

2 Literature Review

2.1 Introduction

This chapter presents a review of the literature relevant to the research area established in chapter one. The review describes the work of others' in several fields of importance and significance in establishing the current boundary of knowledge with respect to the research area.

As Jigless Assembly is the ultimate goal that this research is attempting to contribute towards, the definition of a 'jig' needs to be clarified and stated in order that the concept of Jigless Assembly can be understood and the use of related terms, such as 'jigs, fixtures and tooling', is consistent throughout the thesis.

After these definitions have been offered, the rationale for Jigless Assembly is described and the reasons why many aerospace manufacturers are heavily pursuing this goal.

There are several examples of Jigless Assembly that have been implemented within the aerospace industry or are under development in academia and these are provided, next, along with some examples from other non-aerospace industries. These examples show the very, wide variety and application of Jigless Assembly techniques.

Any methods or methodologies developed to produce designs for jigless assembly and model the jigless assembly process must be able to explicitly deliver and represent a Jigless Assembly solution, and at the same time cater for more conventional forms of assembly that require the use of jigs.

The remainder of the literature review is devoted to three major areas of study and research that have a significant part to play towards the attainment of Jigless Assembly:

Design and Assembly Processes’ Methods and Methodologies, Feature Based Methods and Tolerance Representation and Analysis.

Design and Assembly Processes’ Methods and Methodologies describe a number of established examples developed by various researchers and practitioners. The section is divided into Design related Methods and Methodologies and Assembly Process related Methods and Methodologies, which could be of use in designing for jigless assembly. The Design part of the section deals with the range of existing Formal Design Methods that have been developed to formalise the design process and the Assembly Process part of the section outlines two examples of Assembly Modelling Methodologies.

As stated in the following section on Feature Based Methods, ‘Features’ are becoming more and more prevalent in the design, manufacturing and assembly of products for a number of reasons, not least because a ‘feature’, however it is defined, can hold much more information than geometry alone. Hence, the use of Feature Based Methods has evolved from Feature Based Design to many other areas, in particular Feature Based Design for Assembly and Feature Based Costing. As a result of this, Feature Based Methods are advocated in designing for jigless assembly and the work of others is depicted to illustrate the current state-of-the-art in Feature Based Methods.

Finally, the last section introduces a number of examples of Tolerance Representation and Analysis, all of which are Feature Based. The operation of one such example, AnaTol, is highlighted to demonstrate the typical functionalities of Computer-Aided Tolerancing systems, as an enabler towards jigless assembly.

2.2 Definitions of Jigs, Fixtures and Tooling

As the main subject of this thesis is ‘Jigless Assembly’, there needs to be a definition of what a ‘Jig’ is to understand what Jigless Assembly would mean. Jigs are often mentioned in the same phrase as ‘Jigs, Fixtures and Tooling’; consequently definitions are required for Fixtures and Tooling, also.

One definition of Jigs and Fixtures is (Pollack, 1976) :-

- A *Jig* is a workpiece locating and holding device which positions and guides or controls a cutting tool
- A *Fixture* is a workpiece locating and holding device used with machine tools, inspection, welding and assembly; it does not control the position of the tool or instrument which is being used
- Elements of the Jig or Fixture must also be present which *Support* the work and elements, called locators, which *Position* the work
- Once located and positioned, the work is *Clamped* so that it will not move off the supports or locators

This definition has been refined to the following and includes a definition of Jigless Assembly, which will be used as the standard throughout this work (Burley and Corbett, 1998).

- A *Jig* is defined as a manufacturing aid that either holds a part or is itself located on the part and is fitted with devices to guide a cutting tool ensuring the correct location of the machining path relative to the part
- A *Fixture* is defined as a manufacturing aid for holding and locating parts during machining or assembly operations, which do not provide definite guidance for the cutting tools
- *Tooling* is used as the generic name for jigs and fixtures and also the tools set from the master gauges for calibrating jigs and fixtures
- Hence, *Jigless Assembly* is assembly without the use of jigs; it requires that parts are manufactured to sufficient accuracy to ensure correct assembly; it is not necessarily fixtureless [or toolless] assembly

2.3 Rationale for Jigless Assembly

Jigless Aerospace Manufacture, in essence, is about eliminating or reducing product specific jigs, fixtures and tooling. Within the airframe manufacturing industry, it is generally accepted that approximately 10% of the overall manufacturing costs of each airframe can be attributed to manufacture and maintenance of assembly jigs, fixtures and other ‘special to type’ tooling (Burley et al., 1999). For civil aircraft, the costs are split into Non Recurring Cost (NRC), ‘initial investment’, and Recurring Cost (RC). Tooling costs are principally part of NRC and for Airbus aircraft the part of NRC dedicated to tooling represents more than a third (ECATA, 1995). This means a massive capital investment, with long pay back periods.

There are other disadvantages with the present form of tooling in use today. The assembly tooling being ‘product specific’ is inflexible and when an aircraft program contracts, it is likely that it will be under utilised extending the pay back period. The tooling should be recalibrated frequently to ensure the required accuracy but this is proving difficult and costly. The different material of the assembly jigs and the tooling/factory configuration is resulting in different thermal expansions of wing components. There are several problems with the assembly jigs concerning metrology and in-process measurement: the design of the jig does not facilitate measurement of the wing within the assembly jig; optical measurement is proving to be almost impossible; the use of sensors mounted on the jig for measurement purposes is proving difficult due to the differential thermal expansions. The limitations of measuring the wing within the assembly jig results in measurement being delayed until it is located in the final stage when it is structurally complete, making it very expensive and impracticable to correct any defects highlighted by measurement of the wing. (Lewis, 1993).

2.4 Jigless Assembly Examples

There are several examples of Jigless Assembly currently existing within the aerospace and other industries. Many aerospace companies have recently been looking at modifying their tooling practices.

Examples of applications specific to the aerospace industry range from structural technology to manufacturing and assembly processes.

An example of a structural application is Goodrich Aerostructures Group' GRID-LOCK® technology (Goodrich, 2001). GRID-LOCK® is an innovative method of joining structural components with simple tongue and groove joints. The result is a structurally efficient, double-skinned, ribbed-core structure that is approximately twice as strong as and stiff as a stiffened-skin or isogrid structure of equal weight. See Figure 2.1 below.

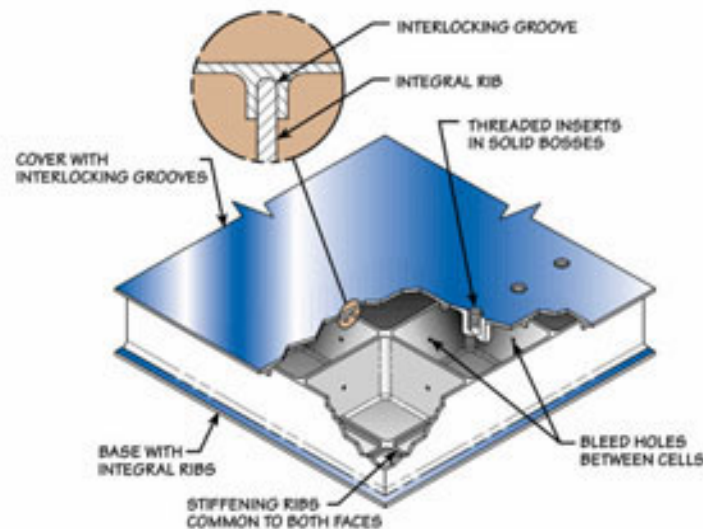


Figure 2.1 GRID-LOCK® method of joining structural components with simple tongue and groove joints (Goodrich, 2001)

It has the following attributes:-

Structurally Efficient	– Comparable to honeycomb structures, yet stronger and stiffer than isogrid structures
Damage Tolerant	– Exceeds that of honeycomb sandwich Structures
Suppresses Structural Harmonics	– Tailored to eliminate unwanted modes
Strong	– Provides localised strength where needed
Efficient Shear Capacity	– Mechanical locking joints augment the adhesive bond
Corrosion Resistant	– Thicker internal sections that are easily coated and drained
Repairability	– Simple riveted patch repairs

The CNC machined GRID-LOCK® greatly reduces part count, simplifies assembly and minimises inspection costs enabling Lean Manufacturing and its emphasis on rapid set-up times, single-piece flow and low inventory levels.

GRID-LOCK® has been applied on:-

- F-15 Fighter Aircraft Rudder Fairings, Ailerons, Vertical Stabilisers, Flap Shroud and Horizontal Aft Box Assemblies
- AV-8B Harrier Bulkheads
- Rigid Cargo Barriers for the Boeing 727, MD-11/MD-10 and A300-600 civil aircraft
- Payload Applications for Space Products, e.g. truss structures for the Hughes HS702 and other mobile satellites
- F-16 N Fighter Aircraft Nose Landing Gear Doors
- C-5 Transport Aircraft Pylons and Nacelles Systems

An example of a manufacturing process that could eliminate the need for assembly, and hence, jigs is the Friction Stir Welding process (Airbus News, 2000). The method was invented and developed by The Welding Institute, UK. Friction Stir

Welding enables metal components to be welded together instead of being riveted – saving time, money and weight.

It works by running a welding tool between the pieces of metal that are being joined. The tool spins at very high speeds, creating friction, which heats the metal, in the case of aluminium alloys, to temperature of about 450 degrees Celsius. As the tool moves along the joint, it softens the metal, causing it to become plasticated, resulting in a high strength weld forming behind the tool. Since Friction Stir Welding does not involve melting the metal, there are none of the traditional problems of welding like cracks or porosity, which could lead to metal fatigue.

The process has already been used in a range of other industries, like shipbuilding and bridge building. An example of a Friction Stir Welder is shown in Figure 2.2, below.

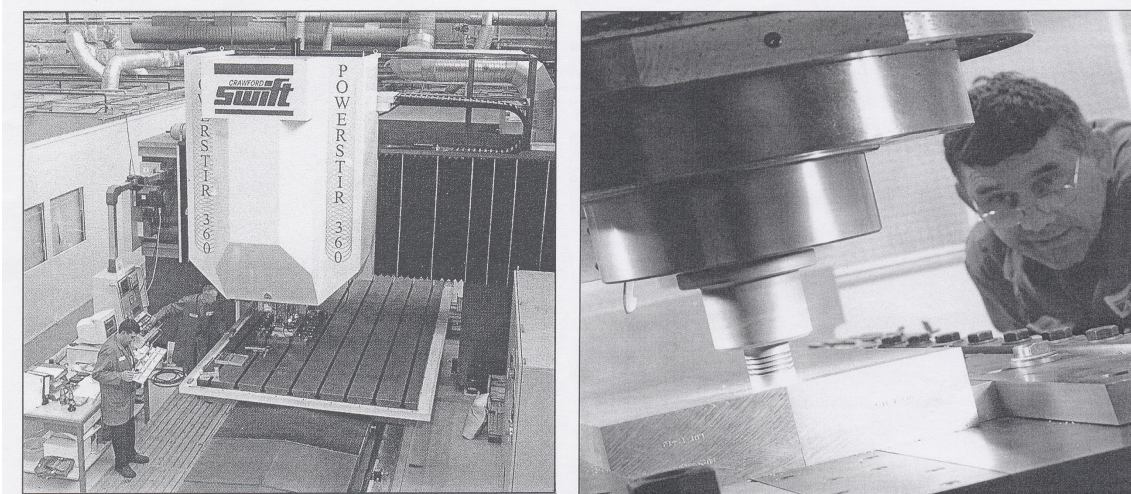


Figure 2.2 Friction Stir Welder (Airbus News, 2000)

There are quite a few examples of assembly processes that employ Jigless Assembly techniques.

One example of this is Boeing's Accurate Fuselage Assembly (AFA)/Fuselage Assembly Improvement Team (FAIT) programme used for the first time on a 747 aircraft (Norris, 1999). This is a new, computer-defined "snap-together" assembly technique with the goal of a 40% cut in assembly flow time over the next five years. AFA involved the digitising of the original 1960s drawings of the aircraft to create a

digital database that could be manipulated using the CATIA computer-aided design and manufacturing system. Northrop Grumman, which builds the bulk of the 747 fuselage, used the database to make more accurate “super panels” for selected sections of the body. The FAIT effort simplifies assembly techniques by using precision holes in the super panels and other parts of the structure to “self-locate” the panels to each other. The precision fit of the panels is achieved using laser alignment and computer-controlled positioning systems, and eradicates the need for the traditional assembly tools and jigs which were expensive to maintain and keep within tolerances. The first aircraft to be built under this programme, a Boeing 747-400 for Japan airlines, was delivered in November 1999.

Airbus UK provides another example of Jigless Assembly processes with their new A340-600 production line (Airbus News, 1999). Here, trials were made for the first of three Low Voltage Electromagnetic Riveting (LVER) machines that formed part of the production line. The LVER machine, similar but larger than the one used on current A320 topskins, will automatically attach stringers to wing panels. The trials involved placing rivets in test pieces and automated cold working, a process that strengthens the metal around the holes into which rivets are inserted, increasing the fatigue life of the aircraft. Although the LVER machines are ‘product’-specific and can only be used for one particular variant of Airbus aircraft – A319/A320/A321 or A330/A340 – they can be used for each type of wing within that aircraft variant as the same wing is used for all types within each variant. The LVER machines replace the manual assembly of stringers to skins, which previously used numerous assembly jigs and fixtures and required a lot of setting-up time and can now be set-up numerically.

An example of an LVER machine is shown in Figure 2.3, below.



Figure 2.3 Example of an LVER machine (Airbus News, 1999)

Another example includes Brötje-Automation's Automated Fuselage Mating. Brötje-Automation GmbH has developed an automated alignment facility designed to accurately position and align major aircraft fuselage sections (Rüscher and Mayländer, 2001).

A major challenge in aircraft manufacturing is the alignment and mating of large aircraft structures, such as the fuselage. Tolerance build-up, inaccurate jigs and poor manufacturing practices can make this task difficult or even impossible. There may also be inaccuracies in the aligning and mating activity itself, which could lead to poor aerodynamic performance and increased assembly costs.

Therefore, new solutions have to be developed for system manufacturers to meet these challenges. For this reason, Brötje-Automation developed the automated

alignment facility to accurately manoeuvre and position aircraft fuselages to ensure alignment and fit, see Figures 2.4 and 2.5, below. Two goals of the facility are the assembly of airframes to a very high aerodynamic standard and the reduction of labour-hours required for mating aircraft sections. Major components of the system include mechanised jacks, an integrated laser tracking system, and control system and software.

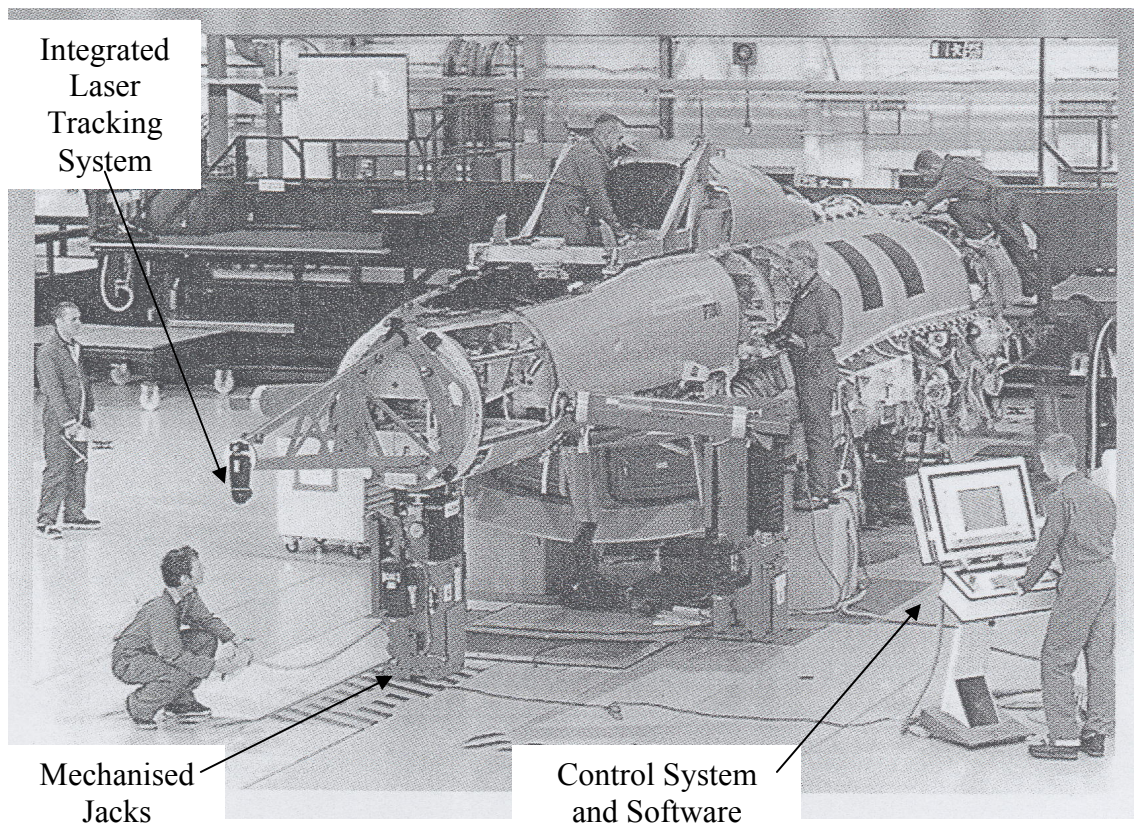


Figure 2.4 Automated alignment facility to accurately manoeuvre and position aircraft fuselages to ensure alignment and fit (Rüscher and Mayländer, 2001)

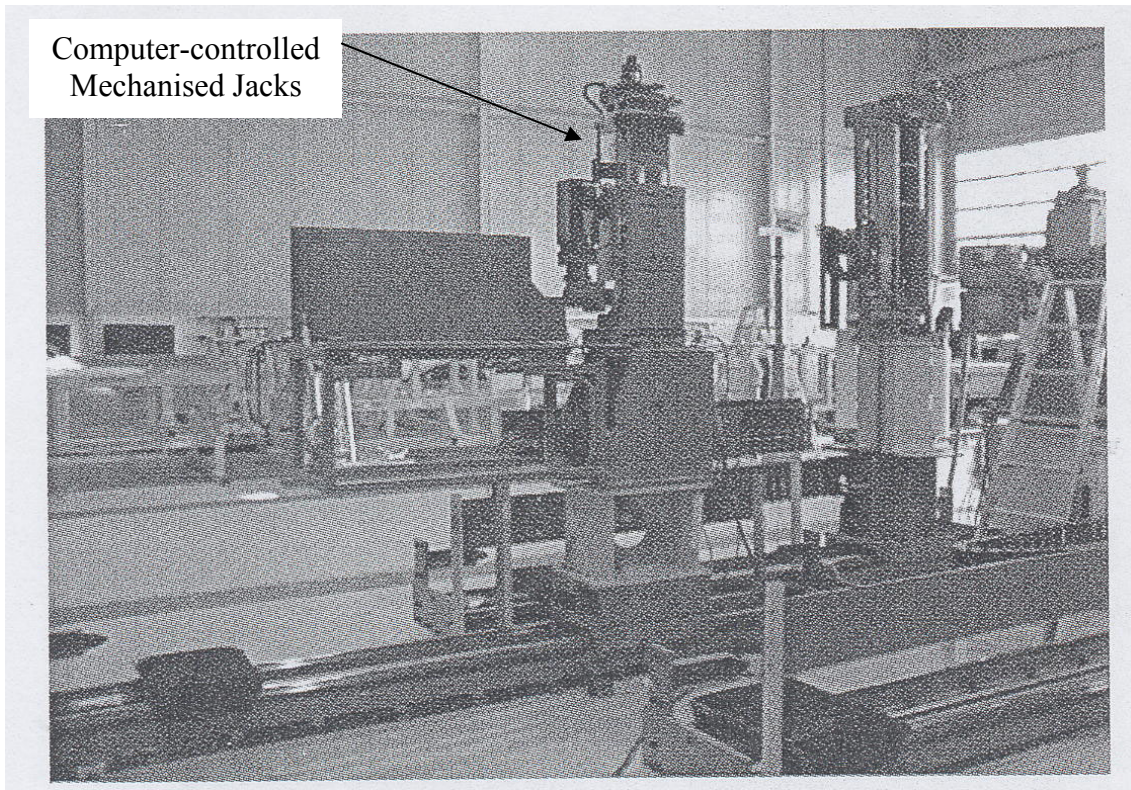


Figure 2.5 Computer-controlled mechanised jacks (Rüscher and Mayländer, 2001)

An example of an assembly process in development is BAE SYSTEMS' Crawler Robot.

