

1 Introduction

1.1 Background to the Research Area

Aircraft manufacture has evolved from small, craft operations since the days of the Wright brothers to the complex, multinational projects of today. Earlier aircraft were built by much smaller teams with design and manufacturing usually located close, if not next, to one another. As aircraft have developed the customer-led demands on performance and cost-effectiveness have increased.

However, tooling systems have not changed radically from the early days of aircraft manufacture. Previously, the use of jigs has been the only way to ensure the attainment of assembly tolerances and build quality. The build process typically involves the parts being clamped in fixtures to enable assembly by riveting; the rivet holes are correctly positioned using drill jigs located on the fixture. After drilling the parts are removed, deburred, reassembled on the same fixture and temporarily pinned before riveting. Smaller sub-assemblies are combined on a main fixture, again positioned using assembly jigs, to assemble the major components: fuselage, empennage and wings. An example of this process is shown in Figure 1.1, below, where wing stringers have been assembled on to the wing skin using the drill jig, which can be seen on the left.



Figure 1.1 Wing stringers assembled on to the wing skin using the drill jig (Round, 1992)

In the case of early aircraft this process produced unique aircraft with no interchangeability of major components. In the past manufacturing and interchangeability specifications were not such serious issues for tooling. However, the increased customer requirements have demanded higher performance that has been supplemented by tighter engineering tolerances for critical dimensions. This has resulted in higher costs of tooling which, other than a tempering of specifications, can be reduced only by improved production engineering and tooling.

Together with the principal drawbacks of high up-front cost and long lead-time, there are further disadvantages with the general use of jigs. These include:

- The difficulty in recovering tooling costs for short production runs
- The increase in tooling needs for increased rates of production
- The requirement for regular maintenance and calibration of the tooling possibly through the use of ‘master’ tooling
- The need to store tooling and ‘master’ gauging when not in use

- The quality resident in the tooling is not necessarily duplicated in the finished part

Tooling has traditionally been overlooked or at least segregated from the main engineering functions but the increasing cost and inflexibility of tooling systems for aircraft manufacture means that aircraft manufacturers are now actively seeking solutions to reduce the up-front cost and increase the flexibility of these systems.

An approach towards the reduction of tooling is ‘jigless assembly’, which seeks to eliminate or minimise product-specific jigs, fixtures and tooling by the application and integration of relevant technologies and methodologies. Recent years have seen technological advances also lead a drive towards the use of jigless assembly techniques. The potential gains of a new philosophy minimising product-specific jigs, fixtures and tooling are significant and would result in large cost savings and enhanced flexibility to the assembly system.

1.2 Establishing the Research Area

For jigless assembly to be enabled and to have the greatest benefit, jigless assembly needs to be designed into the product at the earliest possible stage in the product’s development.

To do this, the development of a methodology is required to purposely *design for jigless assembly*. The methodology must be able to take into account all the design and manufacturing considerations allowing for the limited amount and quality of information available and work as part of an integrated design for manufacture and assembly strategy, rather than yet another ‘Design for X’ method with conflicting requirements. The methodology should also be simple to use and easily implementable within a commercial environment, with the ability to analyse and compare different technologies and processes using a logical and repeatable set of criteria.

No such methodology to specifically design for jigless assembly exists, with its importance growing as aircraft manufacturers continually endeavour to reduce assembly time and cost.

There are numerous methodologies developed to promote design for manufacture and assembly and these can and have been built upon in developing a methodology to design for jigless assembly, nevertheless, they possess some drawbacks that make them unsuited to achieve jigless assemblies effectively. These include:

- Not addressing jigless assembly explicitly
- Addressing another specific field in isolation
- Being too complex to use or still in development
- Being used too late in the product's development

The research described in this thesis attempts to answer this need by firstly reviewing the relevant work of other researchers and practitioners, building upon it and then developing a methodology that fulfils all of the above requirements.

The initial starting point has been to review the latest research on Formal Design Methods and Assembly Process Modelling. This has led to the development of a methodology that combines the functionalities of both research areas, with the addition of the specific requirement to deliver designs for jigless assembly.

