research, to develop a process to design for jigless assembly, as it was deemed to be pointless to 're-invent the wheel'. Consequently, the MIT theory acts as the 'backbone' for the methodology to design for jigless assembly. The methodology develops this theory to broaden its scope, in particular, through the areas of an Assembly Feature Selection Process and Library for Jigless Assembly, Error Budgeting of Assembly Features and Cost Incorporation via Feature Based Costing.

The methodology developed is presented below, with brief descriptions of the individual design tools used.

3.2.1.1 Time, Cost and Quality – Costings Analysis

The first building block to be considered should be cost and its analysis. Clearly, cost has an overriding impact on most issues and will be one of the main success factors in determining the value of jigless assembly, i.e. has it reduced the total cost of tooling, consistent with the required quality? The cost implications can be represented by a classical Time, Cost and Quality model, as shown in figure 3.2.2 below. Today in the aerospace industry products are being produced to a minimum acceptable standard, so time and cost can be optimised. The assembly cost is related to the assembly time, because the longer the time the greater the cost. Therefore, the cost is indeed the prime factor.

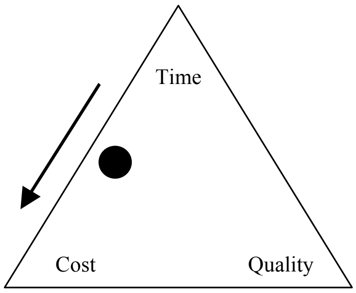


Figure 3.2 Classical Time, Cost and Quality model for production in the aerospace industry (Naing et al, 2000)

3.2.1.2 Geometric Dimensioning and Tolerancing (GD&T) and Datum Allocation

In recent years there has been a growing understanding of the importance of GD&T. This is because GD&T can act as a common language between engineers in the different functions of design, manufacturing, tooling and assembly (Naing et al, 2000). The GD&T symbols and terminology summarised in Figure 3.3, below, also provide a clearer illustration of design intent that can be better understood by manufacturing and tooling engineers. The application of a GD&T system also forces the user to allocate primary, secondary and tertiary datums. This results in good engineering practice that is also important for the Error Budgeting technique, which is described later.

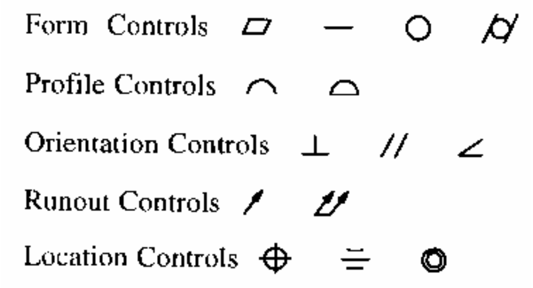


Figure 3.3 Geometric characteristics categories (Odi et al, 2000a; Odi et al, 2000b; Odi et al, 2001a and Odi et al, 2001b)

3.2.1.3 Key Characteristics (KCs) – Product Key Characteristics (PKCs), Assembly Key Characteristics (AKCs) and Manufacturing Key Characteristics (MKCs)

The concept of Key Characteristics was developed by researchers at Massachusetts Institute of Technology. Their definition of Key Characteristics is as follows:

> "Key Characteristics are product features, manufacturing parameters and assembly features for which any significant variation would affect the product's compliance to quality standards, or is likely to significantly affect the customer's satisfaction (Lee and Thornton, 1995 and Cunningham et al, 1996)"

As such, Key Characteristics have been used as a variation management tool which has resulted in a reduction in the use of assembly tooling. However, the process as referred to earlier is somewhat ill defined; although it should be noted that Key Characteristics can play a powerful role in variation management.

Key Characteristics can be further divided into three fundamental categories (Lee and Thornton, 1995 and Cunningham et al, 1996):

- **Product Key Characteristics (PKCs**) *are a product's geometric features and material properties that are highly constrained or for which minute deviations from nominal specifications (regardless of manufacturing capabilities) have a significant impact on the product's performance, function and form at each product assembly level.*
- **Assembly Key Characteristics (AKCs)** *are the features during each assembly stage on the product, tool, fixture or procedures that significantly affect the realisation of a product KC at the next higher assembly process level during the assembly process.*
- **Manufacturing Key Characteristics (MKCs**) *are the manufacturing machine process parameters and/or workpiece fixturing features for machine tools and*

equipment that significantly affect the realisation of a product or an assembly process KC at the part feature level.

Figure 3.4 demonstrates a useful representation of the flowdown of the Key Characteristics from PKCs at the part level to MKCs, if the PKCs were delivered directly through the machining process, and then to the actual assembly features or processes by which these PKCs are delivered at the part level or higher levels, which are identified as AKCs. However, care needs to be taken with this figure because the KCs may not necessarily be ordained into such a hierarchical tree structure.