In the world of aerospace manufacturing, the challenge of reducing assembly lead times without degrading quality is ongoing; cutting that lead-time and enhancing product quality can be even more difficult. However, BAE SYSTEMS' (Birch, 2001) has been developing technology to do just that and have developed a new Crawler Robot System, described as being low-cost and fully autonomous, that can perform a variety of manufacturing and assembly processes.

Unlike the automotive industry, introduction of robots into aircraft manufacturing has been very limited. Traditionally, aircraft have been assembled using "highly skilled operatives, expensive tooling, manually operated hand tools and paper-based supporting information," according to BAE SYSTEMS. Yet advances in computer technology have brought the opportunity to eliminate paper-based systems and to control machines via digital information.

The first step toward this was the manufacture of small parts on computer numerically controlled machines. Although this reduced time and cost and enhanced product quality of small items, the assembly process continued to be labour-intensive.

By the early 1990's, the company was examining possible applications of digital models to improve assembly techniques and launched a program aimed at reducing the amount of tooling while increasing quality and throughput. Its first stage involved the installation of large, fixed robots guided by complex programming of locations and movements from the digital model. The downside of this was limited flexibility, lengthy programming times and overall cost. BAE SYSTEMS therefore moved on to introduce 3-D laser projection to directly display the information from the digital model onto the component. This removed expensive hard tooling and templates from the assembly cycle, although this approach was still reliant on skilled manual labour.

Next came the introduction of a micro-positioning tool. By integrating laser-guided bomb technology with the 3-D laser projection system, BAE SYSTEMS has developed a small, semi-autonomous robot that can drill holes directly from the digital image. The new Crawler Robot is the latest phase in this steady development. By harnessing digital technology, engineers are able to control machines directly from the computer interface, reducing assembly times while increasing quality, according to BAE SYSTEMS.

Nevertheless, the use of robots in assembly has been well established for some time within the automated assembly and automotive areas. Numerous examples are available (Braggins, 1984). At a Swedish car plant, a vision system-equipped ASEA robot handled a selection of shafts at the same station. Some are too similar to be distinguished by outline, so the robot held up the 'ambiguous' parts to a second, close-up camera, which uses marks on the shaft to make the necessary distinctions. An example of an ASEA robot is illustrated in Figure 2.6, below.

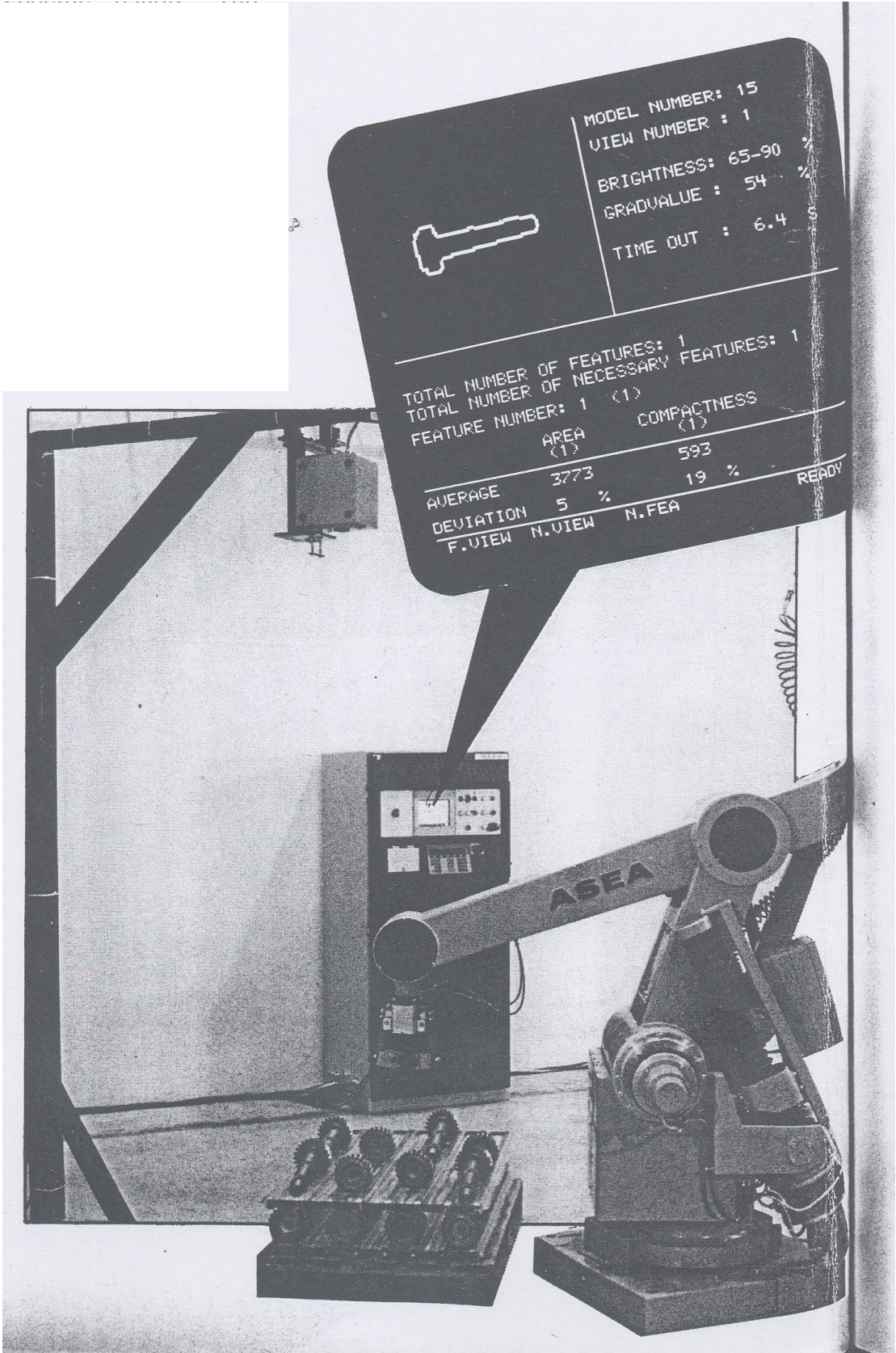


Figure 2.6 An example of an ASEA robot (Braggins, 1984)

The application of vision for placing the front and rear windows into Montego bodies at Cowley, Oxfordshire, UK, is a good example of how this problem was solved. Once the bodies were baked in paint ovens, the absolute position of the two window apertures could vary by up to 10mm, yet the glass had to be positioned to within 1mm. Four linear array cameras allowed VS Engineering to solve this problem, automating a previously labour intensive task.

In Germany, KUKA used Bosch SAM vision units to calculate the degree of rotation needed for aligning wheels to hubs, guiding robots at a car assembly plant to fit front and rear wheels in 38 seconds/car.

Automatix, USA, supplied an ‘eye-in-hand’ robot system that can tighten the bolts used to adjust car windows to a snug fit, regardless of the location of the bolt along a slideway.

The cost of adding intelligence to a system was not prohibitive. In 1984, the basic ASEA vision system added typically under £18,000 to the price of a robot. Electronic Automation of Hull, UK, offered a tiny camera and controller, which centred a robot arm on a hole or marked spot for less than £4,000. Other sensors, such as Polaroid ultrasonic range finding units, cost under £1,000 in 1984.

Finally, an example of an assembly process under research is the ‘Fixtureless Assembly of Sheet Metal Parts for the Aircraft Industry’ (Walczyk et al, 2000). Although, under the definitions of this research presented in section 2.2, the research of Walczyk et al can be considered as an example of jigless assembly. Here, a method is presented for jigless assembly of simple sheet metal parts, i.e. consisting of flat patterns and simple bends, used in the aircraft industry. Current industry practice relies on manually intensive procedures and rigid jigs and fixtures for part assembly. The proposed method relies on carefully toleranced alignment holes that are computer numerical control machined into the parts at the fastener locations, as illustrated in Figure 2.7, below. Parts are temporarily fastened at these alignment holes for their proper alignment together into the assembly and then permanently fastened at all rivet and bolt locations. A simple procedure is used to characterise empirically the CNC hole drilling process in sheet metal for this method. A simple experiment, illustrated in Figure 2.7, below, involving the assembly of four parts with rivets, successfully demonstrates the potential of jigless assembly.

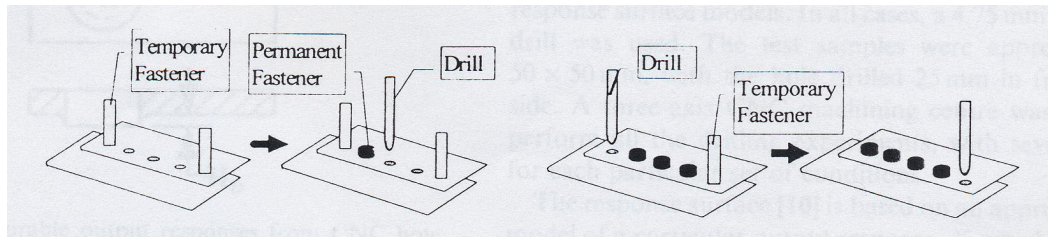


Figure 2.7 Jigless assembly method (Walczyk et al, 2000)

There are also numerous examples of Jigless Assembly currently existing within other industries.

A good example is the No-Adjust Car Build (NACB) concept from Ford, where ‘design features’ and other methods have been used to satisfy a number of objectives for that particular project and in doing so, reduced the amount of assembly tooling (Ford, 1994).

The No-Adjust Car Build concept seeks to manage variation through a total vehicle approach in the design of both the product and the process, achieving a level of process capability and repeatability that will eliminate Ford’s dependence on operator finesse or intervention on the assembly line.

Locators are used to accurately and repeatedly position parts in all stages of manufacturing and assembly. Measuring Points are chosen to provide the data necessary to determine if the process is performing correctly and the part is within specification. Variation Simulation Analysis (VSA) is an additional tool that provides a predicted variation for the entire vehicle. VSA is a software program that uses a variety of inputs to produce a 3D model of the vehicle, major causes of variation can then be investigated and reduced by changing the design of the components, changing the assembly process or as a last resort, changing the vehicle tolerances. Since VSA is used early in the vehicle program before hard tools are developed, any changes can be made without incurring large costs.

There are three configurations of Locators: hole/pins, surfaces, and edges.

Locator Holes are defined as 4-way or 2-way locators based on their specific purpose. 4-way Locator Holes establish a part in four directions (such as up/down and fore/aft). If only the 4-way locator were used, the part would still be free to rotate about

the pin. To prevent rotation, a 2-way locator is used. 2-way locator holes are usually slots.

Locator Surfaces are generally used in conjunction with the holes. The holes provide stability in four directions (such as up/down and fore/aft) while the surfaces maintain a plane and prevent movement in the last two directions (such as in/out).

Locator Edges are not often used. They are mainly used on small parts where it is not feasible or possible to use holes or surfaces.

This is illustrated in Figure 2.8, below.

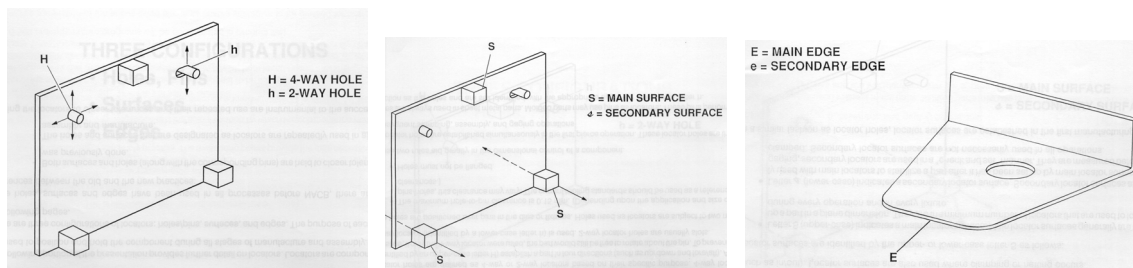


Figure 2.8 NACB Locator Holes, Surfaces and Edges (Ford, 1994)

Indeed, automotive manufacturers have been using flexible tooling and production systems for many years, now. Toyota's factory at Burnaston, Derbyshire, will use an improved version of the company's widely copied production system involving more precise sub-assembly manufacturing and less clamping at the body framing stage. This flexibility means Burnaston will be capable of making three- and five-door Toyota Corolla cars, each with a choice of three types of transmission and six engines (Feast, 2001).

There are other examples of Jigless Assembly in more industries. Manufacturers of Printed Circuit Boards have used jigless in-circuit testers to mount and assemble Printed Circuit Boards (Takahashi, 1990). An example of jigless assembly in the Civil Engineering sector comes from the 'Bailey Bridge' (Moore, 2000). Here, machines are used to drill all the holes in the bridge's beams to maintain the correct clearances and alignment when the beams and panels are erected, along with all of the welding that needs to take place.

There are also examples of individual technologies to enable jigless assembly. The first such example is the Remote Centre Compliance (RCC) device, which is a unique device for aiding assembly insertion operations (Whitney and Nevins, 1979). It is entirely mechanical, deriving its properties from geometry and the elasticity of its parts. Its major function is to act as multi-axis “float”, allowing positional and angular misalignments between parts to be accommodated. Figure 2.9, below, shows an example application of the RCC of a shaft of an alternator being inserted by robot into ball bearings.

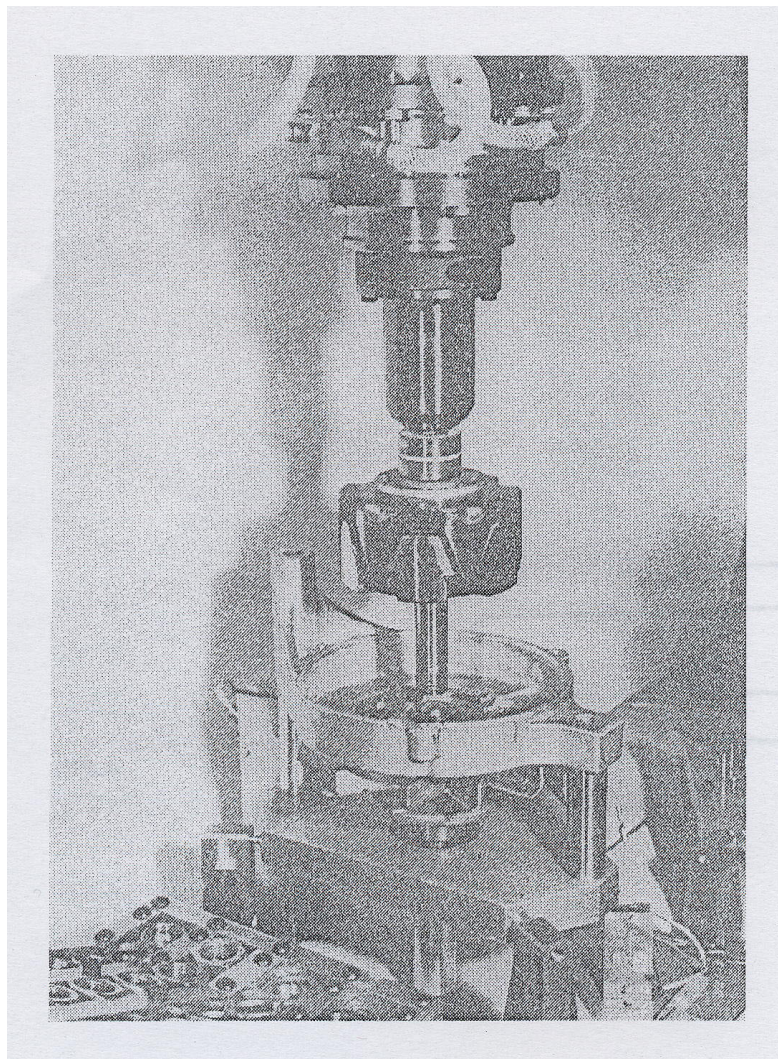


Figure 2.9 Example application of the RCC of a shaft of an alternator being inserted by robot into ball bearings (Whitney and Nevins, 1979)

Another example of an individual technology is the application of Laser Scale technology (Jones, 1999). Fundamentally, a laser scale system can be considered similar to any incremental linear encoder system in that it produces electrical output signals from which linear position can be established. Unlike other forms of linear encoders, however, a laser scale systems does not expand or contract with the machine structure. In fact by fitting a laser scale, a completely independent metrological reference line is established.

A real time compensation system is used, which allows the machine to accurately track thermal expansion of the workpiece. Figure 2.10, below, shows a linear position plot from an application and the process improvements that can be achieved with this type of technology.

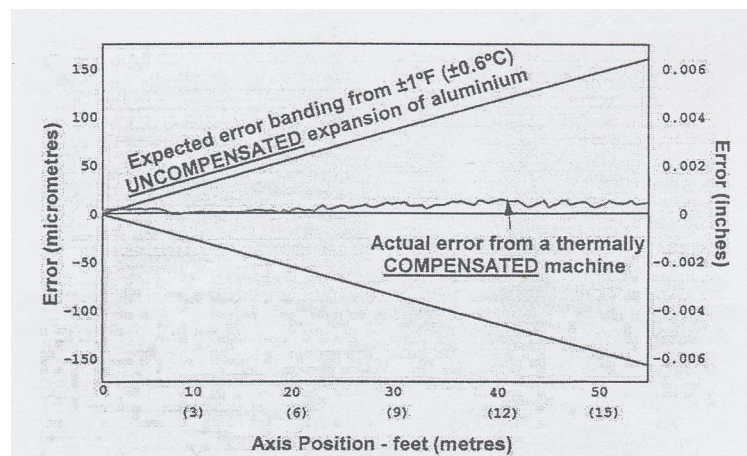


Figure 2.10 Plot of typical laser scale system positioning performance (Jones, 1999)

Lastly, there are examples of integral attachments using snap-fit features. For example, Messler et al (Messler et al, 1997) developed a systematic approach to the selection of locking snap-fit features. This begins with a definition and description of latch and catch components, where a latch is the ‘male’ mating component and a catch is the ‘female’ mating component. Examples of latches are shown in Figure 2.11, below.