The work of others has pointed to the increasing prevalence of Feature Based Methods, simply because features can contain much more information than geometry alone, which is very useful in the early stages of product development when the geometry has not yet been defined.

However, it was found that the current use of Feature Based Methods is too restrictive for the needs and application of designing for jigless assembly. Consequently, the definition and use of features, and in particular 'assembly features', i.e. features within an assembly environment, has been broadened and expanded. This includes the development of an 'Assembly Feature Library' developed to specifically facilitate jigless assembly, as well as conventional assembly using jigs.

Through the adoption and implementation of a methodology to design for jigless assembly, as has been developed in this research study, products could be designed to

be assembled with the minimum use of jigs, whilst still taking all of the applicable design, manufacturing and other considerations into account.

1.3 Research Aim

The literature review presented in chapter 2 describes, in detail, the work of others' previously completed in relation to the research area established in section 1.2.

Definitions of jigs, fixtures, tooling and jigless assembly, which are used as the standard throughout the thesis, are drawn from the literature and stated in section 2.2. The rationale for jigless assembly is highlighted by several authors and is given in section 2.3.

Several examples of jigless assembly, either currently existing in commercial settings or under development in academic environments, have been illustrated in section 2.4. The examples show the diversity of the methods available with which to achieve jigless assembly.

However, for jigless assembly to be realised, it must be 'designed-into' a product and its assembly, preferably as early as possible in the product's development when there is the most scope for change and influence.

The literature points to two interrelated ways of achieving this outcome. The first is to use design methods and methodologies to design for jigless assembly, as described in section 2.5.1, and the second is to use assembly processes' methods and methodologies to model the jigless assembly, as described in section 2.5.2.

Numerous design methods have been developed and they can be classified into three, broad categories: design methods for the generation of ideas for concept design, design methods for concept design evaluation and design methods for a specific design purpose. It was found that all three groups are applicable to design for jigless assembly.

The first group of design methods was found to be adequate in supporting the generation of ideas for designs that enabled jigless assembly. In particular, the 'Classical Brainstorming' design method was used to produce designs for jigless assembly.

For the second group of design methods, the previously existing examples were found to be too generic and not specific enough to sufficiently be able to compare one design for jigless assembly, produced by the ‘Classical Brainstorming’ design method, with another.

This was also the case for the third group of design methods, as none of the existing examples specifically produced a design for jigless assembly, although it was found that all of the specific design methods were relevant. The most applicable of the particular design methods for a specific purpose were the ‘Design for Assembly’ design methods. The greatest difficulty evident in the literature with the ‘Design for Assembly’ design methods were that they tended to carry out the design for assembly analysis after the product had been initially designed and then to re-design the product with ease of assembly in mind. It is pointed out in the literature review that this may be more of a problem in aircraft manufacturing where product life-cycle times are much longer compared, for example, to electronics manufacturing.

The second of the two ways to achieving jigless assembly are to use the assembly processes’ methods and methodologies to model the jigless assembly. Two pertinent examples were found in the literature that was applicable to jigless assembly. The first from Lewis (Lewis, 2000) provided a prototype for an integrated representation of the product design-build process, in particular, emphasising the manufacture and assembly requirements. The second example from Whitney (Whitney, 1995) and Cunningham (Cunningham et al, 1996) provided a theory to model assemblies, which introduced important topics such as constraint, layout, assembly sequence, assembly variation and tolerances.

Although the examples of assembly processes’ methods and methodologies aid towards the modelling of jigless assembly, they do not specifically model for jigless assembly.

In addition, the review of the literature has made it apparent that ‘Feature Based Methods’ should have a large part to play in the enabling of jigless assembly. This is so because ‘features’ are gaining more and more importance in design as they can store much more information than geometry alone.

There are numerous definitions for a ‘feature’ described in the literature and several examples of feature taxonomies have been illustrated in section 2.6.1. The

evolution of ‘Feature Based Design’ is described in section 2.6.2 and an extension of ‘Feature Based Design’ – ‘Feature Based Design for Assembly’ is described in section 2.6.3. Two examples of ‘Feature Based Design for Assembly’ prototype systems are portrayed.