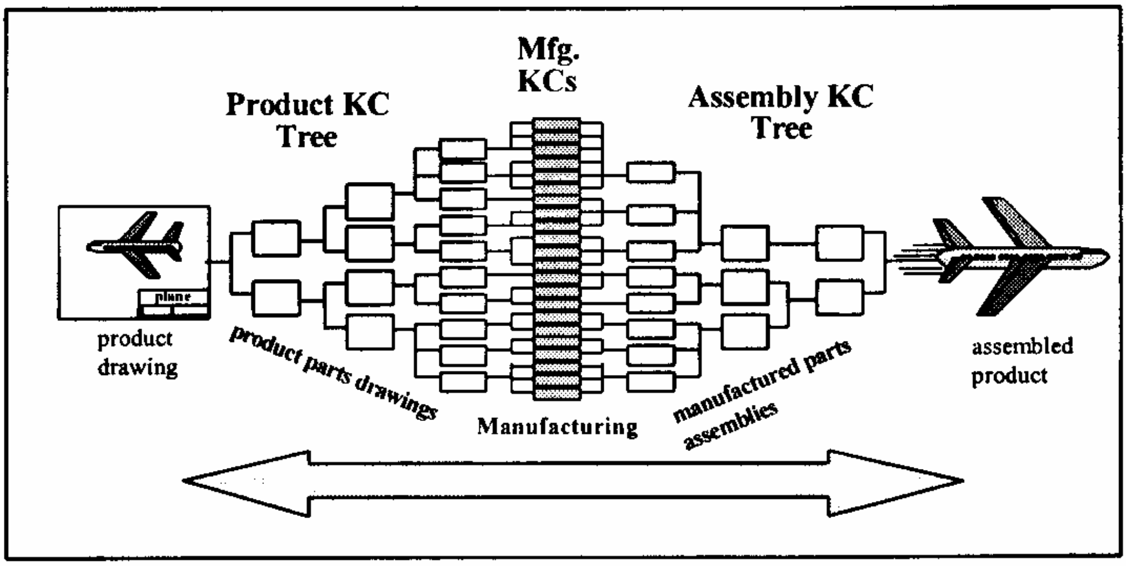


Figure 3.4 Key Characteristics classification tree (Lee and Thornton, 1995 and Cunningham et al, 1996)

The use of Key Characteristics for Jigless Assembly proceeds in very much the same way as advocated by their developers. Within a multidisciplinary group setting, which is very important to come to a balanced and consensus decision, firstly the PKCs are determined, followed by the AKCs and then the MKCs. It is not always easy to make an obvious distinction between PKCs and AKCs. The difference between the original use of KCs and their use for jigless assembly is in their application. For jigless assembly, KCs are used to highlight areas of the product build where tooling could be reduced. Another modification that has been implemented for practical considerations is the ownership of KC groups. Hence, for an aerospace company PKCs would be 'owned' by the design function, as they set most of the PKCs, such as aerodynamic specifications, design tolerances, etc., AKCs would be 'owned' by the assembly function and MKCs would be 'owned' by the manufacturing function. However, the identification process should always rest upon the participants of all the functions.

3.2.1.4 Datum Flow Chains (DFCs) and Featurised Datum Flow Chains (FDFCs)

Datum Flow Chains have been devised by Mantripragada et al (Mantripragada et al, 1996) to represent the underlying logic of an assembly at an abstract level. The DFC methodology is part of a new approach to conceptualise the design of complex assemblies. It is now being accepted that not all links between parts have the same importance when it comes to assembly. Those links, which establish and transfer a dimensional location between parts, can now be differentiated, and as such they define geometric relationships between the parts. These are called **mates** and those that are simply there for strength or support are called **contacts**.

A DFC diagram is a way to represent graphically the dimensional transfers for given assemblies, i.e. "*A datum flow chain is a directed acyclic graph representation of the assembly with nodes representing the parts and arcs representing dimensional relationships between them* (Mantripragada et al, 1996)."

To illustrate the main ideas, one can consider two concepts for assembling three sheet metal components, as shown in Figures 3.5 and 3.6 below. The main criterion is the overall length of the assembly. This can be thought of as a Key Characteristic (KC) of the assembly. The first concept uses one fixture, F1, to help with the assembly whereas the second concept relies on the use of two fixtures to do the same job.

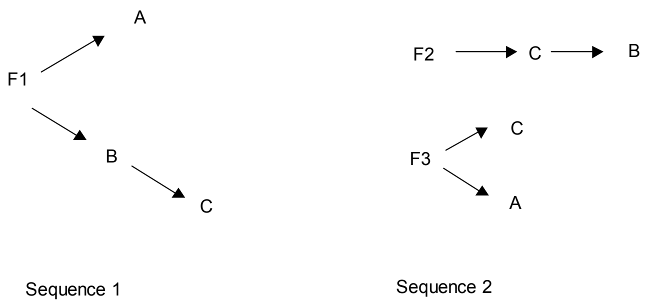


Figure 3.5 Two alternative assembly sequences for three sheet metal parts (Mantripragada et al, 1996)

The datum flow chains for the two sequences are:

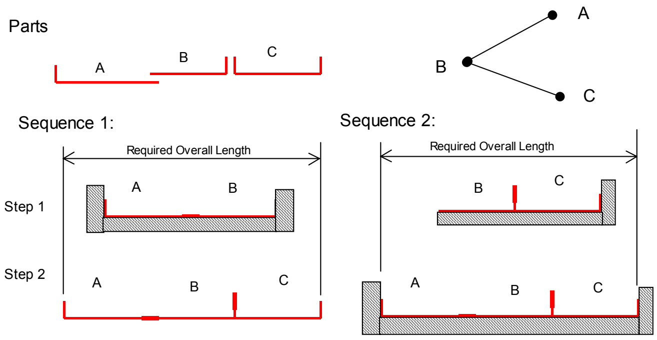


Figure 3.6 Datum Flow Chains for the two alternative assembly sequences (Mantripragada et al, 1996)

The above example shows how DFCs can be used to express the underlying assembly logic. These two sequences are alternative ways of assembling the three metal sheets. Crucially, the DFC method allows the presence of the fixtures to be acknowledged.

The initial work of Mantripragada and co-workers has been extended by Schwemmin (Schwemmin, 1999) to incorporate the actual features that participate in the assembly of the product. This has resulted in the featurised DFC method which is intended to assess the assemblability of a given assembly concept via the inclusion of manufacturing process capability data. Figure 3.7 below shows an example of a featurised DFC. The thick arrows denote dimensional transfer within the part. Schwemmin's method is primarily geared towards existing products so that assembly problems can be traced and better understood. Hence the reliance on manufacturing process capability data. Furthermore, variations that are due to rotations of parts are not accounted for by this method. Nevertheless, the featurised DFC method remains a useful and powerful tool for analysing assembly, using a language accessible to most engineers.