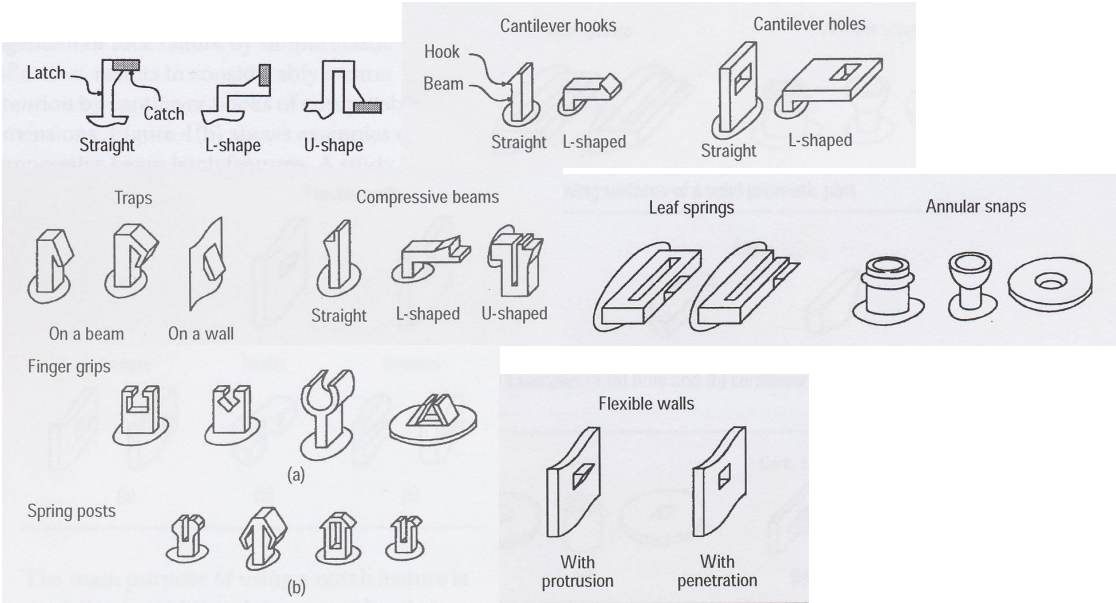


Figure 2.11 Examples of Latches (Messler et al, 1997)

And examples of catches are shown in Figure 2.12, below.

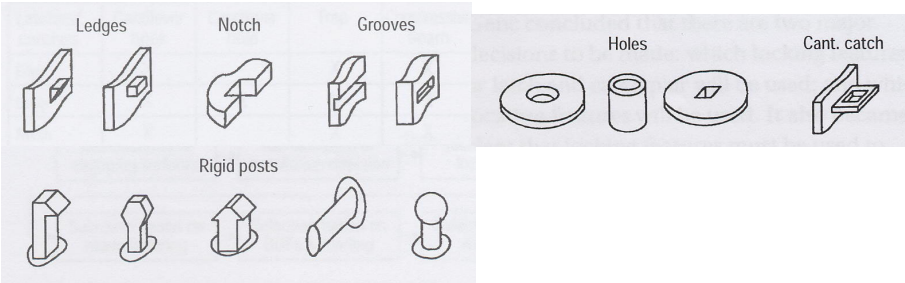


Figure 2.12 Examples of Catches (Messler et al, 1997)

Table 2.1, below, shows the matrix of possible combinations of latches and catches to enable locking.

Latches/ catches	Cantilever hook	Cantilever hole	Trap	Compressive beam	Leaf spring	Annular snap	Finger grip	Spring post	Flexible wall
Edge	X		X	X	X				X
Ledge	X	X	X	X	X				X
Notch	X		X	X				X	X
Hole	X		X	X	X	X		X	X
Cantilever catch	X		X					X	
Groove	X		X	X	X				X
Rigid post						X	X		X

Table 2.1 Matrix of possible combinations of latches and catches to enable locking (Messler et al, 1997)

The proposed methodology for locking feature selection involves six steps. This is illustrated in Figure 2.13, below.

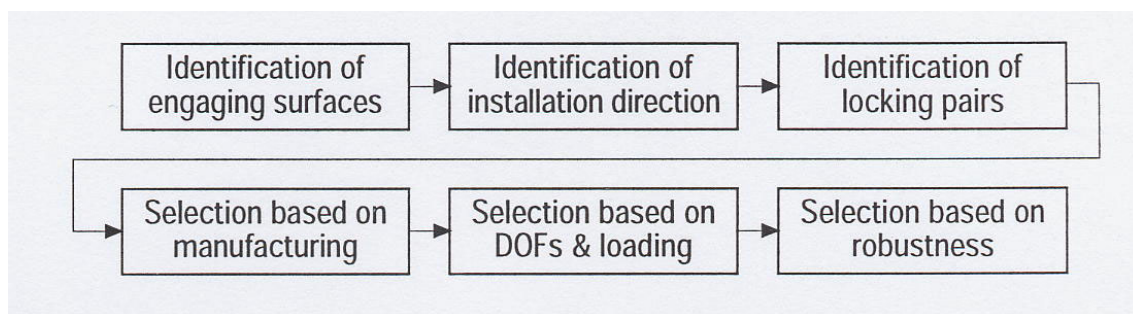


Figure 2.13 Six-step methodology for locking feature selection (Messler et al, 1997)

A case study using those methodologies was presented for the design of a grill that could fit into an opening in the front spoiler of a sports car. Figure 2.14, below, shows the shapes of the openings in the spoiler and a representative grill. Design objectives were multiple and included structural performance, ease of assembly, ease of manufacture and aesthetics. Integral attachment is clearly preferred for ease of assembly. Figure 2.15, below, shows the design inputs before the feature selection process.

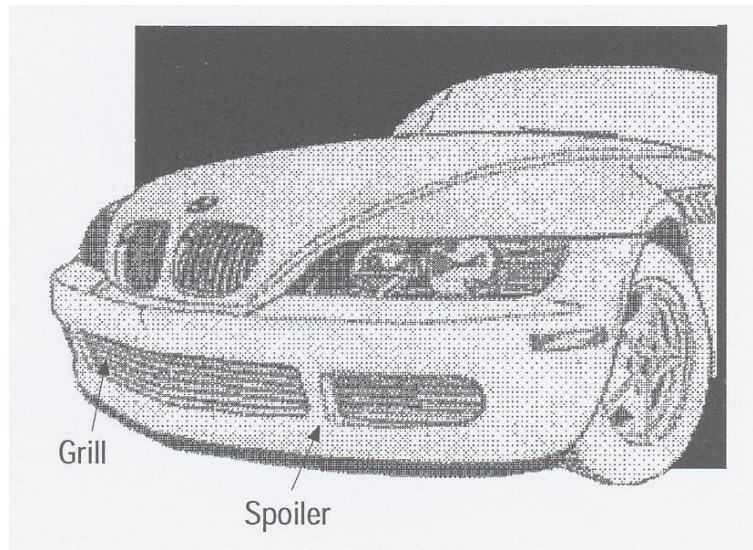


Figure 2.14 Shape of spoiler and grill (Messler et al, 1997)

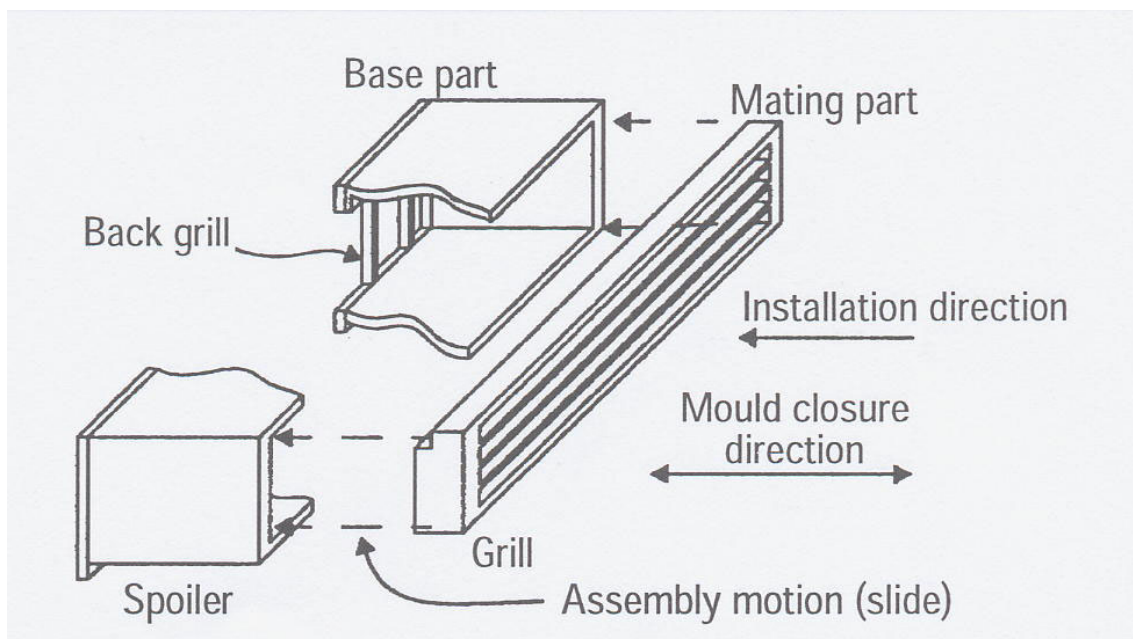


Figure 2.15 Design inputs before the feature selection process (Messler et al, 1997)

The following Figures 2.16 and 2.17 show some results for the application of the Six-step methodology for locking feature selection at various stages in the methodology.

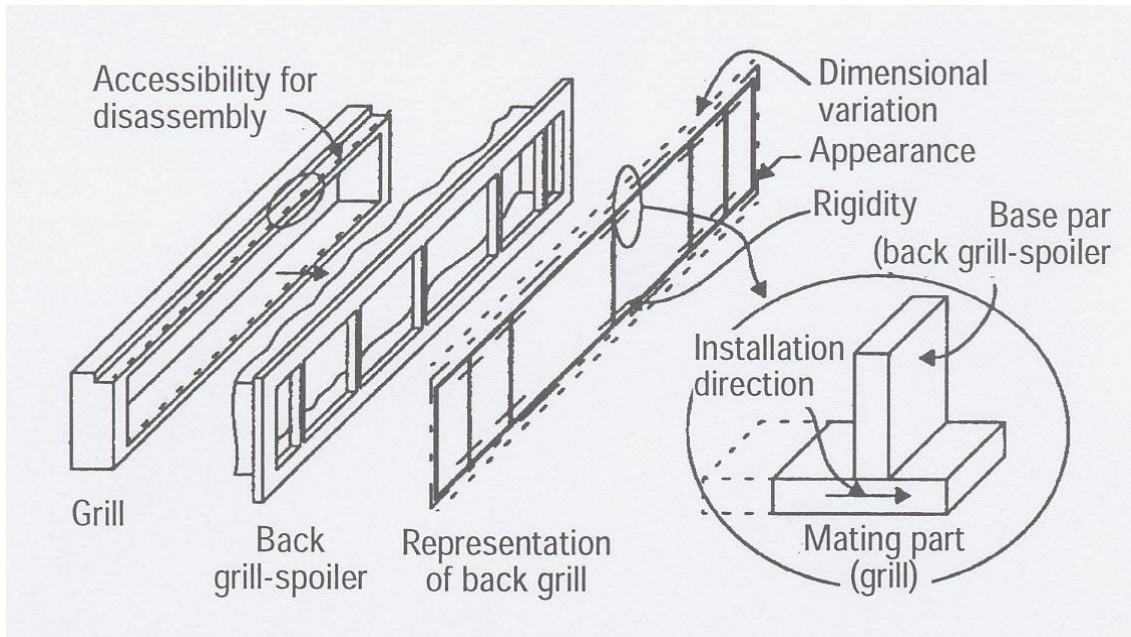


Figure 2.16 Identification process of engaging surfaces (Messler et al, 1997)

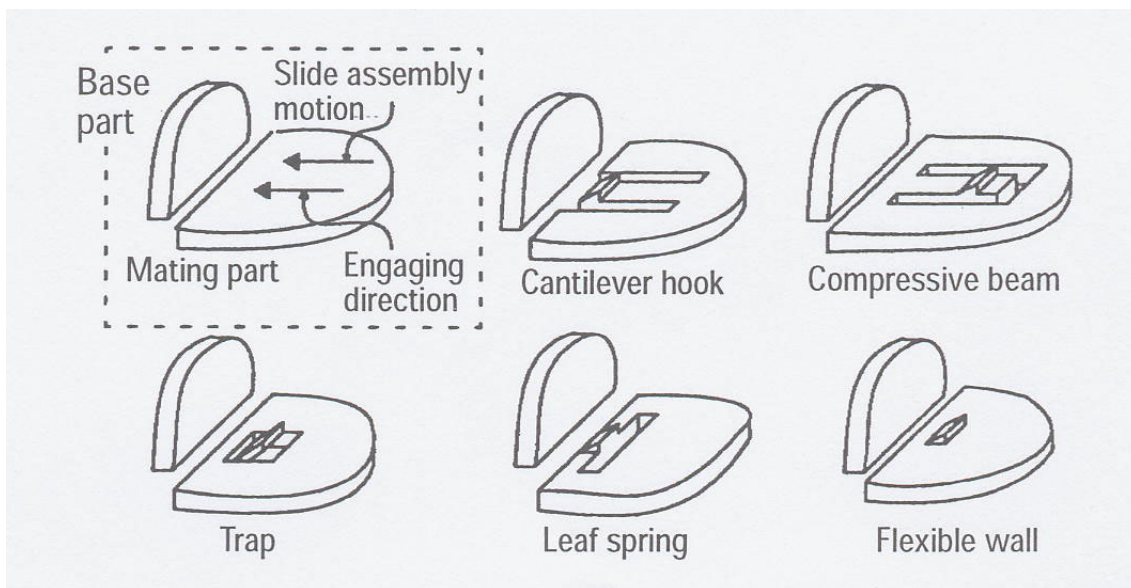


Figure 2.17 Alternative latches for an edge catch pair (Messler et al, 1997)

2.5 Design and Assembly Processes' Methods and Methodologies

The previous section 2.4 illustrated that there are many examples of Jigless Assembly. These examples of Jigless Assembly come in many forms. In order to be most effective, any form of Jigless Assembly that is to be adopted has to be considered and accounted for at the design stage of a product's development. This is so that the design can be optimised with the manufacturing and assembly methods, in terms of issues such as design for manufacture and assembly, production planning, etc.

It is evident then that two sides of an equation need to be answered. One side is that there must be a structured and repeatable process of designing a product, which enables jigless assembly to be achieved but also continues to cater for more conventional forms of assembly using jigs. The other side of the equation is that there must also be a structured and repeatable process, as for the design, of describing the manufacturing and assembly methods available for selection to produce the product.

These two processes for the design, and manufacture and assembly a product must subsequently provide justifications as to why the final design, manufacture and assembly concepts were chosen.

There are already many design methods that are well established. The next section gives a brief review of some of these design methods.

2.5.1 Formal Design Methods

Formal design methods can be classified into three, broad categories (Gouvinhas, 1998).

1. Formal design methods for the generation of ideas for concept design
2. Formal design methods for concept design evaluation

3. Formal design methods for a specific design purpose, which aims to help designers improve their design in terms of, for example, ease of manufacture and assembly and quality, cost, etc.

There is a great deal of literature covering all three groups of formal design methods, listed above. Examples and appropriate references for each of the three groups is detailed in Table 2.2, below.

Formal Design Methods	Examples	References
1. Generation of ideas for concept design	• Classical Brainstorming	Van Gundy, 1987
	• Fish Bone Diagram	Fox, 1993 & Todd, 1995
2. Concept design evaluation	• Pugh's Matrix	Pugh, 1994
	• Morphological Chart	Jones, 1992 & Cross, 1994
	• Checklists	Van Gundy, 1987; Jones, 1992 & Ion and Smith, 1996
	• Weighting and Rating Method	Jones, 1992; Cross, 1994; Pugh, 1994 & Ion and Smith, 1996
	• Combinex Method	Fox, 1993
3. Specific design purpose	• Design for Assembly Methods	
	□ Design for Assembly	Andreasen et al, 1988; Wallace, 1995; Boothroyd and Dewhurst, 1991; Fernandez, 1993; Ashley, 1995 & Boothroyd, 1996
	□ Hitachi Assemblability Evaluation Method	Andreasen et al, 1988; Boothroyd and Alting, 1992 & Boothroyd, 1994
	□ Lucas DFA Method	Miles, 1989 & Miles & Swift, 1992
	• Design for Manufacture Methods	Corbett, 1983; Mietrach, 1985; Miles, 1989; Stoll, 1988; Swift, 1989; Dean and Salstrom, 1990; Miles, 1990; Dieter, 1991; Gill, 1991; Hodgson and Pitts, 1991; Stoll, 1991; Fabricius, 1994; Syan and Swift, 1994 & Swift and Booker, 1997
	• Quality Related Formal Design Methods	
	□ Quality Function Deployment	Salminen et al, 1990; Clausing and Pugh, 1991; Almqvist, 1992; Atkinson, 1992; Brown, 1992; De Vries, 1992; Guinta and Praizler, 1993 & Ramaswamy and Ulrich, 1993

	❑ Failure Modes and Effect Analysis	Dale and Shaw, 1989; EITB, 1991; Ashley, 1993; Gardner et al, 1993 & Stamatis, 1995
	❑	
	❑ Taguchi Methods	BSI, 1981; Taguchi, 1986; Box and Bisgaard, 1988; Taguchi and Clausing, 1990; Unal and Dean, 1991; Ferguson, 1992; Gardner et al, 1993 & Fowkles and Creveling, 1995
	• Functional Tree Analysis Methods	Ion and Smith, 1996
	❑ Function Analysis System Technique	Fowler, 1990 & Fox, 1993
	❑ Functional Analysis Method	Cross, 1994
	❑ The Function Diagram	Fox, 1993
	❑ Function-Cost Method	Fowler, 1990
	• Cost Evaluation Related Formal Design Methods	
	❑ Design for Cost	Corbett, 1983; Wierda, 1988; Dewhurst and Boothroyd, 1989; Allen and Swift, 1990; Wierda, 1990; Sheldon et al, 1991; Ullman, 1992; Derek et al, 1993; Ferreira et al, 1993; Li et al, 1993; Hundal, 1993a; Hundal, 1993b; Mcilhenny, 1993; Zenger, 1993; Essawi, 1994; Harmer and Wallace, 1994; Lenau and Haudrum, 1994; Hundal, 1995 & Lenau and Egebol, 1995
	❑ Value Analysis / Value Engineering	Whitney, 1988; Fowler, 1990; Cross, 1994 & Roozenburg and Eekels, 1995

	❑ Activity Based Costing	Johnson and Kaplan, 1987; Cooper and Kaplan, 1988; Bettner, 1991; Collins and Werner, 1991; Innes and Mitchell, 1991; Yamfwa, 1991 & Bush and Sheldon, 1993
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Table 2.2 Examples and appropriate references for each of the three groups of Formal Design Methods (Gouvinhas, 1998)

All three groups of formal design methods would be applicable to design for jigless assembly.

The first group, for the generation of ideas for concept design can be used to formulate alternative concepts for jigless assembly. Indeed, ‘Classical Brainstorming’ techniques were employed to generate alternative concepts for the Case Study described in Chapters 5 and 6.

The second group of formal design methods, for concept design evaluation, can be used to select alternative concept designs based on a list of criteria the design concept must satisfy. Any one of the examples in this second group could be used as an aid to select alternative concepts for jigless assembly. However, none were used for the Case Study because a concept selection methodology was being developed that was specifically tailored for jigless assembly, although this does not preclude the use of any of the other methods as further means of selection.

Hence, the remaining group of formal design methods are those that are for a specific design purpose. In the case of designing for jigless assembly, all five categories of this particular group of formal design methods were considered: namely, ‘Design for Assembly’ methods, ‘Design for Manufacture’ methods, ‘Quality Related’ formal design methods, ‘Functional Tree Analysis’ methods and ‘Cost Evaluation Related’ formal design methods. Within these categories, only ‘Activity Based Costing’ has been actually used for the Case Study to cost the current design, manufacture and assembly concept against the selected alternative design and manufacture concept to enable jigless assembly. It was found that none of the other methods specifically addressed designing for jigless assembly, although they could be adapted for such a purpose.