‘Feature Based Design’ and ‘Feature Based Design for Assembly’ both use quite narrow and specific definitions for a feature and in particular, for the definition of an assembly feature. To enable jigless assembly, it may not be very efficient to define assembly features in such a limited manner.

Cost must also be taken into consideration for jigless assembly, as it is one of the prime drivers in the rationale for jigless assembly and in this case also, features are beginning to play an increasingly important role. Section 2.6.4 outlines ‘Feature Based Costing’ methods and illustrates a ‘Feature Based Costing System’ that has been developed and is in use at BAE SYSTEMS, Military Aircraft and Aerostructures, which uses the conventional definitions of features in general and assembly features, in particular.

The final subject that the literature review has indicated is of major importance to jigless assembly is Tolerance Representation and Analysis, due to the fact that if the Feature Based Methods described in section 2.6 are to play a significant role, the tolerances of those assembly features that are affecting the assembly become critical.

Examples of methodologies to represent and analyse tolerances in assemblies are outlined in section 2.7 and one example in particular, AnaTole, is described in more detail.

The findings of the literature review of chapter 2, summarised above, have shown that although several elements already exist towards supporting the goal of jigless assembly, there are gaps in the boundary of knowledge to be able to successfully and repeatedly achieve jigless assembly in a logical and coherent manner.

The main deficiency in the current knowledge concerns the integration and interrelationships of the different subjects highlighted above, to specifically and proactively produce designs for jigless assembly, as early in the product’s development as possible. Furthermore, the subject of ‘Feature Based Methods’ needs to be investigated to enable a process by which to design for jigless assembly with the most effectual use of assembly features.

As a result of these findings, the research was initiated with the aim of:

- The development and demonstration of a methodology to design for jigless assembly and a process of selecting assembly features to enable jigless assembly

1.4 Development of the Research Methodology and Objectives

To achieve the research aim, a research methodology was designed that derived from the work of others', as summarised in the literature review. A vital part of the development of the research methodology was the setting of objectives that, when completed, would seek to incrementally fill the gaps in the boundary of knowledge and realise the research aim.

The first stage of the research methodology was concerned with defining the scope and depth of the boundary of knowledge of the research area. This was brought about using two methods: the first was to survey the current academic literature relating to the research area and the second was to make on-going 'field visits' to industrial establishments where practical examples of jigless assembly could be found. These activities served to define the limitations of the existing knowledge in designing for jigless assembly and hence, specified the requirements that any methodology to design for jigless assembly would have to meet.

Once the requirements for a methodology to design for jigless assembly have been specified, the process of developing a prototype methodology to design for jigless assembly, which could be compared against the existing knowledge in designing for jigless assembly, was the next stage of the research methodology. The development of this process originated from the findings of the first stage of the research methodology in that several elements of work that could positively contribute to designing for jigless assembly had been previously developed by other researchers. Consequently, the first task in this stage of the research methodology was to build upon these elements by

integrating and directing them towards the specific aim of designing for jigless assembly. If this first task were successful then it would highlight the areas of understanding that required further development. Thus, the next task in the research methodology was to develop the remaining areas of understanding and integrate them into the previous work of the other researchers.

The development of these areas of understanding could then be identified and were apportioned to the different members of the JAM Project research team, illustrated in section 5.3.1. As described in the previous section as a result of the first stage of the research methodology, ‘Feature Based Methods’ were indicated to have a major role in designing for jigless assembly based on the previous work of other researchers. Hence, a large part of the author’s research activity was focused upon the understanding and development of the way in which features can be used to enable jigless assembly. This activity constituted the next stage in the research methodology and entailed several tasks. The first of these tasks was to comprehend how features are used and defined conventionally to affect assembly. From this point, the next task was to see if this process of using and defining features could be modified or enhanced to support designing for jigless assembly. As a result of these two preceding tasks the final task in this stage of the research methodology would be the development of a specific process to select assembly features to enable jigless assembly. This process would also have to be integrated into the overall methodology to design for jigless assembly that was to be completed in the previous stage of the research methodology.