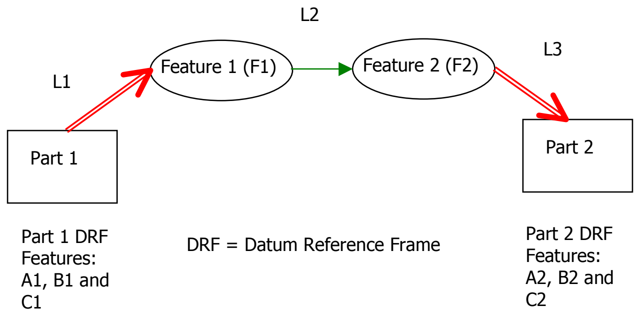


Figure 3.7 A typical featurised DFC diagram (Schwemmin, 1999)

3.2.1.5 Assembly Features – Feature Library For Jigless Assembly

The subject of 'features' has gained increasing significance over the past few years, particularly with relevance to Feature Based Modelling. Feature Based Modelling represents a new, evolving concept where objects are based around 'features' in addition to geometry. This allows the incorporation of functional and technological information such as surface finish, tolerances, material properties, etc., throughout the design, analysis, process planning, manufacturing and maintenance sequence with no loss of information at any stage.

There has been much debate on Feature Based Modelling as to what is the most useful definition of a 'feature' and the classification of such features (Kyriacou, 1998). An example feature classification scheme is shown in Figure 3.8 below. However, the classification of each, individual feature can become quite narrow.

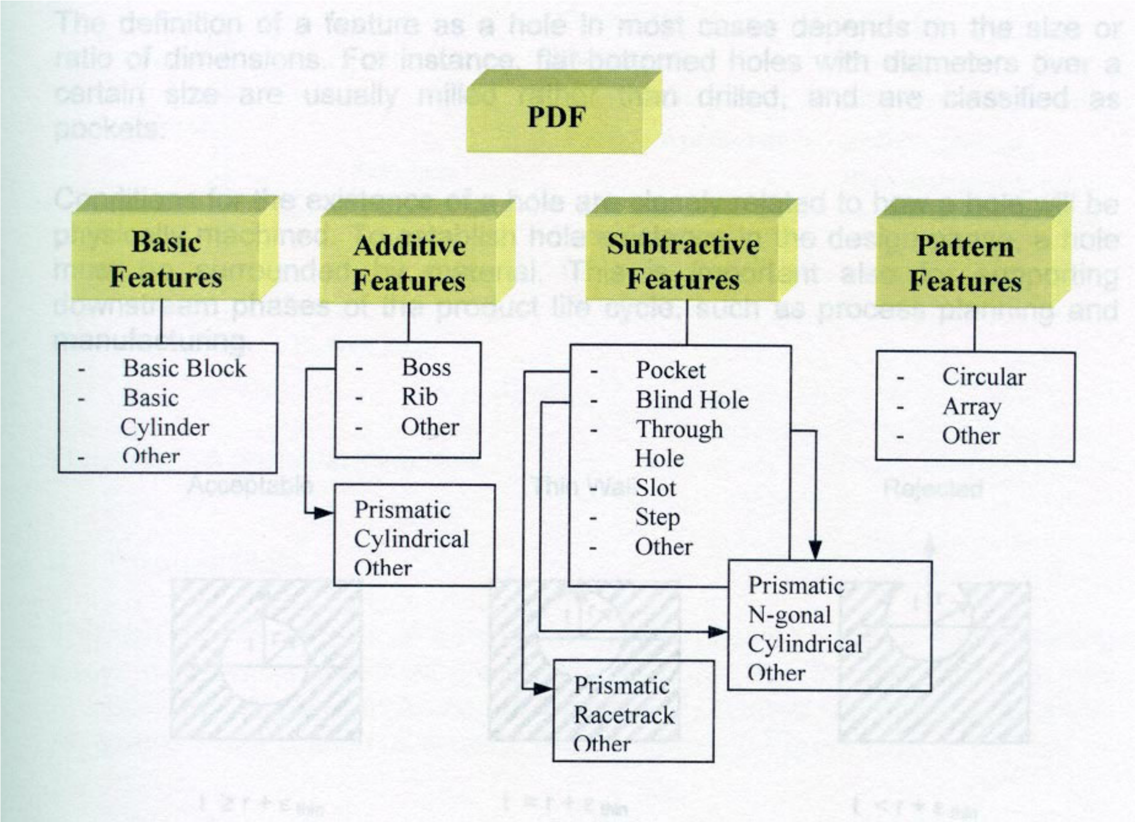


Figure 3.8 Pre-defined features from Feature Based Modelling (Kyriacou, 1998)

The distinction between features stored in a feature library for jigless assembly as opposed to a feature library for Feature Based Modelling is their orientation towards jigless assembly. The features will be selected and used to enable jigless assembly rather than Feature Based Modelling. Also, the features within Feature Based Modelling are limited to geometric shapes. Other assembly methods such as fasteners or mechanisms are not dealt with. Specific assembly features are limited to geometric shapes such as blocks, cylinders, bosses, ribs, holes, slots, etc. Examples of single component fasteners are shown in Figure 3.9. An example of an assembly mechanism is shown in Figure 3.10 from the Bombardier Shorts' Global Express door. The double eccentric bushing comprises two eccentric bushes one inside the other; each bush has eccentric locking holes on its rim. With the outer bush held in position, the inner bush can be eccentrically adjusted in two directions, vertical and horizontal, and when the hole through the bush is in the correct position both bushes can be locked in place using the appropriate locking hole on the rim. The double eccentric bushing is used on a particularly difficult assembly of the Global Express door, where two bolts shoot-out laterally from the door, because their initial alignment to each other cannot be guaranteed. There seems to be no reason why modified mechanisms could not be used for minor adjustment at assembly.