The examples of ‘Design for Assembly’ methods could be more applicable towards the high-volume electronics manufacturing industries where there is a larger emphasis on the automated or robotic ease of assembly, as opposed to the very low-volume aircraft manufacturing industry, which can be argued is traditionally concerned more with product performance and safety than necessarily with ease of assembly. Another drawback of the quoted examples of design for assembly methods is that they tend to carry out the design for assembly analysis after the product has been initially designed and then to re-design the product with ease of assembly in mind. This may not be such a problem in electronics manufacturing where product life-cycle times are low but in aircraft manufacturing where product-life cycle times are measured in decades rather than months or years, it is very costly to design and then re-design a product. A design for assembly method is required that aids in the creation of a design for jigless assembly as soon as possible in the product’s development so that any solutions or problems can be predicted before any parts are even made.

It has proven more difficult to define what design for manufacture methods actually consist of. Essentially, any method that makes a product or part more easily manufacturable can be considered as a design for manufacture method. In the case of jigless assembly, design for manufacture is an enabler towards jigless assembly. As explained in Chapter 4, if there are no jigs present to enable assembly then either other ways must be used to facilitate assembly, such as measurement systems, or the parts must be manufactured to a high enough quality and precision to effectively assemble themselves, which is commonly referred to in the aerospace industry as ‘part-to-part’ assembly. Consequently, design for manufacture methods need to concentrate upon the quality and precision of the parts that they help to produce.

This leads on to the next category of formal design methods for a specific design purpose – ‘Quality Related’ formal design methods. As described in the previous paragraph, quality is a very important issue for jigless assembly. The examples quoted in Table 2.2 can all be used to improve the generic, high-level of a product’s quality. However, in order to achieve the quality required for a jigless assembly to be possible the design method must account for the details of a product’s design, i.e. the tolerances of the part features. Only at this level of detail can the question be answered whether an assembly will fit together without the use of jigs.

None of the examples in the next category of formal design methods for a specific design purpose, ‘Functional Tree Analysis’ methods, were specifically used. However, the general philosophy of decomposition of the basic function of a product into different levels of sub-functions has been applied for the Case Study, even if none of the examples were in fact applied.

The final category of formal design methods for a specific purpose is ‘Cost Evaluation Related’ formal design methods. As stated previously, ‘Activity Based Costing’ is the only method that has been explicitly used for the design of jigless assembly of the Case Study. However, a form of ‘Design for Cost’ in terms of ‘Feature Based Costing’ has been investigated as part of the research study. This is described in further detail in section 2.6.4 of this chapter and throughout the remainder of the thesis. ‘Value Analysis / Value Engineering’ was not used for similar reasons as the ‘Design for Assembly’ methods because the analysis is carried out after the design has been completed.

2.5.2 Assembly Process Modelling

Several researchers have attempted to develop and define methodologies that describe the assembly process. As with Design, there are many elements to Assembly, for example, scheduling, logistics, ergonomics, etc. However, the body of work that seeks to explain how parts are actually fitted together is collectively known as Assembly Process Modelling. Assembly Process Modelling, itself, can be aimed at a particular viewpoint, such as from a quality, or functional, or flexible assembly perspective. The following are a few examples of Assembly Process Modelling methodologies that have been developed to represent the assembly process.

Lewis (Lewis, 2000) describes the implementation of a ‘Quality Product Management (QPM)’ process at BAE SYSTEMS, part of which seeks to model the assembly process. The QPM process is illustrated in Figure 2.18, below, and is achieved by asking the engineering teams the following questions.

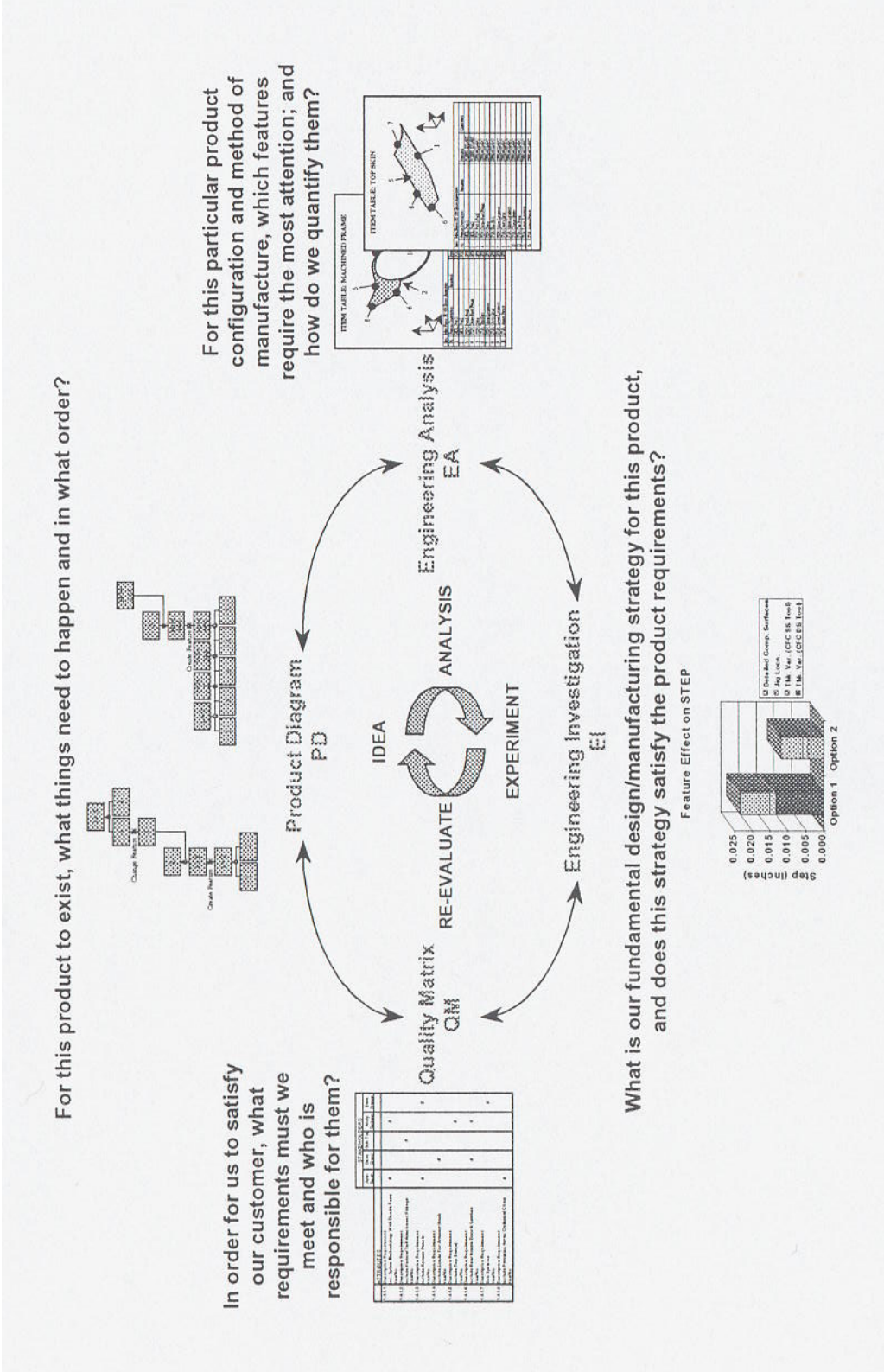


Figure 2.18 Quality Product Management (QPM) process at BAE SYSTEMS (Lewis, 2000)

- **Quality Matrices:** In order for us to satisfy our customer, what requirements must we meet and who is responsible for them?
- **Product Diagrams:** What is the product and in order for it to exist what things need to happen and in what order?
- **Engineering Analysis:** For this particular product configuration and method of manufacture, which features require the most attention?
- **Engineering Investigation:** What is the fundamental design and manufacturing strategy for this product and does this strategy satisfy the product requirements and how much risk is associated with it?

The ‘Quality Matrix’ is a technique that involves defining and clustering product requirements, stakeholder standards and engineering concerns within a database. The Quality Matrix is used to relate and reference responsibility against the product and product requirements. This information is captured in a Quality Matrix Attribute Map, a document that identifies who is responsible for which product requirements and which standards they endorse. An example is illustrated in Figure 2.19, below.

The ‘Product Diagram’ is a tool that graphically represents product items and processes within a type of flow diagram. The tool is used to document and communicate assembly sequence, manufacturing processes, raw material requirements, facility requirements, span/process time, cost and the inter-relationship between tooling and parts. This tool is stated to be fundamental in cascading ‘top down’ assembly requirements and working ‘bottom up’ produceability issues. An example is illustrated in Figure 2.20, below.

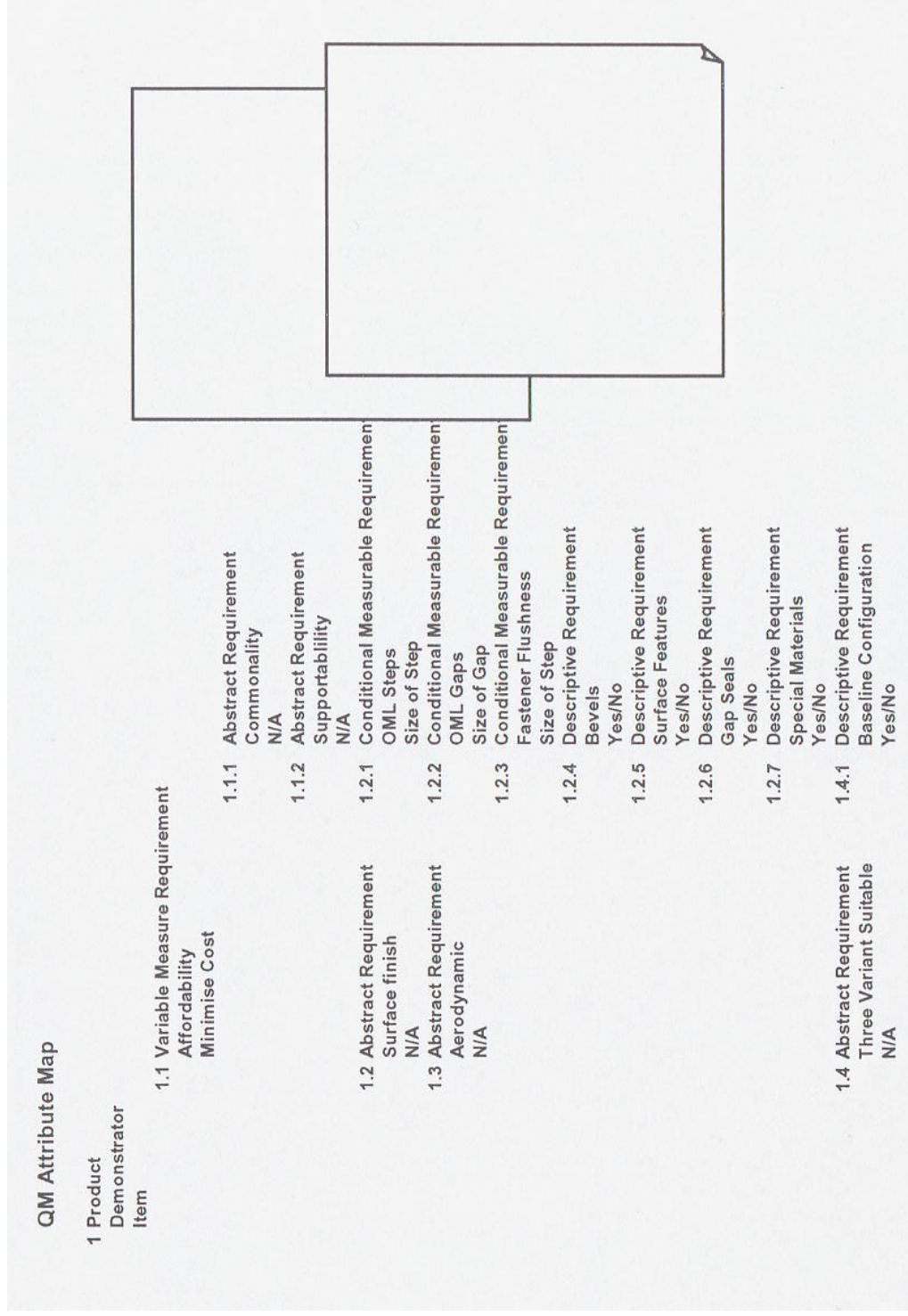


Figure 2.19 An example of a Quality Matrix Attribute Map (Lewis, 2000)

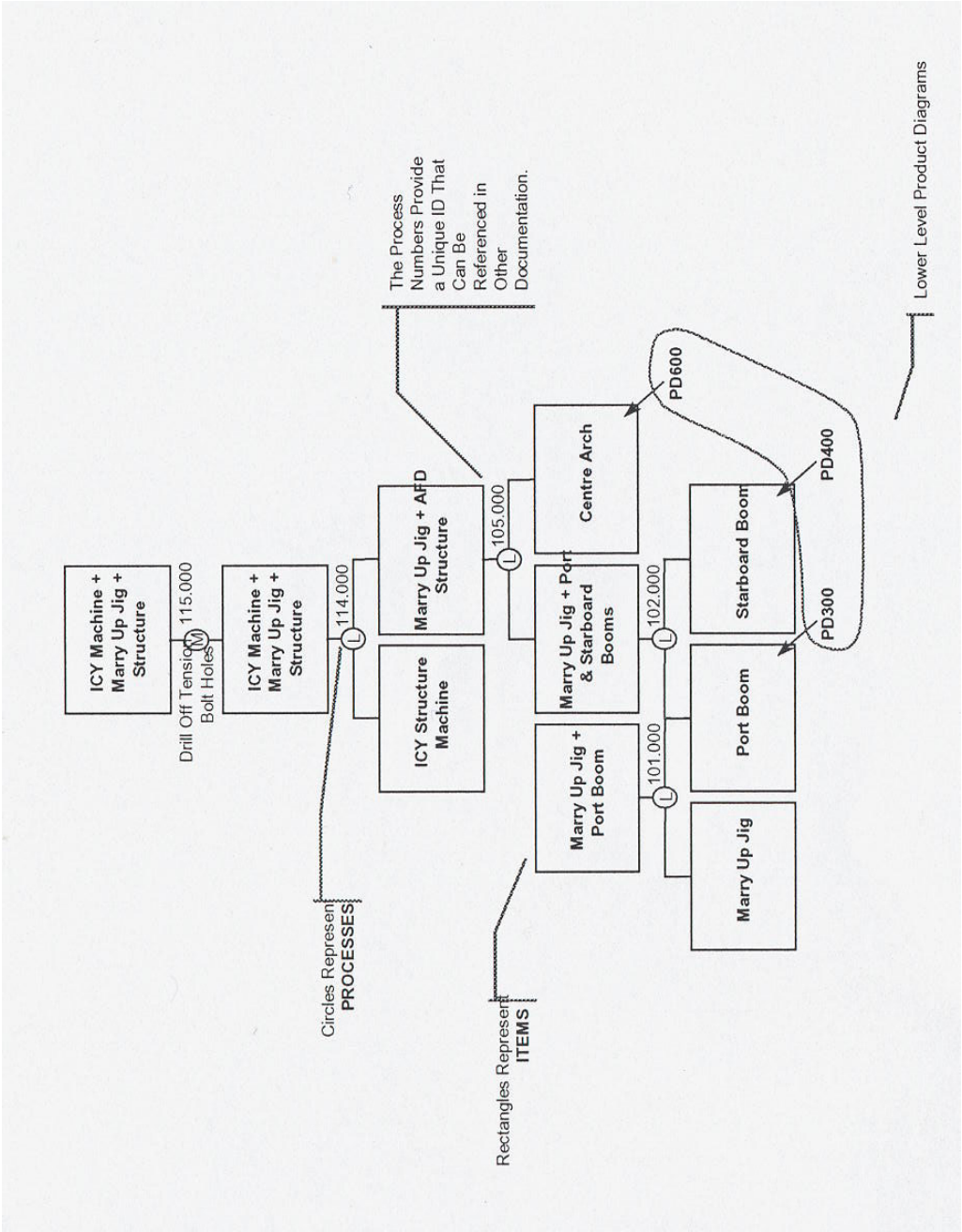


Figure 2.20 An example of a Product Diagram (Lewis, 2000)

The ‘Engineering Analysis’ is a series of tables that facilitate the defining, quantifying and tabulating of geometric features that belong to the product items and processes identified within the Product Diagram. This tool is used to document Key Characteristics, Geometric Dimensioning and Tolerancing (GD&T), Condition of Supply, Statistical Process Control Data, Locator Schemes and Tooling Concepts. This information is captured in an Engineering Analysis Item Table, which documents the geometric features of items to identify (i) *the requirements placed on them*, (ii) *the engineering intent based on basic calculation of accumulative tolerances or best guess* and (iii) *the qualified results through measurement and inspection*. An example is illustrated in Figure 2.21, below.

<i>ITEM: Detailed Part, Assembly, Sub Assembly, Etc.</i>				
<i>ID</i>	<i>Feature Description</i>	<i>Required</i>	<i>Intended</i>	<i>Quantified</i>
<i>Unique ID Associated With A Feature</i>	<i>An Alphanumeric Description of the Feature. Typically preceded by a three letters indicating the type of feature: HOL: Hole PLN: Plane SUR: Surface</i>	<i>Requirement placed on the Feature: From the Customer From Existing Standards</i>	<i>Engineering Intent / Basic Calculation of Accumulated Tolerance. What We Think / Calculate Can Be Achieved</i>	<i>Measurement and Inspection Results What We Have Achieved</i>

Figure 2.21 An example of an Engineering Analysis Item Table
(Lewis, 2000)

The ‘Engineering Investigation’ involves investigating the product by classifying parts and assemblies based on the data gathered within the Quality Matrix, Product Diagram and Engineering Analysis and identifying risk associated with them in order that plans can be developed to mitigate this risk. An example is illustrated in Figure 2.22, below.