As a result of these two preceding stages of the research methodology the research aim would have been partially completed such that a methodology to design for jigless assembly and a process of selecting assembly features to enable jigless assembly had been developed. However, any new methodology must be tested, verified and measured against the existing techniques. The next stage of the research methodology concerns the first two of these activities, namely testing and verification of the developed methodology to design for jigless assembly and assembly feature selection process to enable jigless assembly.

The most appropriate way of completing this would have been to carry out what is commonly described as a ‘double-blind’ experimental study; that is to say, an aircraft is to be designed and manufactured by two separate teams employing two, different

strategies: the first team would design and build the aircraft in the ‘conventional’ manner using the common design, manufacturing and assembly methods of today, i.e. with the aid of jigs, fixtures and tooling, whilst the second team would design and build the aircraft using the developed methodology to design for jigless assembly and assembly feature selection process to enable jigless assembly. The two produced aircraft could then be compared to evaluate how much jigless assembly was incorporated by the second team using the developed methodology to design for jigless assembly and assembly feature selection process to enable jigless assembly, against the first team who were using the common design, manufacturing and assembly methods of today.

Clearly, this would have been a very expensive and impractical way of testing and verifying the developed methodology to design for jigless assembly and assembly feature selection process to enable jigless assembly. However, a similar approach is required to replicate the ethos if not the scale of the ‘double-blind’ experimental study described in the previous paragraph.

This approach must still be able to compare the results of the application of the developed methodology to design for jigless assembly and assembly feature selection process to enable jigless assembly, against the results of the application of the common design, manufacturing and assembly methods of today, in terms of jigless assembly. It is also important that this comparison is carried out within an industrial setting because this is the actual scenario where any methodologies to design for jigless assembly would be applied.

In the light of this, the most practicable approach to test and verify the developed methodology to design for jigless assembly and assembly feature selection process to enable jigless assembly would be to apply them on an existing aircraft structure and compare the results of their application against the way the aircraft is currently assembled today. In effect, the application of the developed methodology to design for jigless assembly and assembly feature selection process to enable jigless assembly would be ‘reverse-engineering’ the chosen aircraft structure to see by how much it could be designed and manufactured in order to be assembled in a jigless manner.

Once this is complete, the third and final activity of this stage of the research methodology can be carried out – measuring by how much the application of the developed methodology to design for jigless assembly and assembly feature selection

process to enable jigless assembly has contributed towards the realisation of jigless assembly. This particular question then raises the issue of what measurement criteria to use to judge the effectiveness of the application of the developed methodology to design for jigless assembly and assembly feature selection process to enable jigless assembly. Any number of measurement criteria can be selected beginning with a simple calculation of the reduction, if any, of product-specific jigs, fixtures and tooling required in the assembly resulting from the application of the developed methodology to design for jigless assembly and assembly feature selection process to enable jigless assembly. However, returning to the section 1.1 describing the ‘Background to the Research Area’, the principal drawbacks with the general use of jigs are their high up-front cost and long lead-time. Consequently, any reduction in the use of jigs would directly lead to a reduction in cost and time, along with all the other disadvantages highlighted previously.

As proposed in section 3.2.1.1, the assembly cost is related to the assembly time because the longer the time the greater the cost and hence, cost is the prime factor. Following this argument, cost has been selected as the measurement criteria for judging the effectiveness of the application of the developed methodology to design for jigless assembly and assembly feature selection process to enable jigless assembly.

However, in order to accomplish a proper ‘cost analysis’ the whole spectrum of activities must be evaluated, compared and assessed, including design and manufacturing, as well as, the resultant cost savings or additions obtained at assembly.

The final stage of the research methodology to fully realise the research aim must be the demonstration of the ease of implementation of the methodology to design for jigless assembly and a process of selecting assembly features to enable jigless assembly within a commercial environment and how this is to be achieved. This stage of the research is important because it outlines the potential ways in which the research could move from the ‘laboratory environment’ to the ‘factory shop-floor’.

The previously described research methodology, which has been designed to realise the research aim, can therefore be summarised in the following research objectives.