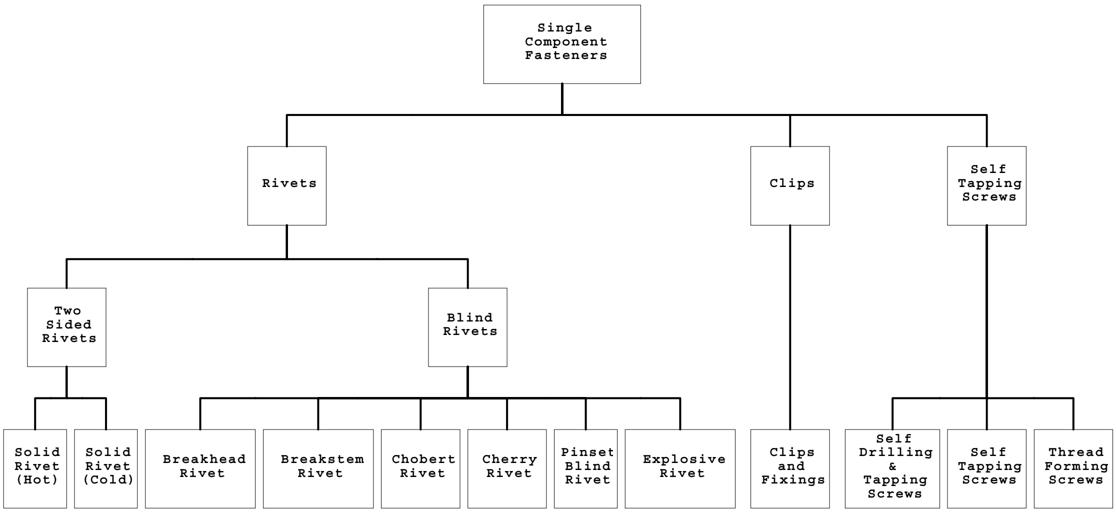


Figure 3.9 Single component fasteners

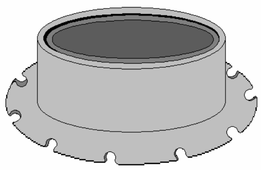


Figure 3.10 Bombardier Shorts' Global Express door Double Eccentric Bushing

Features, such as the examples shown above, can be used in a more cost-effective manner to substitute for the role of jigs. The features can take various forms. They can be integrally designed with the component to facilitate assembly, i.e. 'integrated tooling', or they can aid the use of other jigless assembly methods, e.g. assembly robots, non-contact measurement systems, which reduce the need for jigs, i.e. 'soft tooling'.

Some features will be better than others for particular operations. For example, 'hole-to-hole' features are widely used in aircraft assembly but they do not provide a definite location as it is very difficult to match up two holes in assembly. Different features could be used to provide a more positive location. For example, a milled boss left on a Track Rib could be used to mate with a hole or slot drilled into the Front Spar. However, the constraints of each application have to be taken into account, e.g. the Fixed Leading Edge skin is quite thin so the range of practical features is limited, and underlying all of this is the proviso that these features must not add any extra weight.

Nevertheless, the advantages of using features are apparent. A principal value of the feature library for jigless assembly is that it will allow specific functions to continue developing their responsibilities, such as design or manufacture, whilst providing the means to integrate the separate but concurrent functions at the areas where they interface.

3.2.1.6 Error Budget

Error budgeting has until now been successfully used for the design of precision machines, particularly precision machine tools, co-ordinate measuring machines (CMMs), and optical systems (such as telescopes etc.) (Thompson and McKeown, 1989; Thompson and Fix, 1998 and Homan and Thornton, 1998). Error Budgeting is used in machine design as an analytical tool to predict the total error of the machine system at the design stage. The starting point is a target error for the total machine, which is then distributed through an error budget to set the individual sub-system errors. Error budgets are used at all stages of the machine development process: conceptual design, detail design, planning, prototype development, build, series production, etc.

The original concept has been extended (Odi et al, 2000a; Odi et al, 2000b; Odi et al, 2001a and Odi et al, 2001b) to include the assembly of aerostructures. The main idea for the use of error budgeting in the design of aerostructures is to cast as errors any imperfections or variations on important features which are used to put together components into sub-assemblies and assemblies. This analytical technique relies on the concepts of Key Characteristics (KCs), Datum Flow Chains (DFCs) and Featurised Datum Flow Chains (DFCs), as described previously.

Once KCs have been identified from the system to component level and several assembly strategies put in place, the DFC diagrams are used to capture the underlying logic of the various concepts. The Error Budgeting technique has been developed to assess at all stages of the design process all assembly concepts, allowing designers to discriminate between the concepts that can deliver the KCs and also assess the overall error associated with each concept.

The use of error budgeting to design assemblies results in a need to define concepts. There is also a requirement to express the necessary adaptation to the method as used by machine tool and optical systems designers.

3.2.1.6.1 Error

For an assembly of parts, an error is defined as any variation from the idealised system. Essentially these variations from perfection will be captured by the application of tolerances to ensure the proper function of the assembled product. These variations will include tolerances (dimensional & geometric) but also changes in shape or form due to the environment (temperature, moisture etc.).

3.2.1.6.2 Transfer Error and Mate Error

During the assembly of a product, series of parts or fixtures are used in such a way that parts are positioned, secured and then fastened. The use of DFC and featurised DFC diagrams enable the designer to represent graphically the way parts, fixtures or jigs are used to realise the assembly. Due to the imperfect nature of these elements, the dimensional transfer will be subject to variation. If one considers only one source of variation, namely geometric, the errors that result from the assembly process can be classified into **transfer** and **mate errors**.

Transfer errors are used to capture variations due to the dimensional transfers within the part and the imperfection of the datum features themselves. Thus transfer errors are a combination of datum, form and profile tolerances and assembly feature orientation and location tolerances. If an assembly feature is also part of the part datum reference frame, then the feature orientation and location tolerances are no longer relevant. Transfer errors are applied to both the locating and located features.

Mate errors are a combination of the dimensional, form, profile and runout tolerances of the assembly features that establish and transfer dimensional location between the parts. These mate variations are due to the imperfections of the features themselves. Mate errors are related both to the locating and located features.

The definitions of transfer and mate errors apply equally to fixtures and jigs. The definitions are summarised in Table 3.1.