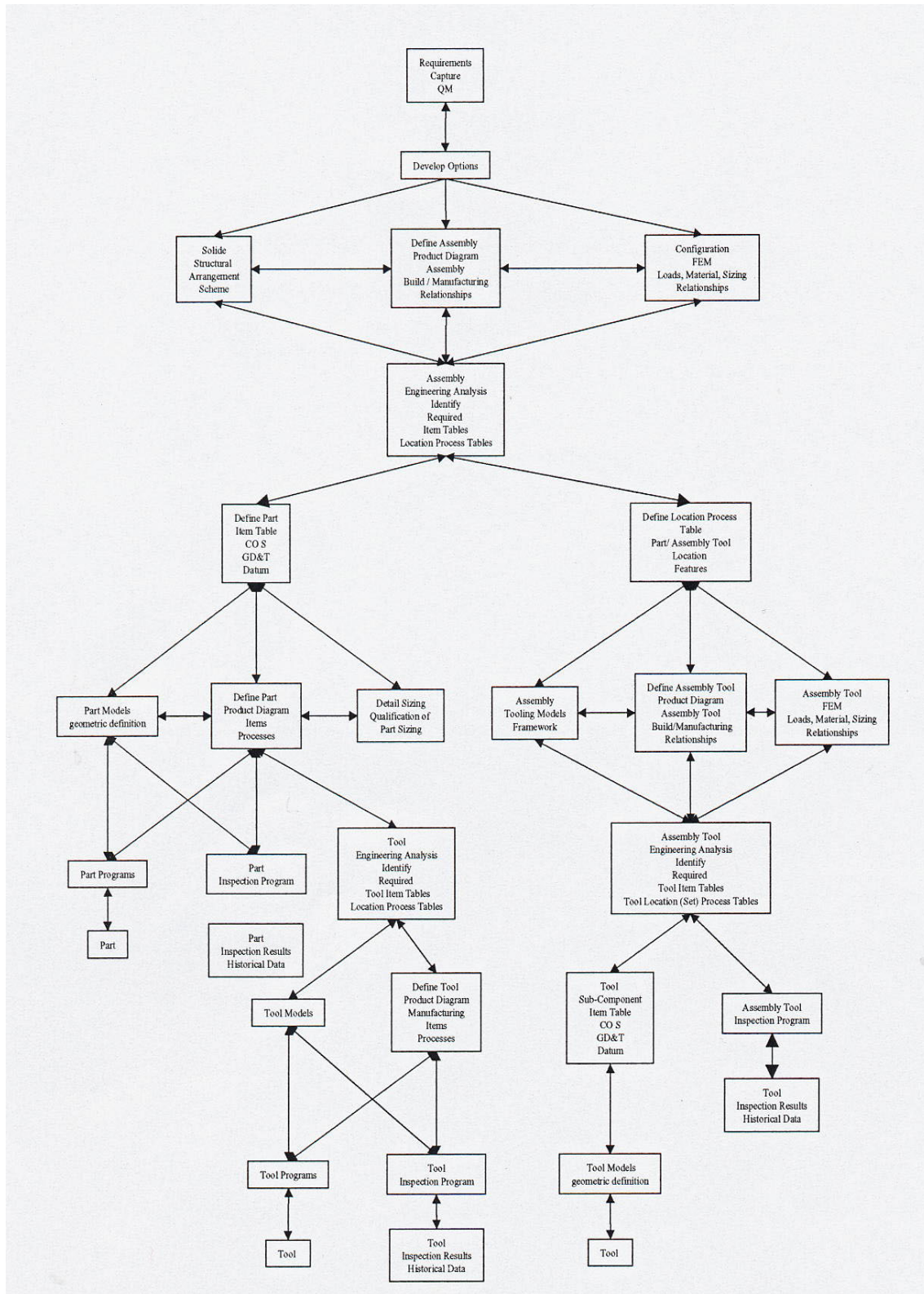


Figure 2.22 An example of an Engineering Investigation Chart (Lewis, 2000)

Researchers at the Massachusetts Institute of Technology (MIT) have also developed a methodology to describe and represent Assembly Modelling (Whitney, 1995 and Cunningham et al, 1996). The notion is put forward that Assembly Modelling is divided into two categories: small and large, the former concentrates on single part-pair relations while the latter includes sets of parts and system issues such as tolerance propagation, product architecture, mixed-model manufacturing, logistics, etc.

Assembly in the small is defined as comprising all single steps or actions of assembly, including descriptions of the regions of parts, called ‘mating features’, that actually assemble to each other or slide past each other during assembly. The mating feature is the foundation for modelling assemblies consistently from the small to the large. Mating features are defined as local regions on parts where they join to other parts (De Fazio et al, 1990 and Shah and Rogers, 1993). Example mating features are shown in Figure 2.23, below. A common element of each of these features is a defining co-ordinate frame, which determines the location and orientation of the feature relative to a reference co-ordinate frame on the part containing the feature (Poppstone et al, 1978).

Mating features are the basis for modelling many aspects of assemblies. Most importantly, features are carriers of design intent: a hole is not a hole but rather, a pocket for a bearing, a seat for a locating pin, a locator for a shaft or pivot, etc. The geometry of mating features is usually governed by their function in the design. The basis for many approaches to functional modelling of assemblies lies in mating features (Eversheim and Baumann, 1991; Lee and Gossard, 1985; Gossard et al, 1988; Srikanth and Turner, 1990; Rocheleau and Lee, 1987; Gui and Mantylä, 1994 and Roy, Banerjee and Liu, 1989).

Assembly in the large refers to assembly issues that involve more than one part, including, geometric domains such as fixturing, assembly tools, tolerance propagation, etc.; domains that combine geometry and relational information such as identifying and choosing assembly sequences, product re-orientation during assembly, operator ergonomics, predicting assembly cost and time, etc. and finally, domains that are primarily relational and only slightly geometric such as options for product architecture, identifying sub-assemblies, logistics and supplier issues, etc.

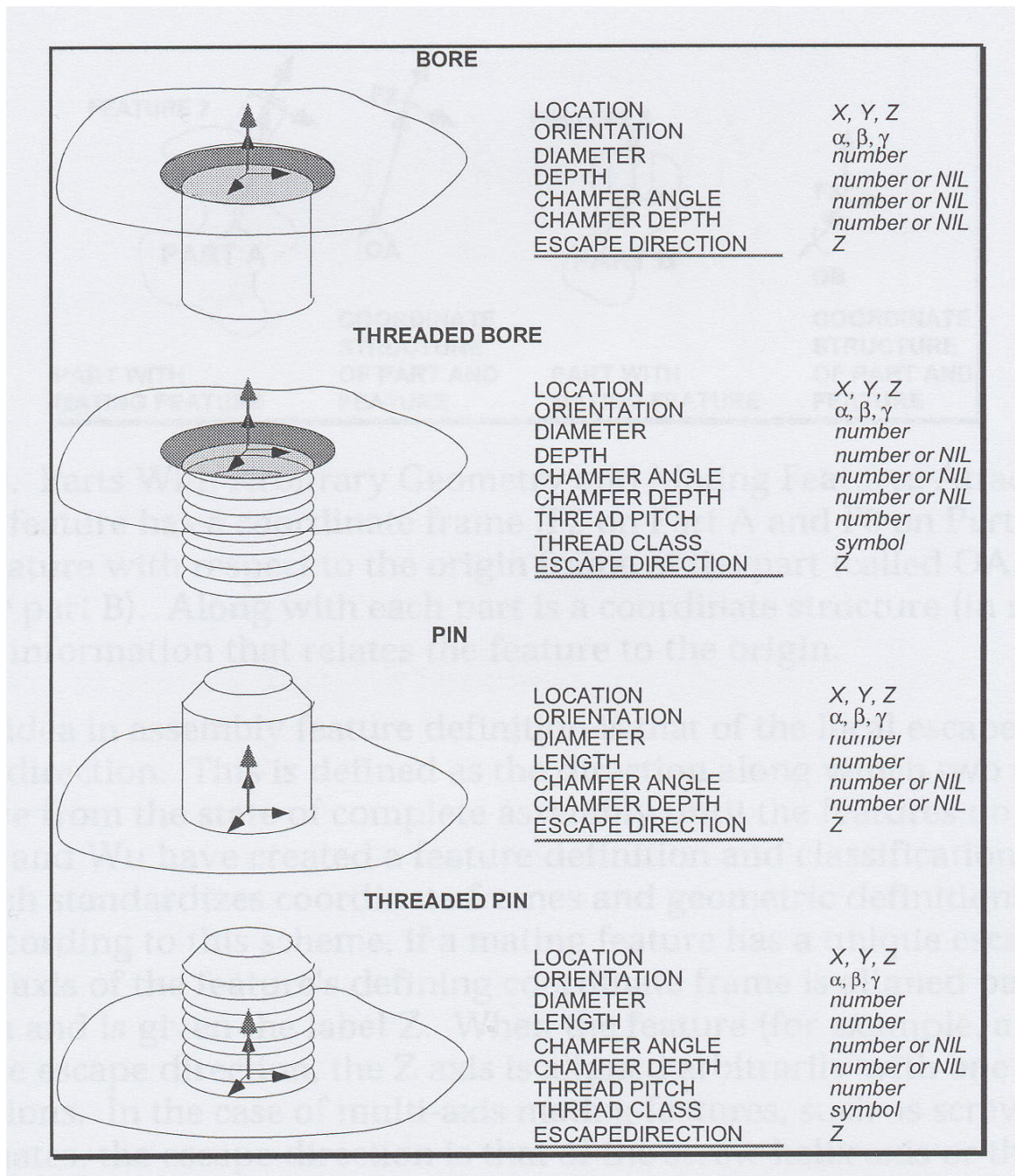


Figure 2.23 Example mating features (Whitney, 1995 and Cunningham et al, 1996)

The Assembly Modelling of assembly in the large has been sub-divided into six, main topics. Each of these topics and the research conducted upon them will be briefly described in the following paragraphs.

1. Nominal connective models of assembly

The researchers at MIT assert that typical CAD systems represent assemblies by one of the following methods:

- Placing the parts in a world co-ordinate system in the correct relative position and orientation but otherwise taking no note of the fact that they are assembled to each other, illustrated in Figure 2.24 (a), below
- Capturing constraints such as ‘against’ or ‘aligned’ that are applied by the designer to various surfaces or axes on parts after they are designed, illustrated in Figure 2.24 (b), below

An alternative assembly model extends and exploits the idea of the assembly mating feature to build up assemblies by joining features and simultaneously building up a relational database (Lee and Gossard, 1985), illustrated in Figure 2.24 (c), below.

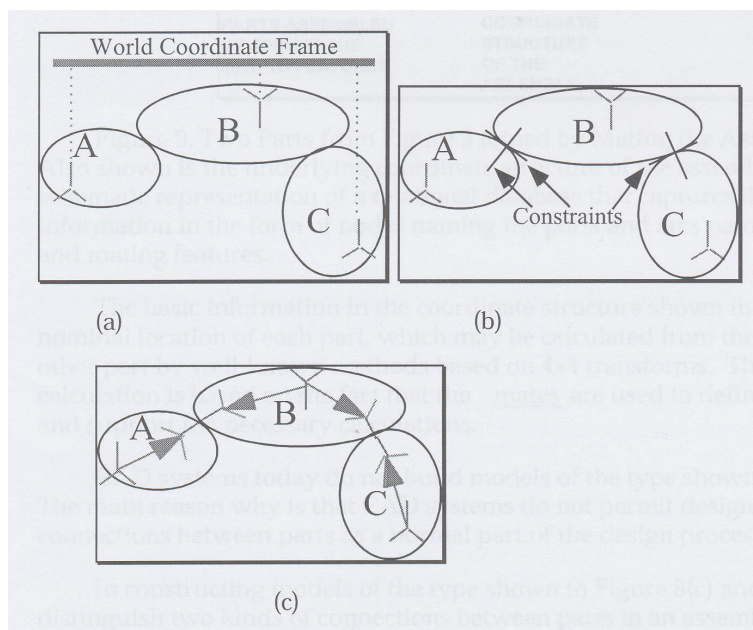


Figure 2.24 Three kinds of assembly models: (a) a non-connective model, (b) a constraint model and (c) a connective model that makes use of mating features (Whitney, 1995 and Cunningham et al, 1996)

CAD systems today do not build models of this type because they do not permit designers to declare connection between parts as a normal part of the design process.

In constructing models of this type, it is crucial to distinguish two kinds of connections between parts in an assembly:

- **Mates** are connections that pass dimensional and locational constraint from one part to another
- **Contacts** are all other connections made to provide strength or reinforcement but not able to provide locational constraint due to clearances, shims or minor structural redundancy

2. Construction of assembly models

As stated above, traditional CAD does not provide tools that are aimed specifically at designing assemblies. Two generic approaches to designing assemblies have been imagined:

- i. Design the parts and place them in the desired relative positions and orientation in space (Shah and Rogers, 1993; De Fazio et al, 1990; Rochelau and Lee, 1987 and Kim and Lee, 1988)
- ii. Design the relationships and interfaces between anticipated parts or sub-assemblies and then design the specific parts that adhere to these relationships (Mantylä, 1990; Eversheim and Baumann, 1991 and Lee and Gossard, 1985)

Approach 1 usually results in assembly models of type (a) or (b) in Figure 2.24. Approach 2 explicitly includes a step called **layout**. Layout used to be practiced routinely before the emergence of CAD. Its disappearance or de-emphasis today may be due to the emphasis in CAD on design of individual parts. The main feature of layout of interest is its focus on defining the dimensional relationships between parts *before* the detailed geometry of those parts is declared; this being an essential element of top-down assemblies.

3. Models of complete and incomplete assemblies

Most models of assemblies represent the assembly as complete with all its parts in place and all mates and contacts fastened. However, the same modelling methods can be used to represent incomplete assemblies. This is important because assembly planning involves considering a series of successively more complete assemblies. Incomplete assemblies may have unconstrained degrees of freedom that will be constrained when the assembly is complete. They may be subject to shape or size variations that the final assembly will not be subject to. Yet these uncontrolled degrees of freedom or variations may cause the next assembly step to fail or may result in a misshapen final assembly and thus have to be considered during the design.

In order to manage these issues systematically, it has been proposed useful to distinguish two types of assembly: Type I and Type II. These are further explored in sections 3.3.1 and 3.3.2, respectively.

4. Application of nominal models: assembly sequence analysis

Assembly sequence analysis according to the researchers is now a well-developed process, supported by a variety of efficient algorithms. However, it has not been embedded in a commercial CAD system. Existing methods stand alone and require that information of type (c) in Figure 2.24 must be put in manually or transferred from the CAD model to the assembly analysis and augmented.

Assembly sequence analysis is defined by the researchers as involving two processes:

- Discovery of physical constraints between parts, or between parts and tools used to locate or fasten them
- Discovery of one or more sequences that do not violate the constraints

5. Varied connective models of assemblies

Up to now it has been assumed that the assembly model depicts perfectly made and assembled parts. The reality is that parts differ and this fact should be represented in the assembly model. Two important types of variation should be represented:

- i. Variations in the interface constraints between parts
- ii. Variations in the geometry or relationships inside individual parts

Ordinary tolerancing standards (ANSI Y 14.5 and its successors) deal only with the second kind of variation. This important fact is one reason why there is no accepted method of ‘designing assemblies’. Yet many important characteristics of assemblies are governed by the first kind of variation.

6. Application of varied models: tolerance propagation

Whitney et al (Whitney et al, 1994) have shown a method to propagate tolerances through assemblies using 4 x 4 matrix methods. The essence of the method is to find a matrix representation of the ANSI Y 14.5 tolerances on feature size.

Finally, the researchers at MIT have taken up some emerging design techniques and indicated how the same kind of model structure described in the previous sub-sections can support these design techniques. These techniques comprise **Key Characteristics** and **Datum Flow Chains** and are intended to merge into a Top-Down method of designing assemblies that is based on defining assembly constraints. **Key Characteristics** and **Datum Flow Chains** are explored in further detail in sections 3.2.1.3 and 3.2.1.4, respectively.

2.6 Feature Based Methods

The preceding review of the literature has shown that ‘features’ have an important part to play in design for assembly and hence, designing for jigless assembly. Indeed, the subject of ‘features’ and their application in design, manufacturing and assembly has grown into a major area of research, in itself, over recent years.

To understand the reasons for this situation, the basic theories of feature principles needs to be provided and their increasing exploitation into many specific fields, such as Feature Based Design, Feature Based Costing and Feature Based Tolerancing, can be described.

2.6.1 Feature Definitions and Taxonomies

There are numerous definitions of what a ‘feature’ is and subsequently, several Feature Classification Schemes to systematise and classify the potentially infinite number of features.

The feature classification scheme by Wilson and Pratt was the first attempt at generating a feature taxonomy. This scheme is depicted in Figure 2.25, below and a cross section through a component showing example features is given in Figure 2.26, below.

Another feature classification scheme is the scheme of STEP (Standard for the Exchange of Product Model Data). This feature classification scheme consists of four units of functionality (UoF) where a UoF is considered a collection of application objects and assertions. This is depicted in Figure 2.27, below.

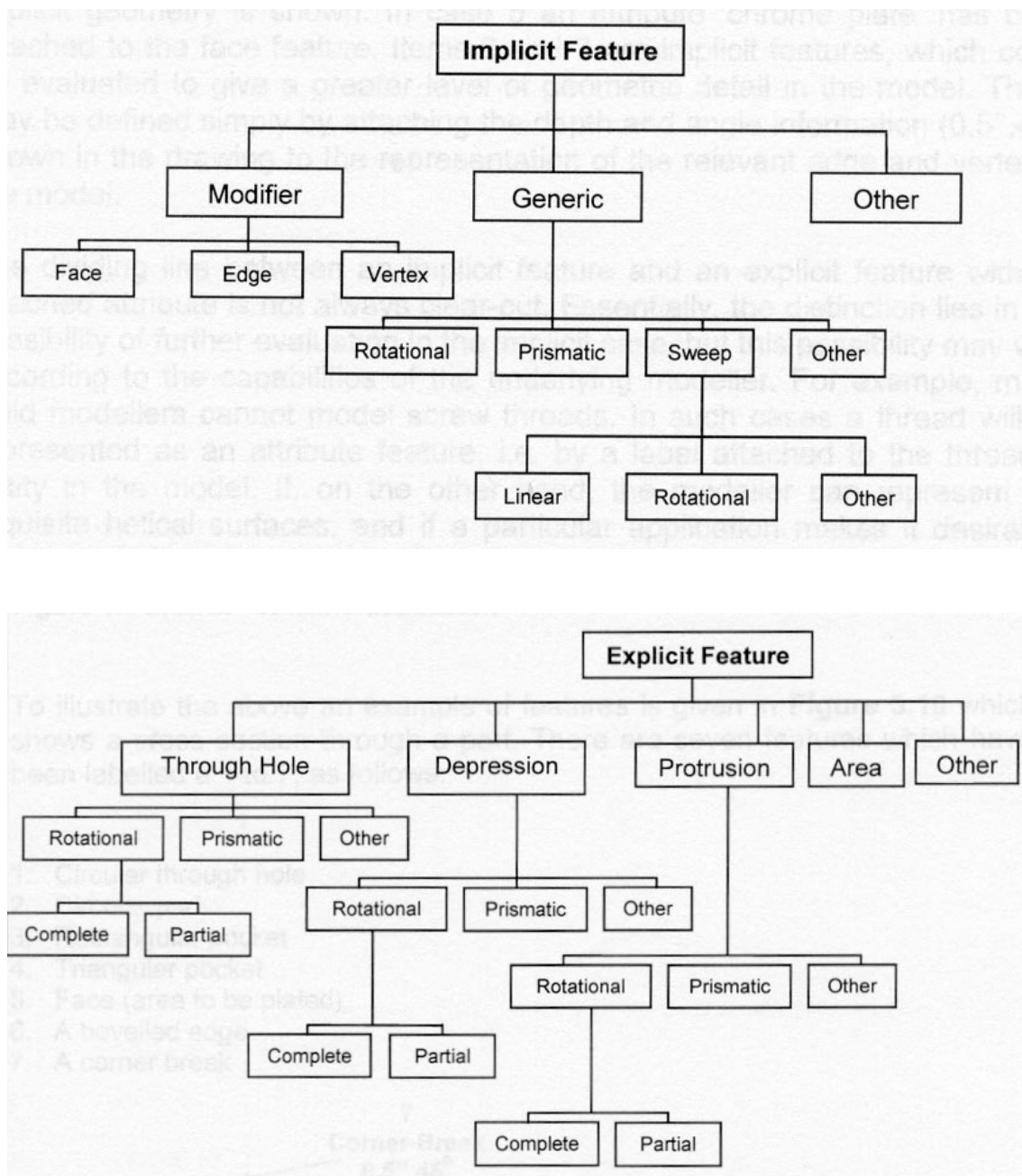


Figure 2.25 Wilson and Pratt feature scheme (Kyriacou, 1998)