- Development of a methodology to design for jigless assembly
- Definition of a selection process of assembly features, in particular for jigless assembly, and the formation of a Feature Library to facilitate jigless assembly
- Demonstration of the methodology, selection process and Feature Library in the redesign of a Case Study demonstrator structure for jigless assembly

1.5 Contribution to Knowledge

Phillips and Pugh (Phillips and Pugh, 1994) have indicated the following ways in which a research programme can be considered to have shown originality:

1. Setting down a major piece of new information in writing for the first time
2. Continuing a previously original piece of work
3. Carrying out original work designed by the supervisor
4. Providing a single, original technique, observation or result in an otherwise unoriginal but competent piece of research
5. Having many original ideas, methods and interpretations all performed by others under the direction of the postgraduate
6. Showing originality in testing someone else's idea
7. Carrying out empirical work that has not been done before
8. Making a synthesis that has not been done before
9. Using already known material but with a new interpretation
10. Trying out something in this country that has previously only been done in other countries
11. Taking a particular technique and applying it to a new area
12. Bringing new evidence to bear on an old issue
13. Being cross-disciplinary and using different methodologies
14. Looking at areas that people in the discipline have not looked at before
15. Adding to knowledge in a way that has not previously been done before

The author contends that this research satisfies ways 7, 8, 9, 11, 13, 14 and 15 as an original contribution to knowledge.

Specifically, this assertion is encapsulated by the following statements:

- The development of an integrated methodology to specifically design for jigless assembly (section 3.2), building upon the work of other researchers and practitioners in the fields (sections 2.5 and 2.6) along with new tools developed by other members of the jigless assembly research team
- The development of a selection process, which incorporates the novel use of Error Budgeting, amongst other tools, for the selection of appropriate assembly features to enable jigless assembly (section 4.3)
- The formation of a Feature Library to facilitate jigless assembly that supports fully the assembly feature selection process as part of the methodology to design for jigless assembly (section 4.4 and Appendix B)
- The demonstration of the use of the methodology, selection process and Feature Library in the redesign of the Case Study demonstrator structure for jigless assembly (section 5.4)

1.6 Thesis Structure

The thesis is organised as follows:

- **Chapter 1**
 - Introduces the background to and establishes the research area. The aims and objectives of the research, the research methodology and the contribution to knowledge are presented.
- **Chapter 2**
 - Provides definitions for jigs, fixtures, tooling and jigless assembly that are used as the standard throughout the thesis. The rationale for and examples of jigless assembly are presented, followed by a comprehensive

and critical review of the recent research into Design and Assembly Processes' Methods and Methodologies, Feature Based Methods and Tolerance Representation and Analysis.

- **Chapter 3**
 - Describes the development and application of a methodology to specifically design for jigless assembly, highlighting the tools incorporated into the methodology developed by other researchers and members of the jigless assembly research team.
- **Chapter 4**
 - Provides a definition of assembly features that has been used throughout the thesis. The development and application of an assembly feature selection process to enable jigless assembly is described in detail and the use of the Feature Library to facilitate jigless assembly is introduced.
- **Chapter 5**
 - Constitutes Part 1 of the Case Study and demonstrates the use of the methodology, selection process and Feature Library in the redesign of the Case Study demonstrator structure for jigless assembly.
- **Chapter 6**
 - Constitutes Part 2 of the Case Study and describes a Costings Analysis completed to compare the financial benefits of adopting a jigless assembly against the current methods of design, manufacture and assembly.
- **Chapter 7**
 - Provides an exploration of an investigation into the best possible route to implementation of the methodology, selection process and Feature Library within a commercial environment, though the use of a Knowledge Based System.
- **Chapter 8**
 - Discusses the results of the use of the methodology, selection process and Feature Library to enable jigless assembly developed in this research study. The relationship between this and the catalogue of previous research on Design and Assembly Processes' Methods and

Methodologies, Feature Based Methods and Tolerance Representation and Analysis is examined and the shortcomings of the tools and techniques developed in this research study are analysed.

- **Chapter 9**

- Presents the conclusions from the research carried out and outlines the recommendations for future work.