	⇒	→
	Transfer Error	**Mate Error**
Datum Feature	- form tolerance, ε_f - profile tolerance, ε_p	
Ordinary Feature	- orientation tolerance, e_0 - location tolerance, e_l	- dimensional tolerance, e_d - form tolerance, e_f - profile tolerance, e_p - runout tolerance, e_r

Table 3.1 Definitions of transfer and mate errors (Odi et al, 2000a; Odi et al, 2000b; Odi et al, 2001a and Odi et al, 2001b)

For assessing KC delivery, an additional error component, called KC error adjustment, is introduced. This component takes into account the variations of the features that directly deliver the KC.

For a typical part-to-part assembly, the error concepts introduced above can be presented, as shown in Figure 3.11, based on GD&T symbols and terminology.

Link	Error type	Datum	Feature	Form				Profile		Orientation			Runout		Location			Dimensional
				⏥	⏤	○	⌭	⌒	⌓	⟂	∥	∠	↗	⌰	⌖	⌯	◎	±
				FLT	STR	CIR	CYL	LPF	SPF	PER	PAR	ANG	CRO	TRO	POS	SYM	CON	DIM
L1	TRF	A		x	x	x	x	x	x									
		B		x	x	x	x	x	x									
		C		x	x	x	x	x	x									
			F1							x	x	x			x	x	x	
L2	MAT		F1	x	x	x	x	x	x				x	x				x
			F2	x	x	x	x	x	x				x	x				x

TRF = Transfer Error
MAT = Mate Error

Form

FLT = Flatness
STR = Straightness
CIR = Circularity
CYL = Cylindricity

Profile

LPF = Line Profile
SPF = Surface Profile

Orientation

PER = Perpendicularity
PAR = Parallelism
ANG = Angularity

Runout

CRO = Circular Runout
TRO = Total Runout

Location

POS = Position
SYM = Symmetry
CON = Concentricity

Figure 3.11 Link-Feature table (Odi et al, 2000a; Odi et al, 2000b; Odi et al, 2001a and Odi et al, 2001b)

For a given feature-to-feature link, the transfer error, E_t, can be expressed as:

$$E_t = f\left(\varepsilon_f, \varepsilon_p, e_o, e_l\right)$$

The mate error, E_m, is given by:

$$E_m = g\left(e_d, e_f, e_p, e_r\right)$$

The transfer errors and mate errors can then be calculated using some form of statistical addition, likely to be the Root Sum Square method, as not all errors will be at their maximum. Although in some cases, the maximum errors may need to be added together to account for Worst Case conditions.

If the Root Sum Square method is used, the total error for an assembly will be given by:

$$\mathrm{E}_A = \sqrt{\sum (E_t)_{Li}^2 + \sum (E_m)_{Lj}^2}$$

This initial error can then be used as a baseline figure for an error budget of the current assembly to compare against error budgets for alternative assembly concepts.

3.2.1.7 Inspection

Finally, the role of inspection needs to be put into the context of the methodology.

"Inspection is used to ensure the components or assemblies are acceptable to customer requirements, it adds nothing to the value of the component. The Jigless philosophy relies on accurate detail parts or at least details with certain accurate features or characteristics" (Mitchell, 1998)

Hence, features designed for inspection of the manufacture and assembly stage are not essential to those processes but they may be added to provide a reassurance that the manufacture and assembly has been carried out to the specified tolerances at certain points.

Consequently, an 'Inspection' element has been incorporated into the design for jigless assembly methodology for this purpose. It sits in between manufacture and assembly, as this is where the parts will be inspected, and at the apex of design, as this is where the inspection features will be specified.

At the manufacturing stage, these features are likely to be inspected by such hardware as Co-ordinate Measuring Machines, both contact and non-contact, and at the assembly stage the hardware is likely to be such things as Step Gauges (detail tooling) and Metrology Devices, such as Laser Trackers or Photogrammetry.

The inclusion of these features is therefore not an integral part of the design for jigless assembly process but nevertheless, one that needs to be considered as an extra, 'practical' task.