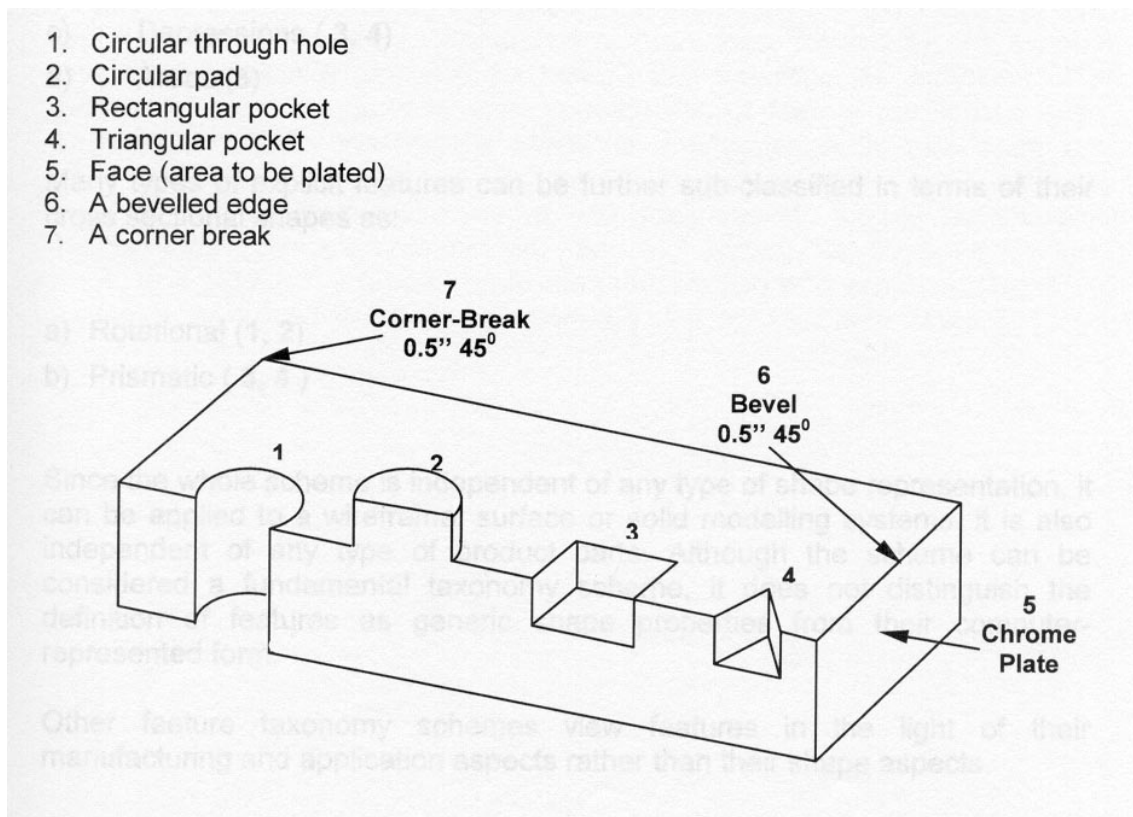


Figure 2.26 Cross section through a part showing example features (Kyriacou, 1998)

General Feature Specification	
Specification	AP 214 <i>general_feature</i> (FF1)
Assessment Purpose	Specifies a general kind of form feature with explicit representations of the feature shape and without specification of feature parameters
Application Object	General Feature
Characteristics	Atomic meaning of the feature Explicit representation

User-Defined Feature Specification	
Specification	AP 214 <i>User_defined_feature</i> (FF2)
Assessment Purpose	Specifies a general kind form feature with specification of feature parameters
Application Object	Feature_parameter_value General_feature_parameter General_feature_with_parameters
Characteristics	Generality of the feature shape Feature parametrisation

Specification of a Feature with Explicit Shape	
Specification	AP 214 <i>form_feature_with_explicit_shape</i> (FF3)
Assessment Purpose	Specifies various kinds of explicitly defined form features Defines two kinds of form features :form features which are identified on an existing shape and those which are used to build the shape of he part, i.e., design features Both kinds of form features include form features for sheet type parts or tools. All form features have an explicit feature shape representation
Application Object	- Angle_taper - Bead_feature - Boss_feature - Catalogue_thread - Chamfer - Circular_boss - Circular_closed_profile - Circular_offset_pattern - Circular_omit_pattern - Circular_path - Circular_pattern - Closed_profile - Complete_circular_path - Compound_feature_in_panel - Compound_feature_in_panel_element - Compound_feature_in_panel_element_relationship - Compound_feature_in_solid - Compound_feature_in_solid_element - Compound_feature_in_solid_element_relationship - Defined_thread - Diameter_taper

Specification of Form Features with Generative Shape	
Specification	AP 214 <i>Form_feature_with_generative_shape</i> (FF4)
Assessment Purpose	Specifies the same kind of form feature as FF3 without explicit shape representation
Application Object	Featured_shape Form_feature_ Form_feature_without_representation

Figure 2.27 STEP feature scheme (Kyriacou, 1998)

Many other examples of Feature Systematisation and Classification Schemes exist but from the two preceding examples it can be seen that the number of features and indeed, schemes, can be limitless. However, the work of the PhD was interested in the application of these features to enable Jigless Assembly rather than the features themselves. Consequently, the work was application-oriented, focusing on features to solve specific problems as opposed to contributing to the development of Feature Based Design. Nevertheless, there is still the need to describe the evolution of Feature Based Design as the subject is central to the thesis.

2.6.2 Feature Based Design

There has been an increasing amount of work carried out in the area of Feature Based Design, following the improvements in computer systems and CAD software. This began with the earliest Wireframe Modelling software in the 1970s, as illustrated in Figure 2.28, below, which had several deficiencies such as ambiguity, nonsense object representation, and the impossibility for interpretation of physically realisable solids (Kyriakou, 1998).

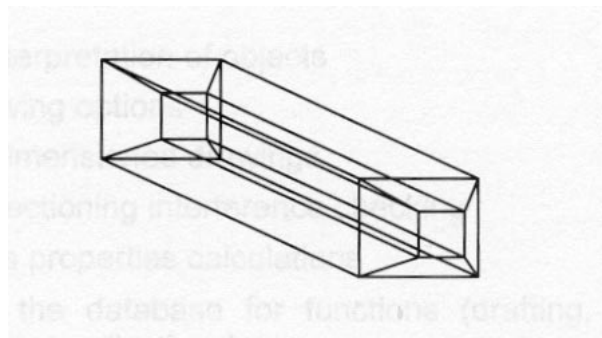


Figure 2.28 Wireframe modelling (Kyriacou, 1998)

Next came Surface Modelling software, which represented objects by a collection of surface elements such as flat surfaces (polygons), analytical surfaces (e.g. parts of spheres or cylinders) or more general free-form surfaces. This progressed to today's

Solid Modelling software. There are different forms of Solid Modelling but the two most common are Boundary Representation (B-Rep) models and Constructive Solid Geometry (CSG) models. B-rep models represent a solid in terms of its spatial boundary, usually the enclosing surface with a convention to indicate on which side of the surface the solid lies (Mortenson, 1985). The enclosing surface can be considered as being bounded by edges, which are in turn bounded by vertices, as shown in Figure 2.29, below.

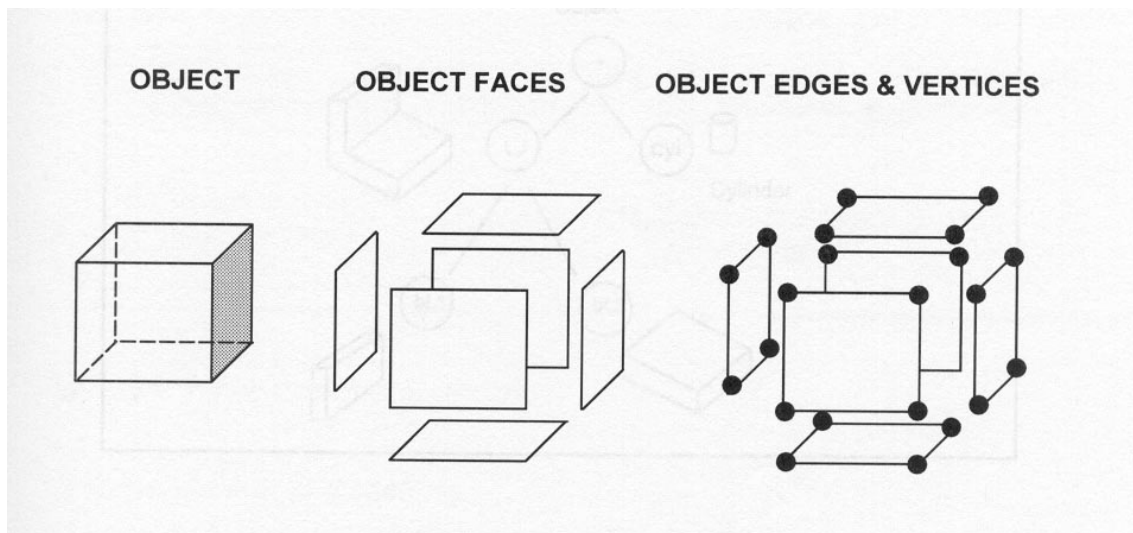


Figure 2.29 Boundary models (Kyriacou, 1998)

CSG representations are based on compositions of primitive solids, such as cubes, cylinders, and spheres determined as sets of 3D points. Boolean operators like union ($\cup$), difference ($-$) and intersection ($\cap$) are used to execute the composition, as shown in Figure 2.30, below.

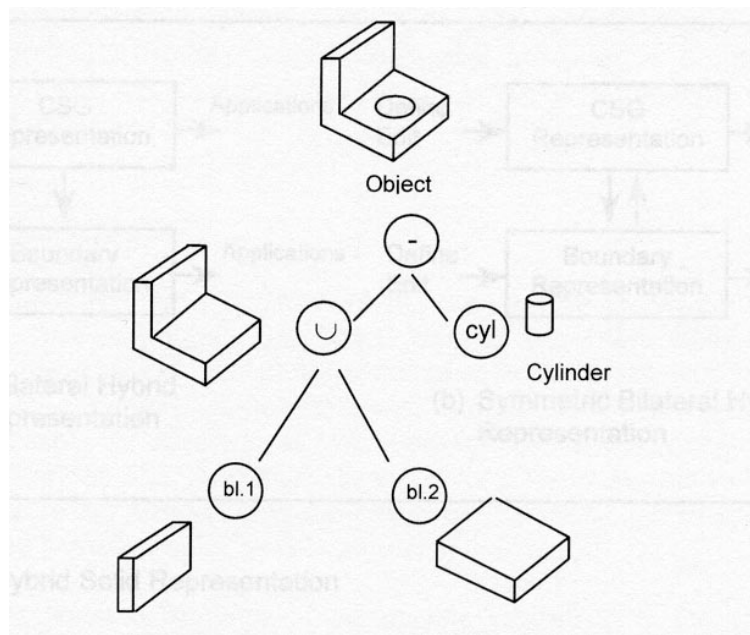


Figure 2.30 CSG tree concept (Kyriacou, 1998)

CAD Modelling systems are predicted to evolve further through advancements such as Non-Manifold Modelling, Parametric Modelling and Constraint-Based Modelling and ultimately Feature-Based Modelling.

Several prototype Feature Based Design systems have been developed by a number of researchers including Case et al (Case et al, 1994), Dong et al (Dong et al, 1995), and Sanchez et al (Sanchez et al, 1992).

2.6.3 Feature Based Design for Assembly

Feature Based Design for Assembly is an extension of Feature Based Design, which seeks to use features in designing parts and assemblies to be more easily assemblable. A comprehensive review of the issues in Feature Based Design for Assembly can be found in O'Grady et al (O'Grady et al, 1996).

Two pertinent examples of Feature Based Design for Assembly and the systems that have been developed to implement the concepts involved are presented here.

The first of these examples, by De Fazio et al (De Fazio et al, 1990), has been referenced previously and follows the Assembly Modelling methodology of the researchers at MIT, as described earlier. Figure 2.31, below, shows in schematic form the topics in a typical design of a product with discrete parts, after the functional requirements have been established and highlights the potential for feature based design for assembly. Figure 2.32, below, shows in schematic form the design process as supported by the prototype software.

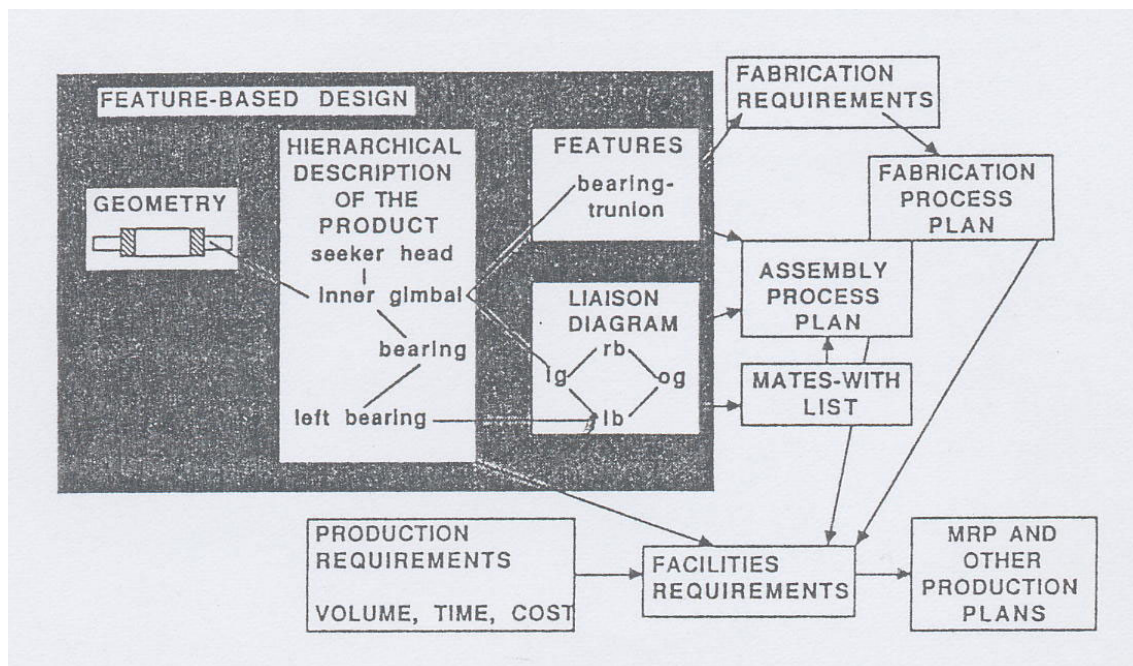


Figure 2.31 Relation of feature based design to the process of designing a discrete parts product (De Fazio et al, 1990)

Upon starting the software, the user constructs a feature-level solid model of the product, and then assembles the parts by indicating feature mates. Features and assembly information are captured in a database in hierarchical form with all the parts and their features, plus mating data in the form of a liaison diagram.

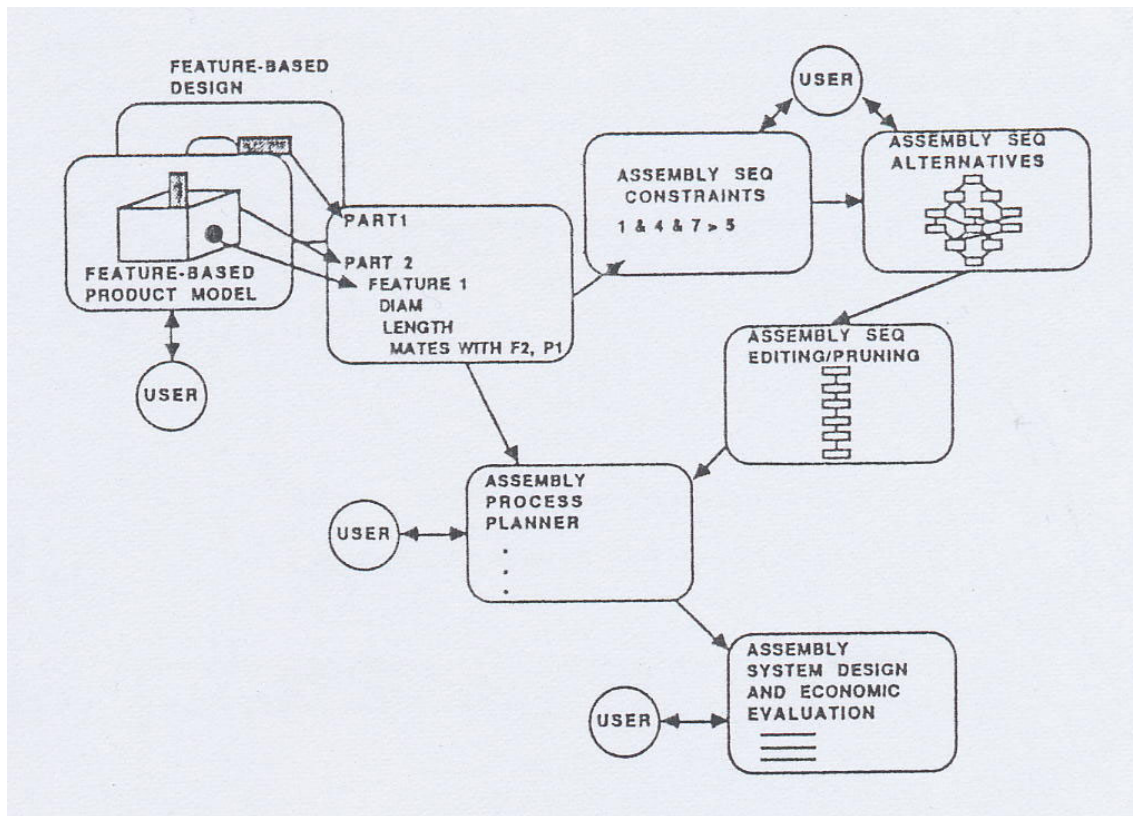


Figure 2.32 Sketch of the design process supported by the software
(De Fazio et al, 1990)

Next, the user invokes the assembly sequence generator, which uses a question-answer dialogue with the designer plus the geometric features to determine the legal assembly operations and generate all the feasible assembly sequences. The designer may then edit the sequences by optionally eliminating assembly states, assembly actions, assembly plans with parallel operations or with converging assembly lines, plus other explicit restrictions, until a satisfactory set of sequences is obtained.

The designer transfers these sequences to an assembly process planner, which uses feature information and user input to plan assembly. The assembly plan contains information on part or sub-assembly orientation, size, weight and task type. This information is passed to an assembly system design module (Gustavson, 1988), which musters assembly resources and creates a least cost assembly system for each candidate assembly sequence that will meet the required production rate and investment targets. The designer may return to any place in this process and make revisions to the original

design, select a different assembly sequence, change cost or production requirements and repeat the process.

The second example is from Bordegoni and Cugini (Bordegoni and Cugini, 1996), who developed a demonstrator for a Knowledge Aided Design system as part of the BRITE/EURAM II project FEAST (FEature based ASsembly Techniques). The project addressed assembly problems and issues related to the interconnection of structures, piping, cabling and wiring. The FEAST demonstrator was an interactive system simulating the environment where assembly features can be used for assembling components (Bordegoni, 1995). An example of a FEAST Demonstrator slide is shown in Figure 2.33, below.