3.2.1.8 Application of the AIM-FOR-JAM Methodology

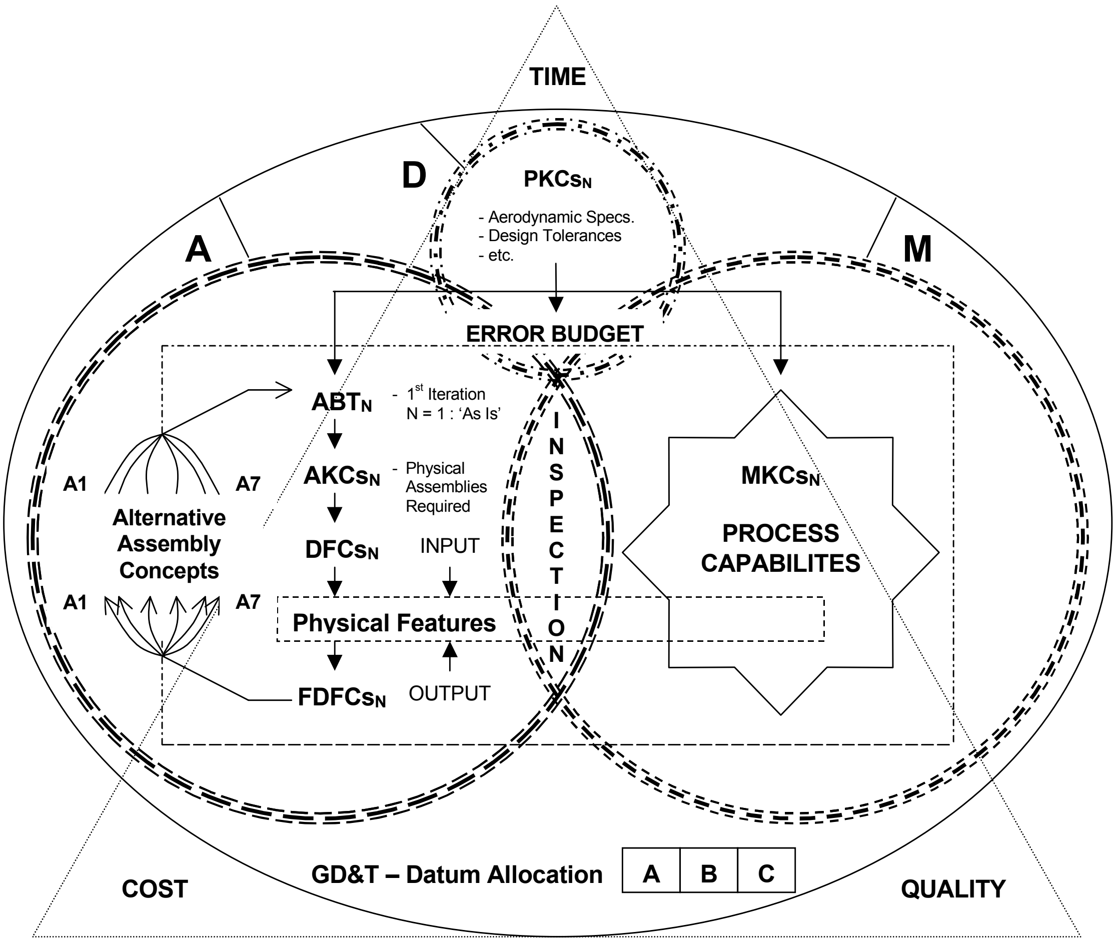
Using the four building blocks shown in Figure 3.2 and the various tools described above, a methodology to design for jigless assembly has been developed. As stated previously, no such explicit methodology to design for jigless assembly existed. The methodology uses tools that have already been developed individually, but here their application is specifically tailored to design for jigless assembly. Other tools have been developed such as the Feature Library, Error Budget and Cost Model.

A special reference must be made with regard to the Manufacturing Key Characteristics (MKCs). The MKCs are the manufacturing machine process parameters that significantly affect the realisation of a product or an assembly process KC at the part feature level. In order to ascertain whether this is being achieved by the current manufacturing processes – process capability data is required. Manufacturing Process Capability data is currently either non-existent or very hard to obtain. If it is available it may be in the wrong form by stating what the machine or process specifications claim is achievable. The data that is needed is what the machine or process actually achieves, but this is very hard to determine. With a better idea of what is achievable the tolerance information can be fed into the Feature Library, Error Budget and Cost Model.

3.2.1.8.1 The Methodology

A graphical representation of the methodology to design for jigless assembly is presented in Figure 3.12 below, 'AIM-FOR-JAM' – An Integrated Methodology FOR Jigless AsseMbly.

The methodology to design for jigless assembly is based upon the Time, Cost and Quality model, discussed previously (Figure 3.2), for production in the aerospace industry, noting that cost has an overriding impact and relation to everything. The methodology begins with the determination of the Product Key Characteristics, which are 'owned' by the design function, as they have the greatest say in these, although their determination should be a group effort. At this point, Design Datums should be allocated, which should be adhered to throughout the build process in order that the design intent, and hence customer satisfaction, is fulfilled. The datum allocation must implicitly take place in a GD&T environment, as datums need to be allocated for GD&T.



Key

GD&T = Geometric Dimensioning & Tolerancing

D = Design

A = Assembly

M = Manufacturing

ABT = Assembly Build Tree

PKCs = Product Key Characteristics

AKCs = Assembly Key Characteristics

MKCs = Manufacturing Key Characteristics

DFCs = Datum Flow Chains

FDFCs= Featurised Datum Flow Chains

Figure 3.12 AIM-FOR-JAM

To design for jigless assembly the methodology is first applied to the current build method, e.g. the 'As Is' scenario. The methodology is then followed to analyse the current build method. The Assembly Build Tree (ABT) is used to establish how the assembly is put together. As with the Design Datums, Assembly Datums should now be allocated, for use throughout the assembly process, to ensure that datums are not lost, so that unnecessary additional errors are not introduced.

If the design is being carried out on a completely new product that has never been developed before or there has not been anything remotely similar to the product, then it will not be possible to analyse the current build method, the 'As Is' scenario. In this case, similar to the principles of QFD, the 'best guess' build method that is likely to be employed should be used as the baseline by which all other alternative assembly concepts can be judged. However, it should be stressed that this particular situation is highly unlikely, especially in the commercial aircraft manufacturing industry that this research is directed towards, due to the following reasons:

- The new product is likely to be a variant of the existing products or if it is a 'step change' from the previous products then it will still use technologies from existing products
- There will be past experience and prior knowledge of the design, manufacturing and assembly methods used on previous products that can be extrapolated to a totally new product
- Research and development would be harnessed to bridge the gap between today's technology and the technology required for the new product, which would provide a clearer picture of the means to go about developing the new product and reducing the risks involved

Whether there is a current build method or one that needs to be envisaged, it will be possible to generate the information required by the design for jigless assembly methodology, the starting point of which remains the Assembly Build Tree.

From the ABT, the Assembly Key Characteristics of the current (or envisaged) assembly are determined. It should be noted that whereas PKCs will not change for any given product, the AKCs may change for each, different assembly strategy of the same product. The AKCs will provide a list of the physical assemblies required. It is very important that the AKCs are physical requirements so that their delivery can be checked in a quantifiable way. The AKCs will be ‘owned’ by the assembly function, as they have the greatest control of the assembly.

After the AKCs have been decided upon in a group setting, the Datum Flow Chains can be worked out for the current assembly. This will show graphically the part-to-part links of how the assembly is put together, including any jigs or fixtures that are used for the assembly.

These three elements: the Assembly Build Tree, the Assembly Key Characteristics, and the Datum Flow Chain serve as an Input of what is required from the assembly. In effect, they are the specifications of the assembly process.