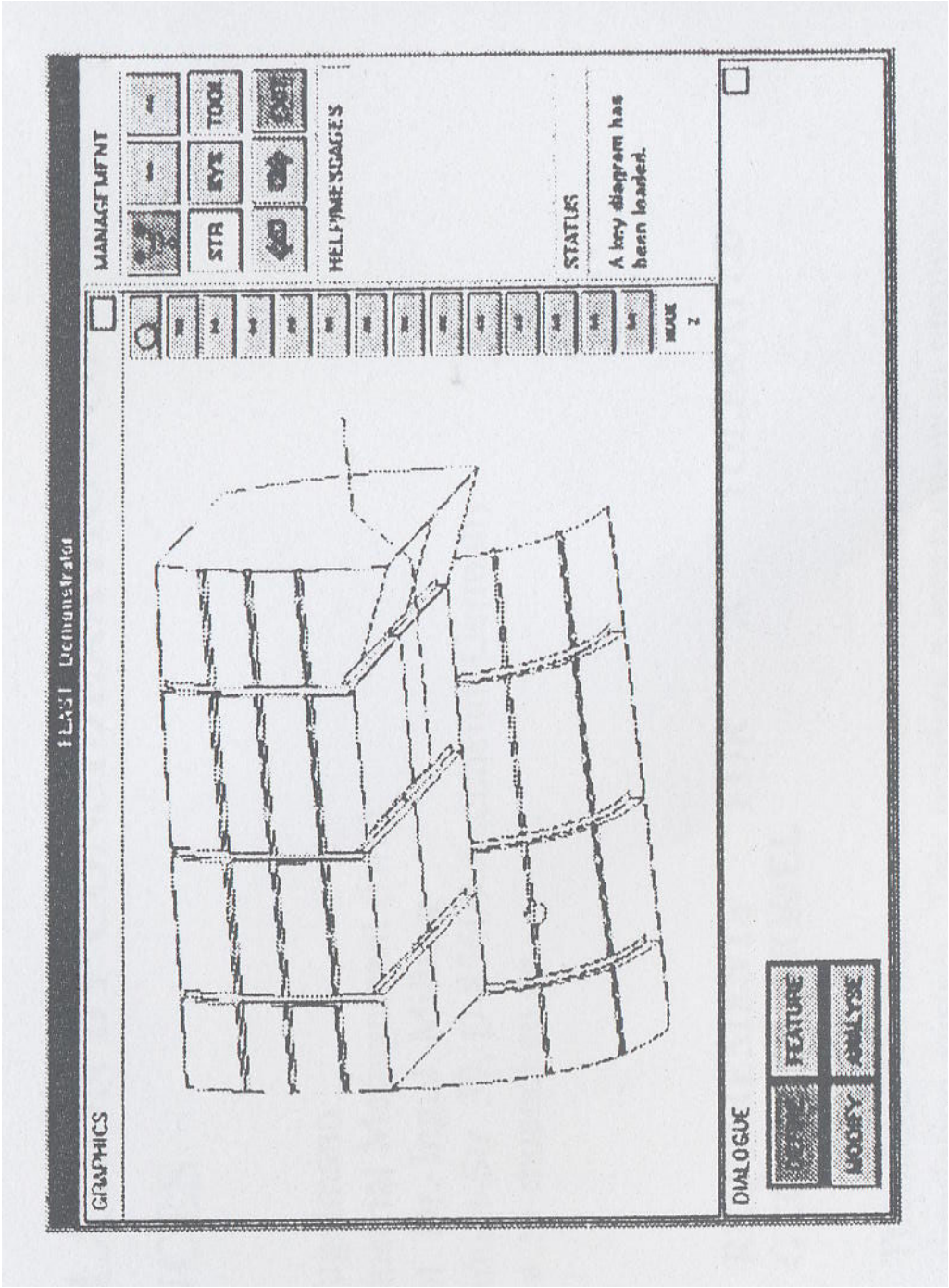


Figure 2.33 Example of a FEAST Demonstrator slide (Bordegoni, 1995)

2.6.4 Feature Based Costing

Features have begun to play an increasingly important role in the costing of the design, manufacture and assembly of a product. In the same way that it is imperative for a product's manufacturing and assembly requirements to be considered as early as possible in its development, the same is also true for the costs to produce the product.

Costing methods in industry include (Roy, 2000):-

- **Traditional Costing**
 - ❑ 'First Sight' and detailed estimates
 - ❑ Experience based
 - ❑ Use of synthetic cost data
 - ❑ Iterative process with the relevant department
- **Activity Based Costing**
 - ❑ Cost of a series of activities
 - ❑ Average cost per activity
 - ❑ Total cost: summation of individual activity costs
 - ❑ $\text{Cost of activity} = \text{average cost} \times \text{number of cycles}$
- **Parametric Costing**
 - ❑ Assign cost to physical or performance measures
 - ❑ Used in early stages of design
 - ❑ Rely on statistical analysis
 - ❑ Cost Estimating Relationship (CER's)
- **Feature Based Costing**
 - ❑ Cost of a feature
 - ❑ More used in manufacturing
 - ❑ Challenge: standardisation of features
 - ❑ Data collection needs automation

A research study carried out by Roy highlighted that the Traditional Costing methods are becoming outdated and that Feature Based Costing is becoming more prevalent. In addition, a survey of current practices in a cross-section of companies

found that most still use Synthetic Time Based tools for manufacturing (Traditional Costing) and that CER's are employed for manufacture but not for design.

The research of Roy recommends a Feature Based Approach using the generation of CER's. The CER's contain 'Cost Drivers', *portions of a system, end item or service that have a large or major effect on the cost of the work activity or work output*, that are both quantitative and qualitative. Quantitative Cost Drivers are defined as the drivers whose primary data can be collected in the form of a number, e.g. mass, velocity, weight, etc. and Roy suggests that these make up approximately 40% of costs, which are called 'Direct Costs'. Qualitative Cost Drivers are defined as the drivers whose primary data is subjective and open to opinion needing conversion into a numeric form, e.g. manufacturability, complexity, quality, aesthetics, etc. and he suggests that these make up the remaining 60% of costs, which are referred to as 'Indirect Costs'.

An example CER may take the form:-

$$T = T_P + T_{SU}$$

where,

T = Total time for the total production quantity

T_P = Total production time

T_{SU} = Total set-up time

There are numerous examples of Feature Based Costing systems that have been developed both in the academic and commercial environments. The current state of the art in all of these Feature Based Costing systems is to use CER's in one form or another coupled with a Feature Based approach.

Examples of academically developed Feature Based Costing systems include Hill et al (Hill et al, 1994), Shehab and Abdalla (Shehab and Abdalla, 2001 and Shehab and Abdalla, 2002), Ou-Yang and Lin (Ou-Yang and Lin, 1997), Creese and Patrawala (Creese and Patrawala, 1998), Hu and Poli (Hu and Poli, 1999) and Jung (Jung, 2002).

An example of a commercially developed Feature Based Costing System is provided by Taylor (Taylor, 1997) at the British Aerospace, Military Aircraft and

Aerostructures, company (now renamed BAE SYSTEMS, Military Aircraft and Aerostructures).

The advent of significantly different structural forms accompanied by radically different materials, such as blended body airframes manufactured using advanced composites and Super-Plastic Forming (SPF) / Diffusion Bonding (DB) titanium meant that the traditional, historically driven parametric models the company uses became unstable without intuitive, experience based factors being applied. Features, in these instances, became a vital element in the cost prediction process particularly during the early phases of design. This was invariably due to the lack of geometrical definition – the usual data type conventional cost prediction techniques employ.

In the absence of a recognised standard, the Cost Engineering group at British Aerospace, Military Aircraft and Aerostructures, defined a series of feature categories to fulfil their requirements. An extract from the database is shown in Figure 2.34, below.

<u>Feature type</u>	<u>Examples</u>
1. Geometric	Length, Width, Depth, Perimeter, Volume, Area, etc.
2. Attribute	Tolerance, Finish, Density, Mass, Material composition, etc.
3. Physical	Hole, Pocket, Skin, Core, PC Board, Cable, Spar, Wing, etc.
4. Process	Drill, Lay, Weld, Machine, Form, Chemi-mill, SPF, etc.
5. Assembly	Interconnect, Insert, Align, Engage, Attach, etc.
6. Activity	Design Eng'g, Structural Analysis, Quality Assurance, Planning, etc.

Figure 2.34 Extract from the feature category database (Taylor, 1997)

The Cost Engineering group were evaluating another commercial software package, Cost AdvantageTM (Cognition Corporation, 1995), as a means to fulfil their requirement for a ‘fourth generation’ Design to Cost toolset.

Cost AdvantageTM is a Design for Manufacture expert system that provides immediate cost data, design guidance and producibility analysis. It captures design and manufacturing knowledge in the form of cost and producibility algorithms that evaluate a design based on features, materials and manufacturing processes.

A diagrammatic view of the interaction between different feature types, which were being built into the Cost AdvantageTM application, is shown below, in Figure 2.35.

Cost is viewed differently by each area of the enterprise and as a consequence each area has developed cost modelling / prediction tools that satisfy its own requirements. This invariably leads to a lack of consistency of data and models. This inconsistency in toolset usage was driving the development of a common toolset at British Aerospace, which uses CER’s whether they be algorithmically or parametrically based, derived from a ‘bottom up’ standard of data generated from Industrial Engineering standards. This approach is depicted in Figure 2.36, below.

The CER’s being used are algorithm based and simulate the following manufacturing processes:-

- **Machining** - Small parts, large parts, high speed, turning
- **Sheet Metal** - Flat & form, stretch, SPF, drawn / extruded
- **Assembly** - Minor, major, final, welded, bonded, SPF / DB
- **Composites** - Hand lay, machine lay, honeycomb manufacture
- **Pipes** - Small bore, large bore, lagging
- **Semi-finished** - Castings, forgings

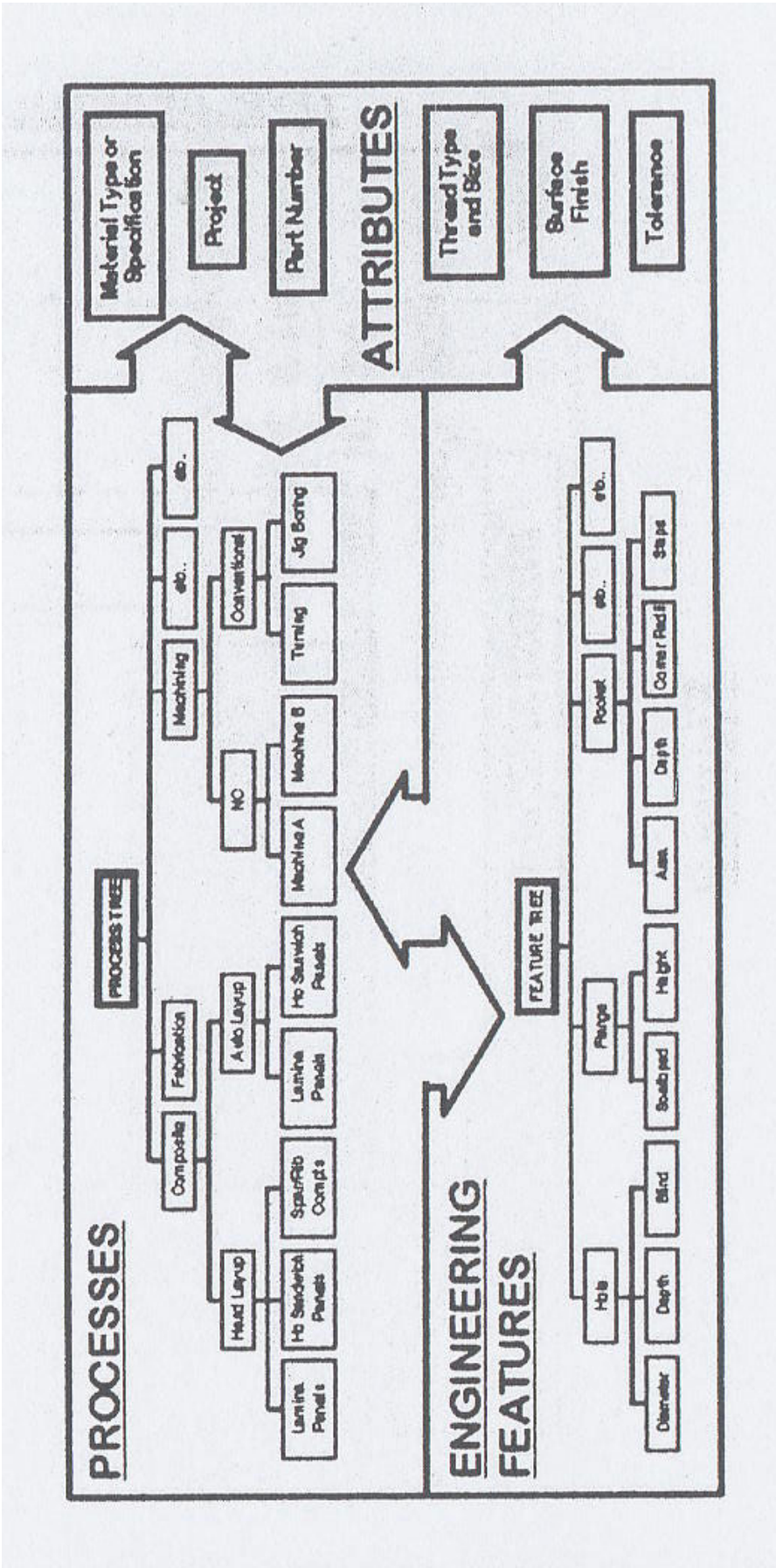


Figure 2.35 Diagrammatic view of the interaction between different feature types (Taylor, 1997)

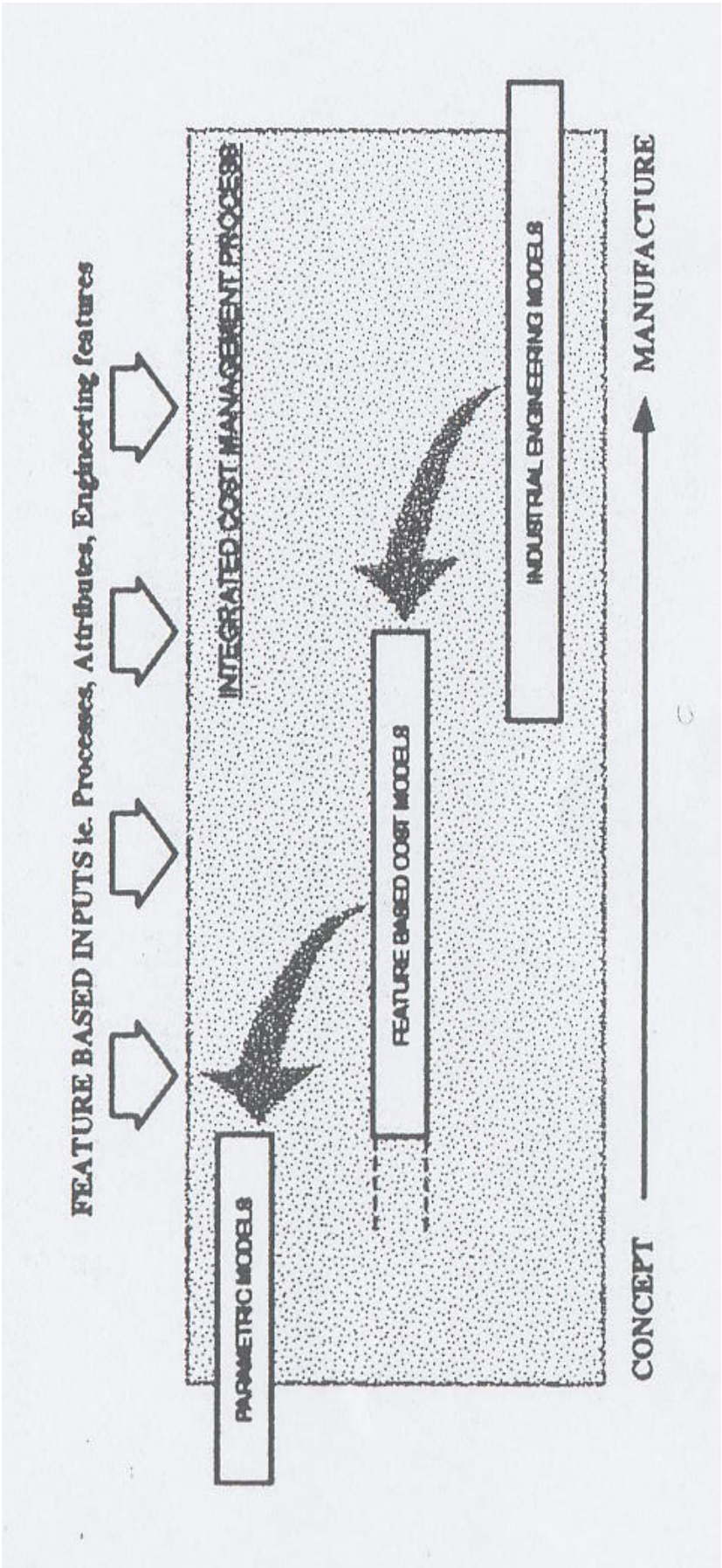


Figure 2.36 Development of a common toolset, which uses CER's (Taylor, 1997)

The algorithms are based on Industrial Engineering standards and are related to engineering features and manufacturing processes. They react to data generated in the CAD sessions, i.e. geometry, holes, flanges, etc., and attribute data called into the sessions from the surrounding databases – such as material type and specification, fastener type and specification, etc.

Commercial data embedded within the Integrated Business Logistic System, such as labour rates, material cost, fastener cost, etc., is applied to the product data and a resultant '£ Sterling' cost is produced. A typical algorithm structure is shown in Figure 2.37, below.

Design rules and producibility rules, which are embedded in Cost AdvantageTM are called upon automatically during the Cost Prediction session and, if the product has violated these rules, will advise the engineer 'what' and 'where' the violation is together with an explanation of 'why' it exists.

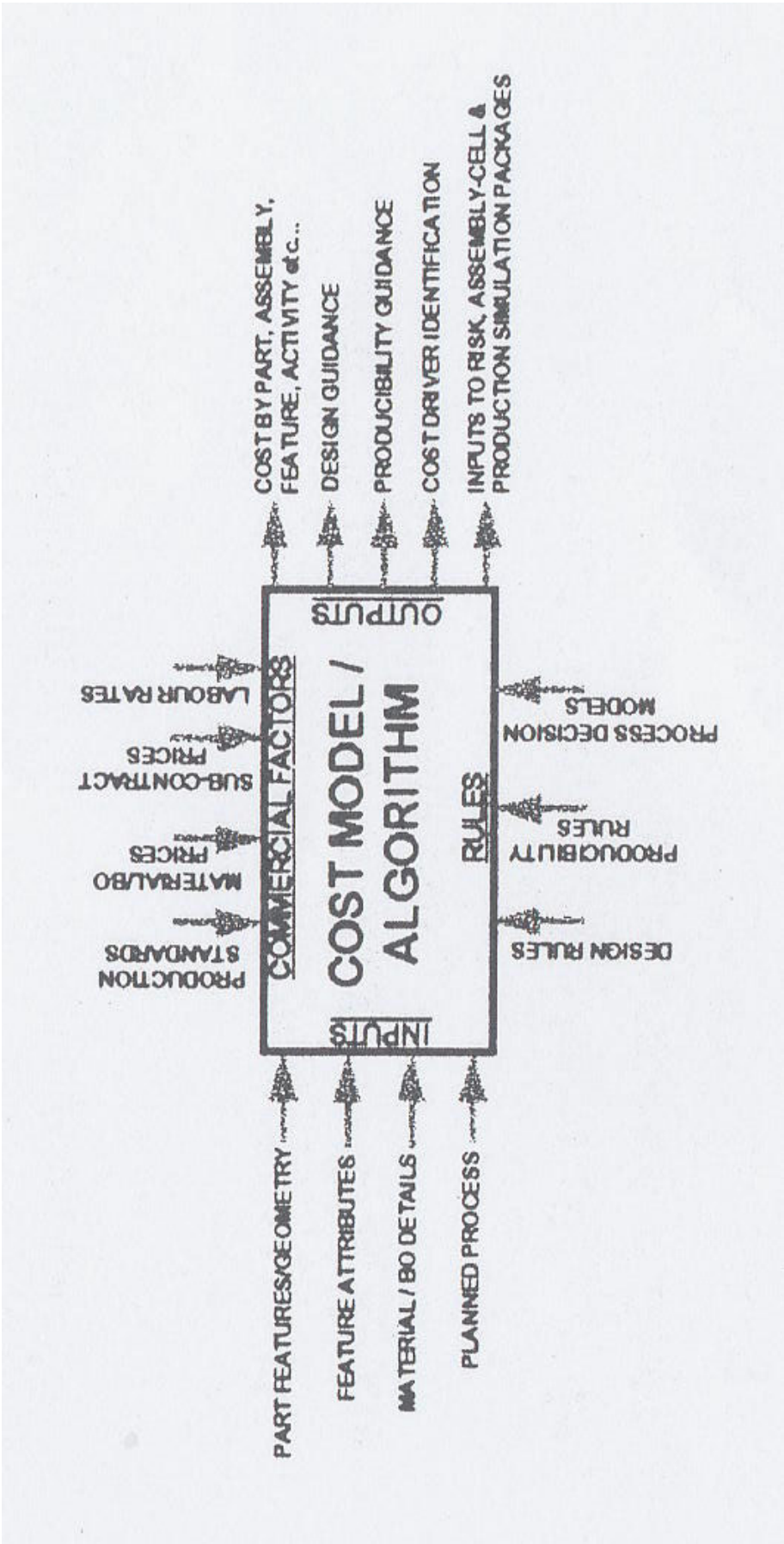


Figure 2.37 Typical algorithm structure of the Integrated Business Logistic System (Taylor, 1997)

2.7 Tolerance Representation and Analysis

The final subject of major importance in designing for jigless assembly is tolerance representation and analysis. This is due to the fact that if features are to play a central role towards the enabling of designing for jigless assembly, then the tolerances of those assembly features that are affecting the assembly become critical.