From the DFC, the Featurised Datum Flow Chain (FDFC) can be extrapolated. This will show graphically the part-to-feature-to-feature-to-part links of the current assembly and how the part-to-part location is actually facilitated by the features. The FDFC acts as an Output of how the assembly is achieved.

Between the DFC and the FDFC are the Physical Features. The Physical Features are the attributes that separate the FDFC from the DFC; they are the ‘physical features’ that realise the assembly. The Physical Features will map across both assembly and manufacturing. The same feature may be used for both assembly and manufacturing but in different ways. Therefore, the same feature will be viewed very differently by the two functions. There will also be other features that are exclusive to both functions. The Physical Features are the enablers between the input required from the ABT, AKCs and DFCs and the output achieved as shown by the FDFC.

This is the first iteration of the design for jigless assembly process: the analysis of the current assembly method. From this starting point, alternative assembly concepts can be conceived to enable jigless assembly. The Product Key Characteristics will not change for the same product but the Assembly Build Tree, Assembly Key Characteristics, Datum Flow Chains, Physical Features and Featurised Datum Flow Chain will be different for each different assembly.

At this point, it must be considered how radical the design for jigless assembly is going to be. At one end of the scale, a completely new conceptual design of the structure may be required, in which case there is great freedom for the design of component parts. The most effective way to reduce jigs is to design them out, i.e. instead of having two parts such as both, individual ribs that are assembled together to make the Track Rib, indicated in Figure 3.13, below, which both need to be held by fixtures and located by jigs, it would be better to have a one-piece Track Rib, which could be integrally forged, casted or machined. Only one set of jigs and fixtures would then be required and the datums on one part would not be lost transferring it to the other.

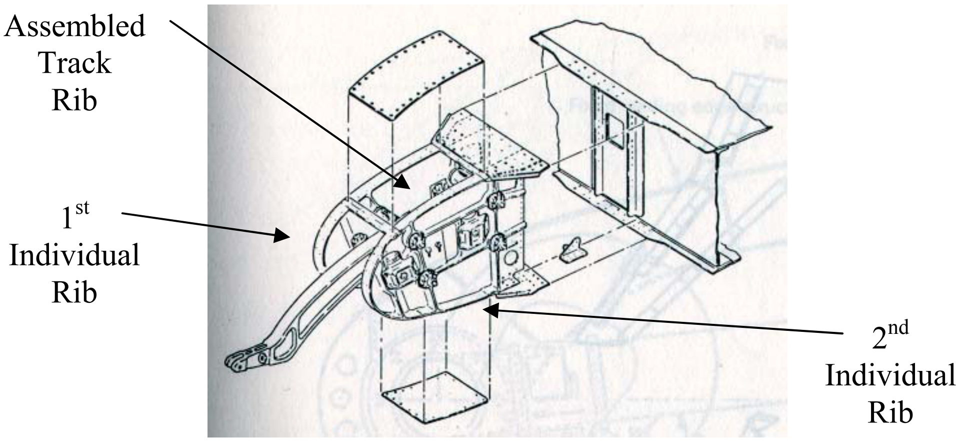


Figure 3.13 Diagram to illustrate the individual ribs that are assembled to form the Track Rib (Niu, 1988)

A much more realistic scenario for a product's development in an actual aerospace company, to reduce the cost and time of production, will be its reengineering. It is very seldom that products start from a 'clean drawing board' and much more likely that an improved product will originate from an older version or variant. Here, the discrete parts will not be radically altered but improvement will be sought through minor modifications to these parts.

The first step is the conception of several alternative assembly strategies with the aim of a reduction in tooling. The current assembly may be as it is because of reasons that no longer apply, such as, historical issues, production rates, technical barriers, etc. The parts will be assemblable by more than one method. Using alternative sequences of assembly will produce a different assembly process with different tooling requirements.

These alternative assembly strategies can then be analysed using the design for jigless assembly methodology. As these strategies are conceptual, how the assembly might be achieved needs to be considered. Thus, for each assembly concept the ABT is determined, the AKCs are decided and the DFCs are extrapolated. At this point, the physical features used for the current assembly are to be replaced by appropriate features from the feature library for jigless assembly. For each specific application, such as Track Rib to Front Spar interface as depicted in Figure 3.13, there will be a selection of features to enable jigless assembly. The aim of this process is to reduce the number of features linking one part to another so those different features are not competing for the same degrees of freedom. Ideally, each degree of freedom would be controlled by one physical feature, although that may not be possible due to practical considerations. After the Physical Features have been decided upon, the FDFC can then be drawn. As many iterations of the methodology are completed as there are alternative assembly concepts, and the result is a traceable catalogue of design parameters that can be used to judge one assembly concept against another.

Although the goal is jigless assembly, manufacturing will clearly have a very important part in the realisation of this, and some manufacturing methods will eliminate or reduce the need for jigs further downstream. The assembly and manufacturing schemes could have attempted to be combined into one, but they and the physical features that go with them are fundamentally different. The concept of Key Characteristics also divides the two into separate entities of Assembly Key Characteristics and Manufacturing Key Characteristics, which were decided as part of the Key Characteristics selection process. As with the design and assembly functions, manufacturing needs to allocate Manufacturing Datums at the beginning of the process so that those datums are maintained. Process Capabilities will undoubtedly play a major role in the analysis of any manufacturing requirements for jigless assembly concepts, and manufacturing will have an impact on the choice of Physical Features for jigless assembly.

Finally, the error budget will be used to quantify the errors for each assembly concept, including the current one. The error budget maps across both the assembly and manufacturing schemes as both go into making up the total error. If the tolerances at the design stage are treated as design intent, the error budget can be used to see whether the assembly and manufacturing methods will deliver the tolerances required. In this way, tolerances will be a reflection of the error taken account for in the system rather than the current situation of issuing relatively arbitrary standard or 'blanket' tolerances.

Hence, it can be seen that a clear, logical methodology has been followed. The result of which will be several designs for jigless assembly with justifiable and quantifiable parameters on which to judge each design. The methodology provides an integrated, holistic framework that includes design, manufacture and assembly with definite areas where each interfaces with the other in terms of datums, physical features and an error budget.

3.3 Assembly Concept Selection

At the assembly conception selection stage of the design for jigless assembly methodology, a distinction between two types of assembly needs to be made. This distinction has been identified by the researchers at MIT (Whitney, 1996) and is important because the choice of assembly type will greatly affect the efficacy and economics of the assembly involved.

According to the MIT researchers, the two types of assemblies are called Type-1 and Type-2; these are distinguished by whether they require fixtures for their assembly (Type-1), and whether they can be adjusted to achieve their Key Characteristics (Type-2).

3.3.1 Type-1 Assemblies

Type-1 comprises typical machined or moulded parts that have their mating features fully defined by their respective fabrication processes prior to final assembly, such as would normally be the case for an automotive engine. These are also called *part-defined* assemblies, because the variation in the final assembly is determined completely by the variation contributed by each part in the assembly, assuming that all the 'rules' of assembly (correct bolt torque, cleanliness, etc.) are followed. The assembly process merely puts the parts together by joining their pre-defined mating features. The assembly process is thus passive and cannot influence the distribution of variation in the assembly. The mating features are almost always defined by the desired function of the assembly, and the designer of the assembly process has little or no freedom in selecting mating features.

Type-1 assemblies are kinematically constrained. As reported in the MIT research, the literature on kinematic assemblies focuses exclusively on Type-1 assemblies.

Defined in terms of the Datum Flow Chain, a Type-1 assembly is one where the part has at least one *mate* with at least one other part in the assembly. Fixtures, if present, merely immobilise the base sub-assembly and present it to the part being assembled in the desired position and orientation.

In Type-1 assemblies, the Datum Flow Chain describes the assembly itself.

3.3.2 Type-2 Assemblies

The second type of assembly includes aircraft and automotive body parts that are usually given some or all of their assembly features or relative locations during the assembly process. These parts have slip joints, as illustrated in Figure 3.5, that do not provide complete constraint, usually because it is uneconomical to try to make these parts accurately enough to permit achieving their Key Characteristics as Type-1s. Assembly of these parts requires placing them in close proximity and then drilling holes or bending regions of parts, as well as riveting or welding. In-process measurements can be made to adjust the location of these parts during assembly to tune out the effects of manufacturing variation. Alternatively, rigid fixtures can be relied on to establish the dimensional relations between the parts, passively accomplishing the measurement and adjustment steps.

Type-2 assemblies are kinematically constrained when they are in contact with their fixtures or adjustment/measurement apparatus, and after their contacts have been solidified.

A different datum flow logic, assembly sequence, etc. will result in quite different assembly configurations, errors and quality levels. It is quite possible to build an acceptable Type-2 assembly out of imperfect parts and vice versa by choosing an appropriate or inappropriate datum flow logic. Type-2's are thus called *assembly-defined*.

In Type-2 assemblies, the Datum Flow Chain describes the assembly process together with the assembly.

3.3.3 Assembly Concept Strategy

At this point, it must be remembered that the goal of this process is to reduce the reliance on product-specific, jigs, fixtures and tooling at the design stage. This can be done by following one or a mixture of assembly strategies.

The first strategy is to try to change the assembly, i.e. an aircraft assembly, from a Type-2 to a Type-1, whereby parts readily mate with other parts. This would require that the manufacturing capability to manufacture these parts to the required limit of tolerance was available and repeatable. The capability to do this is not as far-fetched as it may have been just a few years ago. With the continuing advancements in manufacturing technology, tolerances are achievable that were previously unheard of. This is especially the case for military, as opposed to commercial, aircraft where it can be argued that the parts being machined are smaller and hence stiffer, reducing the propensity for thermal growth, which would require closer temperature control at machining and assembly.

As an example obtained through oral evidence, the new fabricating facility employed on the Eurofighter military aircraft can drill holes in sheet metal with an accuracy of +/- 0.05 mm for any hole in relation to another hole on the skin, hence, there is the capability to drill all holes full-size - obviating the need for pilot holes and drilling out. However, this requires a complete redesign of the parts to accommodate issues such as re-jigging for the machines that are used, tightening-up of the assembly features, etc.

For commercial aircraft, it may be uneconomical to implement such a diverse change from the current methods of manufacture and assembly for a large majority of the parts. However, this strategy could be a viable option for selected parts, such as relatively small, stiff components.

A second strategy of assembly concept selection, to reduce product-specific tooling, is to migrate the functions of location and dimensional transfer from specifically the jigs to assembly features that perform the same function. The definition and selection of assembly features to do this is the subject of the following sections.

However, it can be argued that there is no one ‘right way’ of assembling aircraft parts. Clearly, the assembly is a very complex process as there are a great number of parts and many conflicting issues that need to be considered. Indeed, the choice of assembly concept strategy is a major field of itself, particularly within the ‘mechanical products’ industries such as aerospace and automotive. The most cost-effective solution must be found by selecting the optimum solution through consideration of all aspects of the design-build process: design effort, in-house manufacturing and supply-chain capability, shop-floor capacity, production rates, capital investments, etc., as well as the detailed technological requirements and possibilities of competing assembly concepts.

Once the assembly concept strategy has been chosen, the detailed assembly design and analysis can begin, as outlined in the previous AIM-FOR-JAM Methodology Flowchart, Figure 3.12. This situation is analogous to that of the general economy, whereby there is a ‘macro-economic’ environment relating to the more strategic aspects of the economy such as interest rates, inflation, unemployment, etc. and ‘micro-economic’ policy relating to the more tactical aspects of how businesses or individual persons choose to spend their own money. The macro-economic environment will have a wider impact on a particular business but they will use their micro-economic policy to gain the best competitive advantage within that context. Both situations have to be considered and analysed together, and this is also the case for the choice of assembly concept strategy.