Several researchers have developed methodologies and systems to represent and analyse tolerances, particularly in a Feature Based environment. In common with the review of the issues in Feature Based Design for Assembly carried out by O'Grady, Trabelsi and Delchambre (Trabelsi and Delchambre, 2000) have carried out a similar assessment on the current research undertaken on tolerance representation and analysis in assemblies.

Two examples of methodologies to represent and analyse tolerances in assemblies can be found in (i) *Sodhi and Turner (Sodhi and Turner, 1991) and Guilford and Turner (Guilford and Turner, 1993)* and, (ii) *Whitney et al (Whitney et al, 1994) and Adams and Whitney (Adams and Whitney, 1999)*. Sodhi and Turner and Guilford and Turner describe the GEOS system, which carries out tolerance analysis using the Feasibility Space Approach and tolerance synthesis using Taguchi's Quality-Loss Model. Whitney et al and Adams and Whitney propose the application of Screw Theory to constraint analysis and matrix transforms for statistical tolerance analysis, of assemblies.

Like the Feature Based Costing systems, various Feature Based Tolerancing systems have also been developed within academic and commercial environments.

Academic examples include those developed by Salomons et al (Salomons et al, 1995 and Salomons et al, 1996), Qu (Qu, 1995) and Shah et al (Shah et al, 1998).

A commercial example has been developed at the EADS Corporate Research Centre (EADS Corporate Research Centre, 2001), called 'AnaTole'. The goal of AnaTole is to take into account geometrical variations as soon as possible in the design process. Designers and manufacturers are able to predict the impact of geometrical variations on Key Characteristics, without the need for exact geometry. Selection of assembly sequences is then performed before the design completion. AnaTole has been successfully used on different applications with Airbus.

The *first step* in using AnaTol is the creation of assembly links between parts based on assembly principles. All types of assembly links are available; each assembly link fixes one or more degrees of freedom. An example screenshot of step 1 is shown in Figure 2.38, below.

The *second step* is the detection of the over-constraints, which are relaxed according to the assembly sequence. The *third step* is to obtain manufacturing and assembly capabilities and dispatch them according to the result of the sensitivities analysis. An example screenshot of steps 2 and 3 are shown in Figure 2.39, below.

The *fourth step* is performing a worst-case and statistical analysis for any Key Characteristics. Two example screenshots of step 4 are shown in Figures 2.40 and 2.41, below.

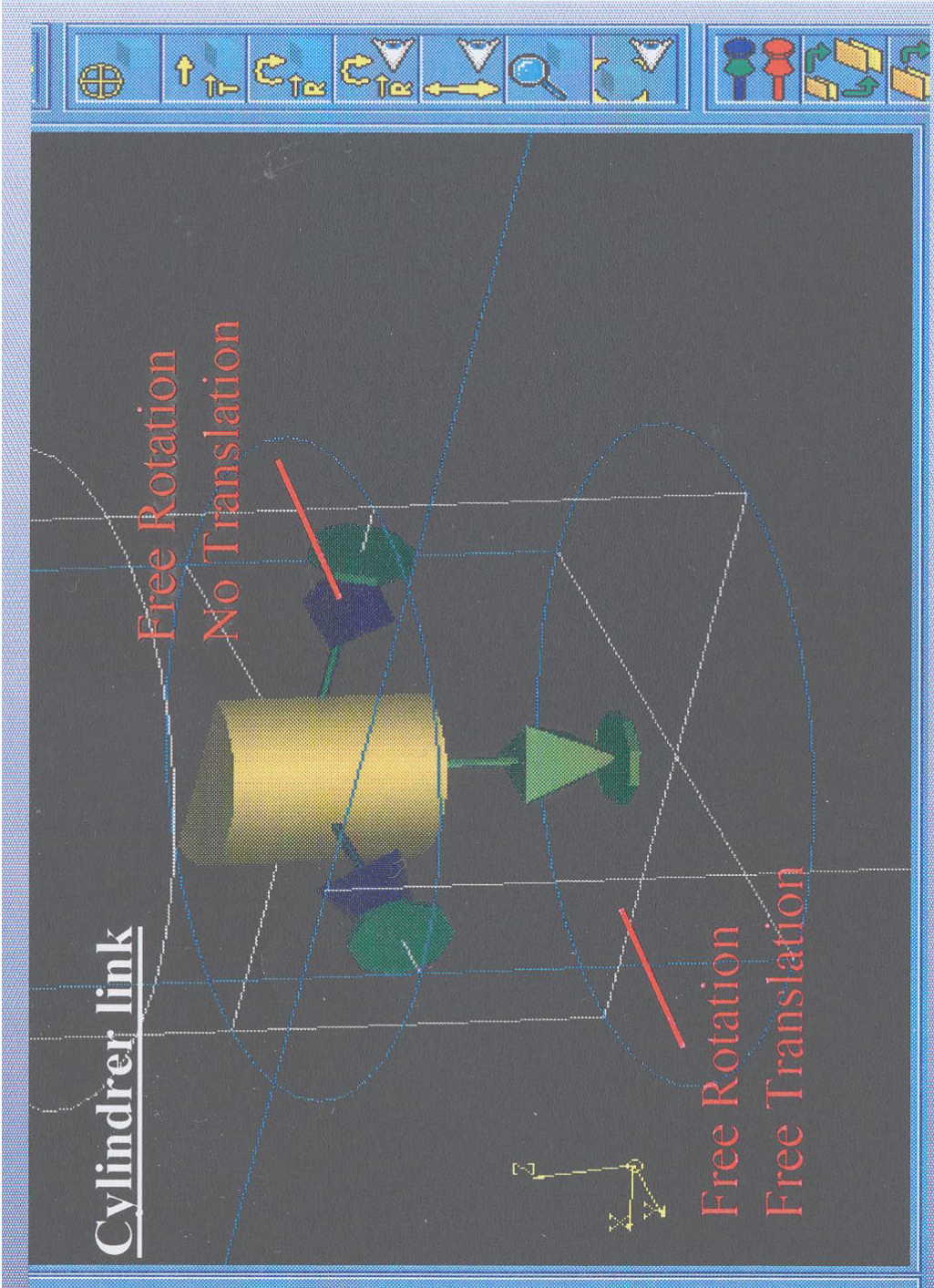


Figure 2.38 Example screenshot of the first step in AnaTol (EADS Corporate Research Centre, 2001)

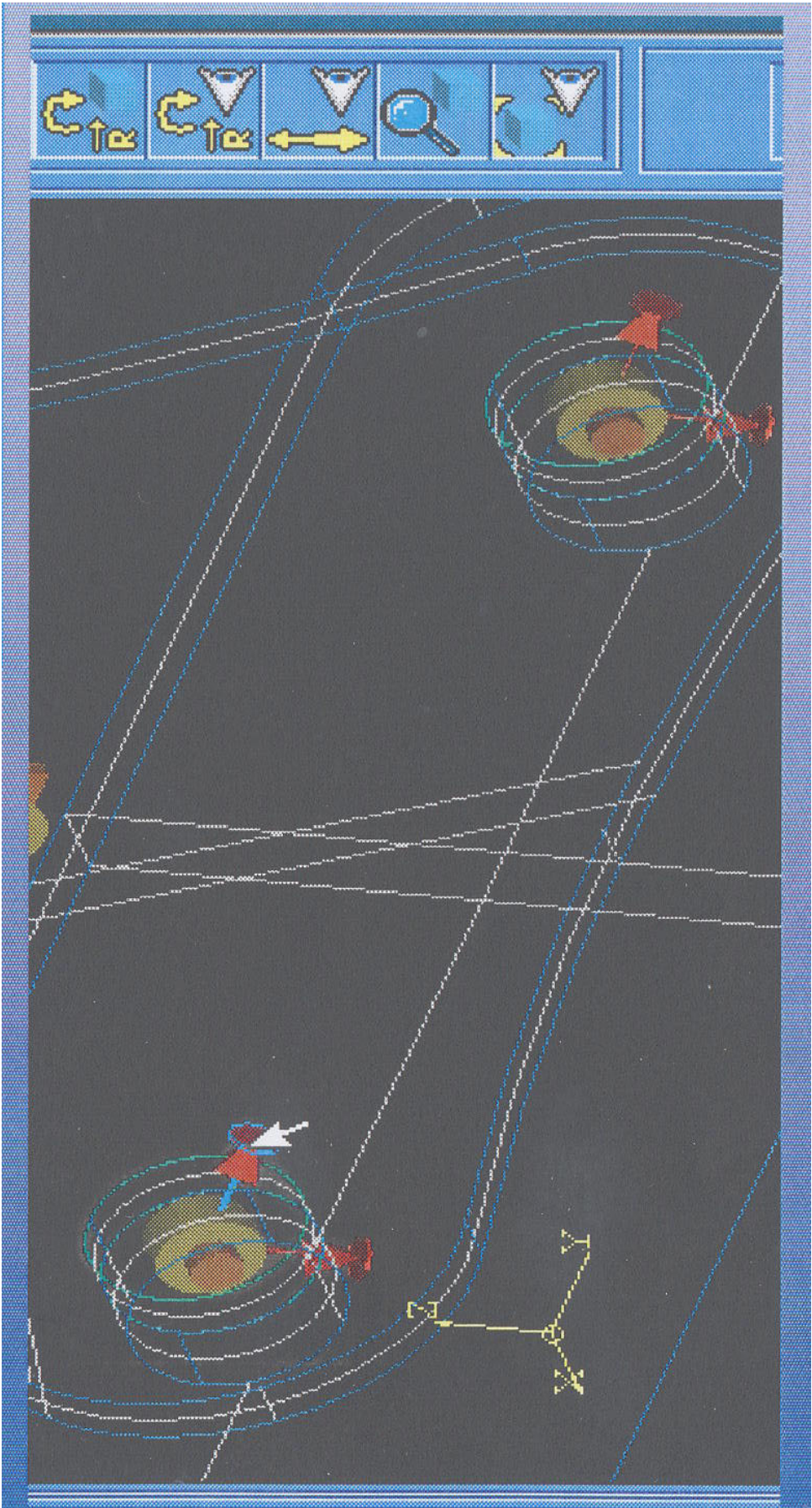


Figure 2.39 Example screenshot of the second and third steps in AnaTole (EADS Corporate Research Centre, 2001)

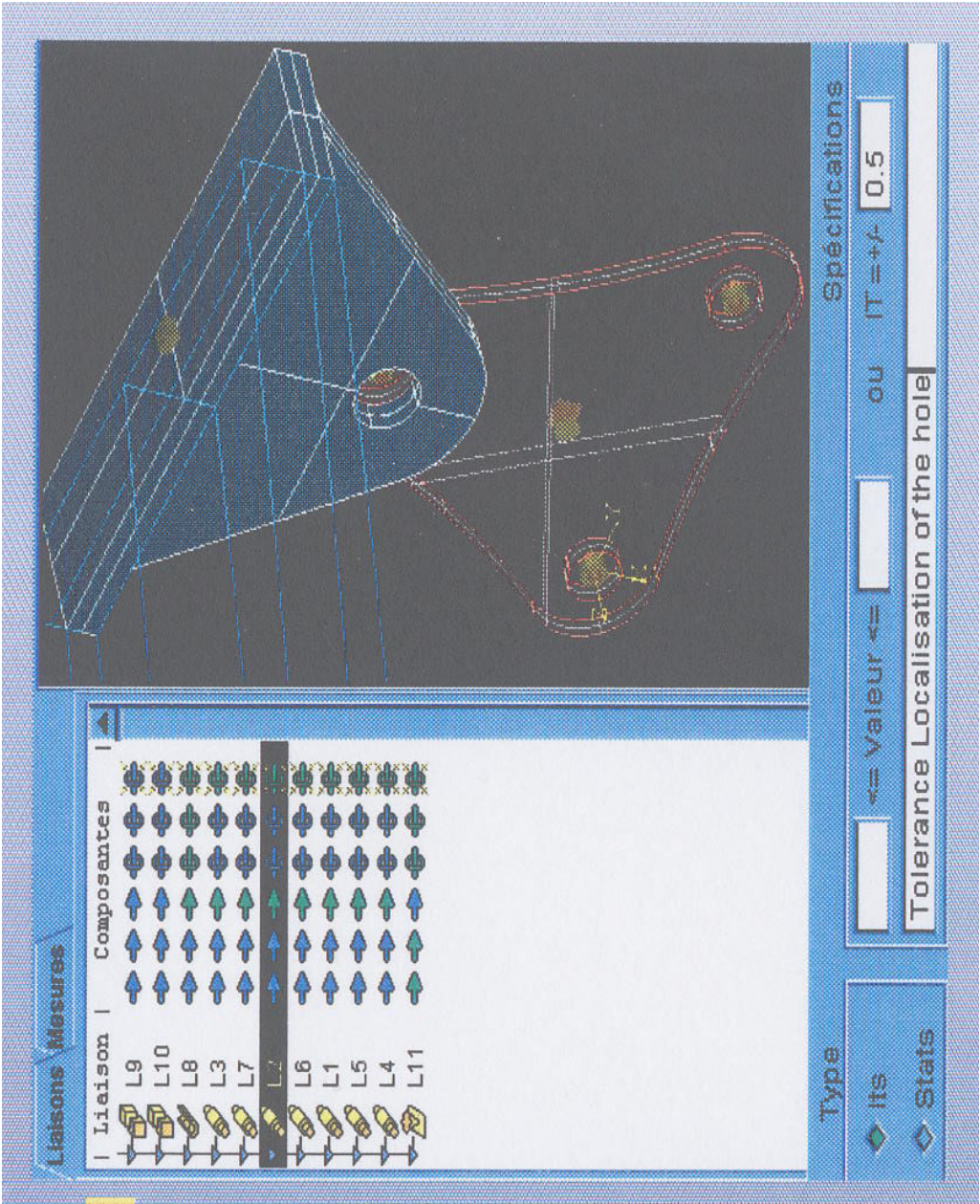


Figure 2.40 First example screenshot of the fourth step in AnaTol (EADS Corporate Research Centre, 2001)

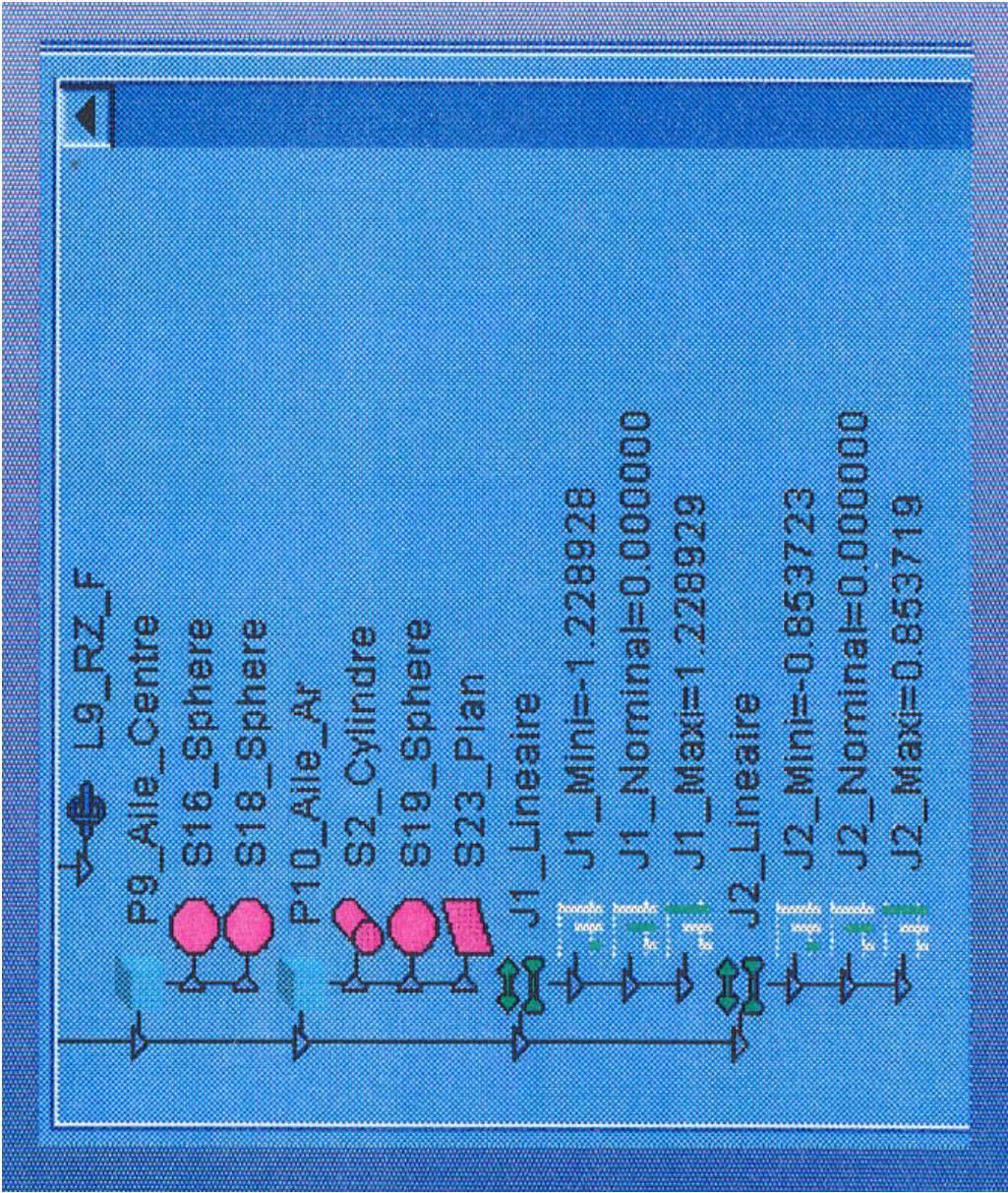


Figure 2.41 Second example screenshot of the fourth step in AnaTol (EADS Corporate Research Centre, 2001)